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**Insulation co-ordination –
Part 2: Application guidelines**

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**Insulation co-ordination –
Part 2: Application guidelines**

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

INSULATION CO-ORDINATION –

Part 2: Application guidelines

FOREWORD

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International Standard IEC 60071-2 has been prepared by IEC technical committee 28: Insulation co-ordination.

This fourth edition cancels and replaces the third edition published in 1996. This edition constitutes a technical revision.

This edition includes the following significant technical changes with respect to the previous edition:

- a) the annex on clearance in air to assure a specified impulse withstand voltage installation is deleted because the annex in IEC 60071-1 is overlapped;
- b) 4.2 and 4.3 on surge arresters are updated;
- c) 4.3.5 on very-fast-front overvoltages is revised. Annex J on insulation co-ordination for very-fast-front overvoltages in UHV substations is added;
- d) Annex H on atmospheric correction – altitude correction is added.
- e) Annex I on evaluation method of non-standard lightning overvoltage shape is added.

The text of this International Standard is based on the following documents:

FDIS	Report on voting
28/255/FDIS	28/256/RVD

Full information on the voting for the approval of this International Standard can be found in the report on voting indicated in the above table.

This document has been drafted in accordance with the ISO/IEC Directives, Part 2.

It has the status of a horizontal standard in accordance with IEC Guide 108.

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INSULATION CO-ORDINATION –

Part 2: Application guidelines

1 General

1 Scope

This part of IEC 60071 constitutes an application guidelines and deals with the selection of insulation levels of equipment or installations for three-phase electrical systems. Its aim is to give guidance for the determination of the rated withstand voltages for ranges I and II of IEC 60071-1 and to justify the association of these rated values with the standardized highest voltages for equipment.

This association is for insulation co-ordination purposes only. The requirements for human safety are not covered by this document.

This document covers three-phase systems with nominal voltages above 1 kV. The values derived or proposed herein are generally applicable only to such systems. However, the concepts presented are also valid for two-phase or single-phase systems.

This document covers phase-to-earth, phase-to-phase and longitudinal insulation.

This document is not intended to deal with routine tests. These are to be specified by the relevant product committees.

The content of this document strictly follows the flow chart of the insulation co-ordination process presented in Figure 1 of IEC 60071-1:2006. Clauses 4 to 7 correspond to the squares in this flow chart and give detailed information on the concepts governing the insulation co-ordination process which leads to the establishment of the required withstand levels.

This document emphasizes the necessity of considering, at the very beginning, all origins, all classes and all types of voltage stresses in service irrespective of the range of highest voltage for equipment. Only at the end of the process, when the selection of the standard withstand voltages takes place, does the principle of covering a particular service voltage stress by a standard withstand voltage apply. Also, at this final step, this document refers to the correlation made in IEC 60071-1 between the standard insulation levels and the highest voltage for equipment.

The annexes contain examples and detailed information which explain or support the concepts described in the main text, and the basic analytical techniques used.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

~~IEC 56: 1987, High-voltage alternating-current circuit-breakers~~

IEC 60060-1:1989 2010, High-voltage test techniques – Part 1: General definitions and test requirements

IEC 60071-1:1993 2006, *Insulation co-ordination – Part 1: Definitions, principles and rules*
IEC 60071-1:2006/AMD1:2010

~~IEC 99-1:1991, *Surge arresters – Part 1: Non-linear resistor type gapped surge arresters for a.c. systems*~~

~~IEC 99-4:1991, *Surge arresters – Part 4: Metal-oxide surge arresters without gaps for a.c. systems*~~

~~IEC 99-5:1996, *Surge arresters – Part 5: Selection and application recommendations – Section 1: General*~~

~~IEC 505:1975, *Guide for the evaluation and identification of insulation systems of electrical equipment*~~

~~IEC 507:1991, *Artificial pollution test on high-voltage insulators to be used on a.c. systems*~~

~~IEC 721-2-3:1987, *Classification of environmental conditions – Part 2: Environmental conditions appearing in nature – Air pressure*~~

~~IEC 815:1986, *Guide for the selection of insulators in respect of polluted conditions*~~

IEC 60505:2011, *Evaluation and qualification of electrical insulation systems*

IEC TS 60815-1, *Selection and dimensioning of high-voltage insulators intended for use in polluted conditions – Part 1: Definitions, information and general principles*

ISO 2533:1975, *Standard Atmosphere*

3 Terms, definitions, abbreviated terms and symbols

3.1 Terms and definitions

No terms and definitions are listed in this document.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at <http://www.electropedia.org/>
- ISO Online browsing platform: available at <http://www.iso.org/obp>

3.2 Abbreviated terms

MOSA	metal-oxide surge arrester
SFO	slow-front overvoltage
FFO	fast-front overvoltage
VFFO	very-fast-front overvoltage
LSA	line surge arrester
EGLA	externally gapped line arrester
NGLA	non-gapped line arrester
LIWV	lightning impulse withstand voltage
SIWV	switching impulse withstand voltage
SDWV	short-duration power-frequency withstand voltage
LIPL	lightning impulse protection level

SIPL	switching impulse protection level
GIS	gas-insulated switchgear
UHV	ultra high voltage
TOV	temporary power-frequency overvoltages
SVU	series varistor unit
ESDD	equivalent salt deposit density
TCV	trapped charge voltage

3.3 Symbols

For the purpose of this document, the following symbols and definitions apply. The symbol is followed by the unit to be normally considered, dimensionless quantities being indicated by (-).

Some quantities are expressed in p.u. A per unit quantity is the ratio of the actual value of an electrical parameter (voltage, current, frequency, power, impedance, etc.) to a given reference value of the same parameter.

A	(kV)	parameter characterizing the influence of the lightning severity for the equipment depending on the type of overhead line connected to it
a_1	(m)	length of the lead connecting the surge arrester to the line
a_2	(m)	length of the lead connecting the surge arrester to earth
a_3	(m)	length of the phase conductor between the surge arrester and the protected equipment
a_4	(m)	length of the active part of the surge arrester
B	(-)	factor used when describing the phase-to-phase discharge characteristic
C_e	(nF)	capacitance to earth of transformer primary windings
C_s	(nF)	series capacitance of transformer primary windings
C_2	(nF)	phase-to-earth capacitance of the transformer secondary winding
C_{12}	(nF)	capacitance between primary and secondary windings of transformers
C_{1in}	(nF)	equivalent input capacitance of the terminals ~~1~~ 1 of three-phase transformers
C_{2in}	(nF)	equivalent input capacitance of the terminals ~~2~~ 2 of three-phase transformers
C_{3in}	(nF)	equivalent input capacitance of the terminals ~~3~~ 3 of three-phase transformers
c	(m/μs)	velocity of light
c_f	(p.u.)	coupling factor of voltages between earth wire and phase conductor of overhead lines
E_0	(kV/m)	soil ionization gradient
F		function describing the cumulative distribution of overvoltage amplitudes, where $F(U) = 1 - P(U)$; see Clause B.3
f		function describing the probability density of overvoltage amplitudes
~~g~~ d_r	(-)	~~g~~ dividing ratio of capacitively transferred surges
H	(m)	altitude above sea-level
h	(-)	power-frequency voltage factor for transferred surges in transformers
H_t	(m)	height above ground

I	(kA)	lightning current amplitude
I_g	(kA)	limit lightning current in tower footing resistance calculation
I_n	(kA)	nominal discharge current of an arrester
J	(-)	winding factor for inductively transferred surges in transformers
K	(-)	gap factor taking into account the influence of the gap configuration on the strength
K_a	(-)	atmospheric altitude correction factor ~~[3.28 of IEC 71-1]~~
K_c	(-)	co-ordination factor ~~[3.25 of IEC 71-1]~~
K_s	(-)	safety factor ~~[3.29 of IEC 71-1]~~
K_{cd}	(-)	deterministic co-ordination factor
K_{co}	($\mu\text{s}/(\text{kVm})$)	corona damping constant
K_{cs}	(-)	statistical co-ordination factor
K_{f+}	(-)	gap factor for fast-front impulses of positive polarity
K_{f-}	(-)	gap factor for fast-front impulses of negative polarity
K_{ev}	(-)	evaluation factor of ratio for lightning overvoltage with respect to standard voltage shape
k	(-)	earth fault factor ~~[3.15 of IEC 71-1]~~
k_h	(-)	parameter for humidity correction
$\underline{L} \text{ } d$	(m)	separation distance between surge arrester and protected equipment
L_a	(m)	overhead line length yielding to an outage rate equal to the acceptable one (related to R_a)
L_t	(m)	overhead line length for which the lightning outage rate is equal to the adopted return rate (related to R_t)
L_{sp}	(m)	span length
M	(-)	number of insulations in parallel considered to be simultaneously stressed by an overvoltage
m	(-)	exponent in the atmospheric correction factor formula for external insulation withstand
N	(-)	number of conventional deviations between U_{50} and U_{spec} of a self-restoring insulation
n	(-)	number of overhead lines considered connected to a station in the evaluation of the impinging surge amplitude
P	(%)	probability of discharge of a self-restoring insulation
P_w	(%)	probability of withstand of self-restoring insulation
q	(-)	response factor of transformer windings for inductively transferred surges
Q_{rs}	(C)	repetitive charge transfer rating of an arrester
Q_{th}	(C)	thermal charge transfer rating of an arrester
R	(-)	risk of failure (failures per event)
R_a	(1/a)	acceptable failure rate for apparatus; for transmission lines, this parameter is normally expressed in terms of (1/a)/100 km
R_{hc}	(Ω)	high current value of the tower footing resistance
R_{km}	(1/(m.a))	overhead line outage rate per year for a design corresponding to the first kilometre in front of the station
R_{lc}	(Ω)	low current value of the tower footing resistance

R_p	(1/a)	shielding penetration rate of overhead lines
R_{sf}	(1/a)	shielding failure flashover rate of overhead lines
R_t	(1/a)	adopted overvoltage return rate (reference value)
R_u	(kV)	radius of a circle in the U^+/U^- plane describing the phase-phase-earth slow-front overvoltages
R_0	(Ω)	zero sequence resistance
R_1	(Ω)	positive sequence resistance
R_2	(Ω)	negative sequence resistance
S	(kV/ μ s)	steepness of a lightning surge impinging on a substation
S_e	(kV)	conventional deviation of phase-to-earth overvoltage distribution
S_p	(kV)	conventional deviation of phase-to-phase overvoltage distribution
S_{rp}	(kV/ μ s)	representative steepness of a lightning impinging surge
s_e	(-)	normalized value of the conventional deviation S_e (S_e referred to U_{e50})
s_p	(-)	normalized value of the conventional deviation S_p (S_p referred to U_{p50})
τt_s	(μ s)	travel time of a lightning surge
U	(kV)	amplitude of an overvoltage (or of a voltage)
U^+	(kV)	positive switching impulse component in a phase-to-phase insulation test
U^-	(kV)	negative switching impulse component in a phase-to-phase insulation test
$U_0 U_{spec}$	(kV)	truncation value of the discharge probability function $P(U)$ of a self-restoring insulation: $P(U \leq U_0 U_{spec}) = 0$
U_0^+	(kV)	equivalent positive phase-to-earth component used to represent the most critical phase-to-phase overvoltage
U_{1e}	(kV)	temporary overvoltage to earth at the neutral of the primary winding of a transformer
U_{2e}	(kV)	temporary overvoltage to earth at the neutral of the secondary winding of a transformer
U_{2N}	(kV)	rated voltage of the secondary winding of a transformer
U_{10}	(kV)	value of the 10 % discharge voltage of self-restoring insulation; this value is the statistical withstand voltage of the insulation defined in 3.23 b) of IEC 60071-1:2006
U_{16}	(kV)	value of the 16 % discharge voltage of self-restoring insulation
U_{50}	(kV)	value of the 50 % discharge voltage of self-restoring insulation
U_{50M}	(kV)	value of the 50 % discharge voltage of M parallel self-restoring insulations
U_{50RP}	(kV)	value of the 50 % discharge voltage of a rod-plane gap
U_c	(kV)	continuous operating voltage of an arrester
U_c^+	(kV)	positive component defining the centre of a circle which describes the phase-phase-earth slow-front overvoltages
U_c^-	(kV)	negative component defining the centre of a circle which describes the phase-phase-earth slow-front overvoltages
U_{cw}	(kV)	co-ordination withstand voltage of equipment [3.24 of IEC 71-1]
U_e	(kV)	amplitude of a phase-to-earth overvoltage

U_{et}	(kV)	truncation value of the cumulative distribution $F(U_e)$ of the phase-to-earth overvoltages: $F(U_e \geq U_{et}) = 0$ (see Clause B.3)
U_{e2}	(kV)	value of the phase-to-earth overvoltage having a 2 % probability of being exceeded: $F(U_e \geq U_{e2}) = 0,02$ (see Clause B.3)
U_{e50}	(kV)	50 % value of the cumulative distribution $F(U_e)$ of the phase-to-earth overvoltages (see Clause B.3)
U_l	(kV)	amplitude of the impinging lightning overvoltage surge
U_m	(kV)	highest voltage for equipment ~~[3.10 of IEC 71-1]~~
U_p	(kV)	amplitude of a phase-to-phase overvoltage
U_{p2}	(kV)	value of the phase-to-phase overvoltage having a 2 % probability of being exceeded: $F(U_p \geq U_{p2}) = 0,02$ (see Clause B.3)
U_{p50}	(kV)	50 % value of the cumulative distribution $F(U_p)$ of the phase-to-phase overvoltages (see Clause B.3)
U_r	(kV)	rated voltage of an arrester based on temporary overvoltages
U_s	(kV)	highest voltage of a system ~~[3.9 of IEC 71-1]~~
U_w	(kV)	standard withstand voltage
U_{pl}	(kV)	lightning impulse ~~protective~~ protection level of an ~~surge~~ arrester ~~[3.21 of IEC 71-1]~~
U_{ps}	(kV)	switching impulse ~~protective~~ protection level of an ~~surge~~ arrester ~~[3.21 of IEC 71-1]~~
U_{pt}	(kV)	truncation value of the cumulative distribution $F(U_p)$ of the phase-to-phase overvoltages: $F(U_p \geq U_{pt}) = 0$ (see Clause B.3)
U_{rp}	(kV)	amplitude of the representative overvoltage ~~[3.19 of IEC 71-1]~~
U_{rw}	(kV)	required withstand voltage ~~[3.27 of IEC 71-1]~~
U_{T1}	(kV)	overvoltage applied at the primary winding of a transformer which produces (by transference) an overvoltage on the secondary winding.
U_{T2}	(kV)	overvoltage at the secondary winding of a transformer produced (by transference) by an overvoltage applied on the primary winding.
UHV	(-)	ultra high voltage: the highest voltage of the transmission system exceeding 800 kV.
u	(p.u.)	per unit value of the amplitude of an overvoltage (or of a voltage) referred to $U_s \sqrt{2}/\sqrt{3}$.
w_{21}	(-)	ratio of transformer secondary to primary phase-to-phase voltage.
W	(kJ)	required energy absorption of an arrester.
W_{th}	(kJ/kV)	thermal energy rating of an arrester.
X	(m)	distance between struck point of lightning and substation.
X_p	(km)	limit overhead line distance within which lightning events have to be considered.
X_T	(km)	overhead line length to be used in simplified lightning overvoltage calculations.
X_0	(Ω)	zero sequence reactance of a system.
X_1	(Ω)	positive sequence reactance of a system.
X_2	(Ω)	negative sequence reactance of a system.
x	(-)	normalized variable in a discharge probability function $P(U)$ of a self-restoring insulation.

x_M	(-)	normalized variable in a discharge probability function $P(U)$ of M parallel self-restoring insulations.
Z	(kV)	conventional deviation of the discharge probability function $P(U)$ of a self-restoring insulation.
Z_0	(Ω)	zero sequence impedance.
Z_1	(Ω)	positive sequence impedance.
Z_2	(Ω)	negative sequence impedance.
Z_e	(Ω)	surge impedance of the overhead line earth wire.
Z_L	(Ω)	surge impedance of the overhead line.
Z_M	(kV)	conventional deviation of the discharge probability function $P(U)$ of M parallel self-restoring insulations.
Z_s	(Ω)	surge impedance of the substation phase conductor.
z	(-)	normalized value of the conventional deviation Z referred to U_{50} .
α	(-)	ratio of the negative switching impulse component to the sum of both components (negative + positive) of a phase-to-phase overvoltage.
β	(kV)	scale parameter of a Weibull cumulative function.
U_0	(kV)	truncation value of a Weibull cumulative function.
η	(-)	electric field utilization factor.
Φ		Gaussian integral function.
ϕ	(-)	inclination angle of a phase-to-phase insulation characteristic.
γ	(-)	shape parameter of a Weibull-3 cumulative function.
σ	(p.u.)	per unit value of the conventional deviation (S_e or S_p) of an overvoltage distribution.
ρ	(Ωm)	soil resistivity.
τ	(μs)	tail time constant of a lightning overvoltage due to back-flashovers on overhead lines.

4 Representative voltage stresses in service

4.1 Origin and classification of voltage stresses

In IEC 60071-1, the voltage stresses are classified by suitable parameters such as the duration of the power-frequency voltage or the shape of an overvoltage according to their effect on the insulation or on the ~~protective~~ protection device. The voltage stresses within these classes have several origins:

- continuous (power-frequency) voltages: they originate from the system operation under normal operating conditions;
- temporary overvoltages: they can originate from faults, switching operations such as load rejection, resonance conditions, non-linearities (ferroresonances) or by a combination of these;
- slow-front overvoltages: they can originate from faults, switching operations or direct lightning strokes to the conductors of overhead lines;
- fast-front overvoltages: they can originate from switching operations, lightning strokes or faults;
- very-fast-front overvoltages: they can originate from faults or switching operations in gas-insulated substations (GIS);
- combined overvoltages: they may have any origin mentioned above. They occur between the phases of a system (phase-to-phase), or on the same phase between separated parts of a system (longitudinal).

All the preceding overvoltage stresses, except combined overvoltages, are discussed as separate items under 4.3. Combined overvoltages are discussed where appropriate within one or more of these items.

In all classifications of voltage stresses, transference through transformers should be taken into account (see Annex D).

In general, all classes of overvoltages may exist in both voltage ranges I and II (see IEC 60071-1). However, experience has shown that certain voltage classifications are of more critical importance in a particular voltage range; this will be dealt with in this document. In any case, it should be noted that the best knowledge of the stresses (peak values and shapes) is obtained with detailed studies employing adequate models for the system and for the characteristics of the overvoltage limiting devices.

In the analysis of power system, digital simulation tools, such as electromagnetic transients simulation tool, have been used in many countries. In some countries, the comparison of analysis results and measured values is also performed in each country. Its validity has been confirmed up to UHV systems. For example, in the case of UHV lines in Japan and China, the maximum error between measurements and simulation for switching overvoltages is about 5 %, which is agreeable in the design of transmission lines. From more detailed information, reference can be made to the CIGRE activity [1]¹.

4.2 Characteristics of overvoltage ~~protective~~ protection devices

~~2.2.1~~ General remarks

~~Two types of standardized protective devices are considered:~~

- ~~— non-linear resistor type surge arresters with series gaps;~~
- ~~— metal-oxide surge arresters without gaps.~~

¹ Numbers in square brackets refer to the Bibliography.

~~In addition, spark gaps are taken into account as an alternative overvoltage limiting device, although standards are not available within IEC. When other types of protective devices are used, their protection performance shall be given by the manufacturer or established by tests. The choice among protective devices, which do not provide the same degree of protection, depends on various factors, e.g. the importance of the equipment to be protected, the consequence of an interruption of service, etc. Their characteristics will be considered from the point of view of insulation co-ordination and their effects will be discussed under the clauses dealing with the various overvoltage classes.~~

~~The protective devices shall be designed and installed to limit the magnitudes of overvoltages against which they protect equipment so that the voltage at the protective device and the connecting leads during its operation do not exceed an acceptable value. A primary point is that the voltage produced across the terminals of the arrester at any moment prior to and during its operation must be considered in the determination of the protection characteristics.~~

~~2.2.2 Non-linear resistor type surge arresters with series gaps~~

~~Where the surge arrester comprises a silicon carbide non-linear resistor with series gap, the characteristics are given in IEC 99-1. However, where the arrester consists of a metal-oxide non-linear resistor with series gap, the characteristics may differ from those given in IEC 99-1. The selection of arresters will be dealt with in IEC 99-5.~~

~~2.2.2.1 Protection characteristics related to fast-front overvoltages~~

~~The protection characteristics of a surge arrester are described by the following voltages (see table 8 of IEC 99-1):~~

- ~~— the sparkover voltage for a standard full lightning impulse;~~
- ~~— the residual voltage at the selected nominal discharge current;~~
- ~~— the front-of-wave sparkover voltage.~~

~~The lightning impulse protective level is taken as the highest of the following values:~~

- ~~— maximum sparkover voltage with 1,2/50 μ s impulse;~~
- ~~— maximum residual voltage at the selected nominal discharge current.~~

~~This evaluation of the protective level gives a value representing a generally acceptable approximation. For more information on wave-front protection by surge arresters, reference should be made to IEC 99-1.~~

~~NOTE — Traditionally, the front-of-wave sparkover voltage divided by 1,15 was included in the determination of the lightning impulse protective level. As the factor of 1,15 is technically justified only for oil-paper insulation or oil-immersed insulation like transformers, its application to other type of equipment may result in reduced insulation margin design. Therefore, this alternative has been omitted in the determination of the lightning impulse protective level.~~

~~2.2.2.2 Protection characteristics related to slow-front overvoltages~~

~~The protection of a surge arrester is characterized by the sparkover voltages for the switching impulse shapes specified in 8.3.5 of IEC 99-1.~~

~~The switching impulse protective level of a surge arrester is the maximum sparkover voltage for these impulse shapes.~~

~~If the arrester contains active gaps the total surge arrester voltage exhibited by the surge arrester when discharging switching surges shall be requested from the manufacturer, because it may be higher than the sparkover voltage.~~

~~2.2.3 Metal oxide surge arresters without gaps~~

~~The definition of such surge arresters and their characteristics are given in IEC 99-4.~~

~~2.2.3.1 Protection characteristics related to fast-front overvoltages~~

~~The protection of a metal-oxide surge arrester is characterized by the following voltages:~~

- ~~— the residual voltage at the selected nominal discharge current;~~
- ~~— the residual voltage at steep current impulse.~~

~~The lightning impulse protective level is taken for insulation co-ordination purposes as the maximum residual voltage at the selected nominal discharge current.~~

~~2.2.3.2 Protection characteristics related to slow-front overvoltages~~

~~The protection is characterized by the residual voltage at the specified switching impulse currents.~~

~~The switching impulse protective level is taken for insulation co-ordination purposes as the maximum residual voltage at the specified switching impulse currents.~~

~~The evaluation of protective levels gives a value representing a generally acceptable approximation. For a better definition of the protection performance of metal-oxide arresters, reference should be made to IEC 99-4.~~

~~2.2.4 Spark gaps~~

~~The spark gap is a surge protective device which consists of an open air gap between the terminals of the protected equipment. Although spark gaps are usually not applied in systems with U_m equal to or higher than 123 kV, they have proved satisfactory in practice in some countries with moderate lightning activity on systems operating at voltages up to 420 kV. The adjustment of the gap settings is often a compromise between absolute protection and consequences of spark gap operation.~~

~~The protection against overvoltages is characterized by the voltage-time characteristic of the gap for the various voltage shapes, the sparkover voltage dispersion and its polarity dependence. As no standard exists, these characteristics shall be requested from the manufacturer or established by the user on the basis of his own specifications.~~

~~NOTE — The fast voltage collapse and possible consequences on the insulation of windings have to be taken into account as an overvoltage characteristic.~~

4.2.1 General remarks

To ensure a safe, reliable and economic design and operation of high voltage networks, substations and equipment, the use of overvoltage protection devices is necessary.

The overvoltage protection devices shall be designed and installed to limit the magnitudes of overvoltages at the terminals of the equipment to be protected. Generally, an effective overvoltage protection is provided against slow-front overvoltages (SFO) and fast-front overvoltages (FFO).

It has to be regarded that, especially under FFO conditions, the overvoltage at the terminals of the overvoltage protection device and of the equipment to be protected are in general not the same. Inductive voltage drops across connecting leads and, much more, travelling wave processes are responsible for that.

Metal-oxide surge arresters (MOSA) without gaps are the "standard" arresters that are to be installed in all substations or directly at the pole mounted transformers and cable terminations in distribution lines. As surge arresters have a limited protection distance in the range of only a few, up to several tens of meters, depending on the system voltage level, they shall be installed as close as possible to the equipment to be protected. It may be necessary to install additional arresters at the line entrances of substations.

In some countries, MOSA with internal series gaps are used, which are applied to power systems of U_s up to 52 kV and which are covered by their own test standard (IEC 60099-6).

Besides this general application of MOSA as protection devices, line surge arresters (LSA) are often used for overhead transmission and distribution lines. They prevent insulator flashovers due to direct lightning strikes to the conductor of an unshielded line, by a shielding failure of a shielded line or due to back flashovers. For this purpose, externally gapped (EGLA) and non-gapped (NGLA) line arresters are used.

In addition, spark gaps are still sometimes taken into account as an alternative overvoltage limiting device, although standards are not available within IEC. In general, however, surge arresters should be preferred, as spark gaps produce steep voltage rises directly at the equipment to be protected, and their sparkover characteristic under FFO is sometimes critical. As no standard exists, their sparkover voltage versus time characteristics should be requested from the manufacturer or established by the user on the basis of his own specifications.

4.2.2 Metal-oxide surge arresters without gaps (MOSA)

4.2.2.1 General

The protection characteristics and application of MOSA are specified by IEC 60099-4 and IEC 60099-5.

The general procedure for selection of surge arresters is recommended in IEC 60099-5:

- determination of continuous operating voltage U_c ;
- determination of rated voltage U_r based on temporary overvoltages;
- determination of required energy absorption W and selection of nominal discharge current I_n ;
- determination of lightning impulse protection level U_{pl} and switching impulse protection level U_{ps} .

The protection levels can be used for representative slow-front and fast-front overvoltages. The co-ordination lightning impulse withstand voltage is determined under consideration of the lightning performance of the overhead lines, the acceptable failure rate of the equipment and the protection zone of the arrester.

The procedure is iterative. If, after the selection procedure, the protection levels of MOSA are too high, a lower continuous voltage, a higher nominal discharge current, a higher energy absorption capability or a reduced distance between the arrester and the protected equipment should be investigated. These measures will result either in lower MOSA residual voltages at a given impressed impulse current amplitude or in reduced overvoltage levels at the protected equipment for a given MOSA residual voltage.

The evaluation of protection levels gives a value representing a generally acceptable approximation. IEC 60099-5 gives detailed information about the protection performance of surge arresters.

4.2.2.2 Protection characteristics related to fast-front overvoltages

The following voltages characterize the fast-front protection level of a MOSA:

- lightning impulse protection level U_{pl} (also designated as LIPL);
- maximum residual voltage at steep current impulse.

The lightning impulse protection level is the maximum residual voltage at the nominal discharge current with an 8 μ s to 20 μ s (IEC 60099-4). For the insulation co-ordination of UHV

systems, surge arresters with low protection levels are of particular importance. The nominal discharge current for UHV arresters is typically 20 kA.

The resulting steep current impulse (with a front time of 1 μ s) protection voltage has to be considered in case of inductive voltage drops across the connection leads and the arrester length. The background is described in IEC 60099-5.

4.2.2.3 Protection characteristics related to slow-front overvoltages

The slow-front protection level of a MOSA is characterized by the switching impulse protection level U_{ps} (also designated as SIPL), which is the maximum residual voltage at the specified switching impulse discharge current as specified in IEC 60099-4 or at other current magnitudes on agreement between arrester manufacturer and user. Inductive voltage drops and travelling wave phenomena (protection distances) does not have to be considered.

For distribution arresters, switching impulse protection levels are not specified, as this is usually not a concern in distribution systems.

Especially for UHV arresters, other switching impulse currents may be used due to the possible suppression of slow-front overvoltages in UHV systems by adopting the following measures:

- controlled switching;
- circuit breakers with closing or closing/opening resistors;
- any combination of the above measures.

4.2.2.4 Energy handling capability

Energy handling capability of a MOSA is defined by two characteristics.

- a) For distribution ("D") arresters, which are further sub-classified as DH, DM, DL arresters (the letters "H", "M" and "L" in the designation standing for "high", "medium" and "low" duty, respectively):
 - repetitive charge transfer rating, Q_{rs} ;
 - thermal charge transfer rating, Q_{th} .
- a) For station ("S") arresters, which are further sub-classified as SH, SM, SL arresters:
 - repetitive charge transfer rating, Q_{rs} ;
 - thermal energy rating, W_{th} .

NOTE The former line discharge class system for station arresters does not exist anymore since IEC 60099-4:2014.

4.2.3 Line surge arresters (LSA) for overhead transmission and distribution lines

Purpose and characteristics of line surge arresters are described in IEC 60099-5. Non gapped line arresters (NGLA) are basically standard MOSA, tested according to IEC 60099-4, while externally gapped line arresters (EGLA) are tested according IEC 60099-8.

Energy handling capability of NGLAs is defined, in addition to the characteristics of MOSA, by their rated lightning impulse discharge capability.

EGLAs protect insulator assemblies only from lightning-caused flashovers. Therefore, it is important to determine the lightning impulse protection characteristics of the arrester comprising the sparkover voltage for fast-front and standard lightning impulse, and the residual voltages for the nominal discharge current. Additionally, the insulation withstand of the EGLA with respect to maximum slow-front overvoltages on the system has to be determined.

The correct co-ordination between flashover characteristics of the insulator assembly and the sparkover voltage of the EGLA shall be demonstrated with standard lightning impulse voltage and the residual voltages. Any sparkover operation under lightning impulse voltage shall occur in the external series gap of the EGLA without causing any flashover of the insulator assembly to be protected.

EGLAs have no operating duties for slow-front surges and temporary power-frequency overvoltages (TOV).

EGLAs shall not operate, in sound as well as in failed (overloaded) condition of the series varistor unit (SVU), at the specified switching impulse withstand voltage and maximum TOV level of the system.

The rated voltage of an EGLA is the maximum permissible RMS value of power frequency voltage between its terminals, at which it is designed to operate correctly. It shall, therefore, be equal to or higher than the maximum power-frequency temporary overvoltage expected in the intended installation. The rated voltage is also used as a reference parameter for the specification of operating and current interrupting characteristics.

EGLAs are classified by their nominal discharge currents and their high current impulse withstand capabilities. Two alternative classification systems are available ("Series X" and "Series Y"; for details see IEC 60099-8).

4.3 Representative voltages and overvoltages

4.3.1 Continuous (power-frequency) voltage

Under normal operating conditions, the power-frequency voltage can be expected to vary somewhat in magnitude and to differ from one point of the system to another. For purposes of insulation design and co-ordination, the representative continuous power-frequency voltage shall, however, be considered as constant and equal to the highest system voltage. In practice, up to 72,5 kV, the highest system voltage U_s may be substantially lower than the highest voltage for equipment U_m , while, with the increase of the voltage, both values tend to become equal.

4.3.2 Temporary overvoltages

4.3.2.1 General

Temporary overvoltages are characterized by their amplitudes, their voltage shape and their duration. All parameters depend on the origin of the overvoltages, and amplitudes and shapes may even vary during the overvoltage duration.

For insulation co-ordination purposes, the representative temporary overvoltage is considered to have the shape of the standard short duration (1 min) power-frequency voltage. Its amplitude may be defined by one value (the assumed maximum), a set of peak values, or a complete statistical distribution of peak values. The selected amplitude of the representative temporary overvoltage shall take into account

- the amplitude and duration of the actual overvoltage in service, and
- the amplitude/duration power frequency withstand characteristic of the insulation considered.

If the latter characteristic is not known, as a simplification the amplitude may be taken as equal to the actual maximum overvoltage having an actual duration of less than 1 min in service, and the duration may be taken as 1 min.

In particular cases, a statistical co-ordination procedure may be adopted describing the representative overvoltage by an amplitude/duration distribution frequency of the temporary overvoltages expected in service (see 5.3.2).

4.3.2.2 Earth faults

A phase-to-earth fault may result in phase-to-earth overvoltages affecting the two other phases. Temporary overvoltages between phases or across longitudinal insulation normally do not arise. The overvoltage shape is a power-frequency voltage.

The overvoltage amplitudes depend on the system neutral earthing and the fault location. Guidance for their determination is given in Annex A. In normal system configurations, the representative overvoltage amplitude should be assumed equal to its maximum value. Abnormal system configurations, for example system parts with unearthed neutrals in a normally earthed neutral system, should be dealt with separately, taking into account their probability of occurrence simultaneously with earth faults.

The duration of the overvoltage corresponds to the duration of the fault (until fault clearing). In earthed neutral systems, it is generally less than 1 s. In resonant earthed neutral systems with fault clearing it is generally less than 10 s. In systems without earth-fault clearing, the duration may be several hours. In such cases, it may be necessary to define the continuous power-frequency voltage as the value of temporary overvoltage during earth fault.

NOTE Attention is drawn to the fact that the highest voltage at power-frequency which ~~may~~ can appear on a sound phase during the occurrence of an earth fault depends not only on the earth-fault factor but also on the value of the operating voltage at the time of the fault which can be generally taken as the highest system voltage U_s .

4.3.2.3 Load rejection

Phase-to-earth and longitudinal temporary overvoltages due to load rejection depend on the rejected load, on the system layout after disconnection and on the characteristics of the sources (short-circuit power at the station, speed and voltage regulation of the generators, etc.).

The three phase-to-earth voltage rises are identical and, therefore, the same relative overvoltages occur phase-to-earth and phase-to-phase. These rises may be especially important in the case of load rejection at the remote end of a long line (Ferranti effect) and they mainly affect the apparatus at the station connected on the source side of the remote open circuit-breaker.

The longitudinal temporary overvoltages depend on the degree of phase angle difference after network separation, the worst possible situation being a phase opposition.

NOTE From the point of view of overvoltages, a distinction should be made between various types of system layouts. As examples, the following extreme cases ~~may~~ can be considered:

- systems with relatively short lines and high values of the short-circuit power at the terminal stations, where low overvoltages occur;
- systems with long lines and low values of the short-circuit power at the generating site, which are usually in the extra-high voltage range at their initial stage, and on which very high overvoltages ~~may~~ can arise if a large load is suddenly disconnected.

In analysing temporary overvoltages, it is recommended that consideration be given to the following (where the 1,0 p.u. reference voltage equals $U_s \sqrt{2}/\sqrt{3}$).

- In moderately extended systems, a full load rejection can give rise to phase-to-earth overvoltages with amplitude usually below 1,2 p.u. The overvoltage duration depends on the operation of voltage-control equipment and may be up to several minutes;
- In extended systems, after a full load rejection, the phase-to-earth overvoltages may reach 1,5 p.u., or even more when Ferranti or resonance effects occur. Their duration may be in the order of some seconds;
- If only static loads are on the rejected side, the longitudinal temporary overvoltage is normally equal to the phase-to-earth overvoltage. In systems with motors or generators on

the rejected side, a network separation can give rise to a longitudinal temporary overvoltage composed of two phase-to-earth overvoltage components in phase opposition, whose maximum amplitude is normally below 2,5 p.u. (greater values can be observed for exceptional cases such as very extended high-voltage systems).

4.3.2.4 Resonance and ferroresonance

Temporary overvoltages due to resonance and ferroresonance generally arise when circuits with large capacitive elements (lines, cables, series compensated lines) and inductive elements (transformers, shunt reactors) having non-linear magnetizing characteristics are energized, or as a result of load rejections.

Temporary overvoltages due to resonance phenomena can reach extremely high values. They shall be prevented or limited by measures recommended in 4.3.2.7. They shall therefore not normally be considered as the basis for the selection of the surge arrester rated voltage or for the insulation design unless these remedial measures are not sufficient (see 4.3.2.8).

4.3.2.5 Longitudinal overvoltages during synchronization

The representative longitudinal temporary overvoltages are derived from the expected overvoltage in service which has an amplitude equal to twice the phase-to-earth operating voltage and a duration of several seconds to some minutes.

Furthermore, when synchronization is frequent, the probability of occurrence of an earth fault and consequent overvoltage shall be considered. In such cases, the representative overvoltage amplitudes are the sum of the assumed maximum earth-fault overvoltage on one terminal and the continuous operating voltage in phase opposition on the other.

4.3.2.6 Combinations of temporary overvoltage origins

4.3.2.6.1 General

Temporary overvoltages of different origins shall be treated as combined only after careful examination of their probability of simultaneous occurrence. Such combinations may lead to higher arrester ratings with the consequence of higher protection and insulation levels; this is technically and economically justified only if this probability of simultaneous occurrence is sufficiently high.

4.3.2.6.2 Earth fault with load rejection

The combination earth fault with load rejection can exist when, during a fault on the line, the load side breaker opens first and the disconnected load causes a load rejection overvoltage in the still faulted part of the system until the supply side circuit-breaker opens.

The combination earth fault with load rejection can also exist when a large load is switched off and the temporary overvoltage due to this causes a subsequent earth fault on the remaining system. The probability of such an event, however, is small when the overvoltages due to the change of load are themselves small, and a subsequent fault is only likely to occur in extreme conditions such as in ~~heavy~~ massive pollution conditions.

The combination can further occur as a result of a line fault followed by failure of a circuit-breaker to open. The probability of such a combination, although small, is not negligible since these events are not statistically independent. Such an occurrence, which results in a generator connected through a transformer to a faulted long line, can result in significant overvoltage on the healthy phases. The overvoltage consists of a slow-front transient and a prolonged variable temporary overvoltage which is a function of generator characteristics and governor-voltage regulator actions.

If such combinations are considered probable, system studies are recommended. Without such studies, one may be led to believe that it is necessary to combine these overvoltages, but this is considered too pessimistic for the following reasons:

- the earth fault factor changes when it is related to the load rejection overvoltage;
- the system configuration has changed after the load change – for example, the earth fault factor at generator transformers with earthed neutral is less than 1 after being disconnected from the system;
- for system transformers, the loss of full rated load is not usual.

4.3.2.6.3 Other combinations

As resonance phenomena should be avoided, their combination with other origins should only be considered as an additional result of these resonances. In some systems, however, it is not readily possible to avoid resonance phenomena, and, for such systems, it is important to carry out detailed studies.

4.3.2.7 Limitation of temporary overvoltages

4.3.2.7.1 Earth-fault overvoltages

Earth-fault overvoltages depend on the system parameters and can only be controlled by selecting these parameters during the system design. The overvoltage amplitudes are normally less severe in earthed neutral systems. However, an exception exists in earthed neutral systems, a part of which in unusual situations can become separated with unearthed transformer neutrals. In such a situation, the duration of the high overvoltages due to earth faults in the separated part can be controlled by fast earthing at these neutrals, by switches or by specially selected neutral surge arresters, which short-circuit the neutral after failing.

4.3.2.7.2 Sudden changes of load

These overvoltages can be controlled by shunt reactors, series capacitors or static compensators.

4.3.2.7.3 Resonance and ferroresonance

These overvoltages should be limited by de-tuning the system from the resonance frequency, by changing the system configuration, or by damping resistors.

4.3.2.8 Surge arrester protection against temporary overvoltages

Usually, the selection of the rated voltage of the surge arrester is based upon the envelope of the temporary overvoltage expected, taking into account the energy dissipation capability of the surge arrester. In general, matching the surge arrester rating with the temporary overvoltage stress is more critical in range II, where the margins are lower, than in range I. Usually, the energy capability of the surge arrester under temporary overvoltage stress is expressed as an amplitude/duration characteristic furnished by the manufacturer.

For practical purposes, surge arresters do not limit temporary overvoltages. An exception is given for temporary overvoltages due to resonance effects, for which surge arresters may be applied to limit or even to prevent such overvoltages. For such an application, careful studies on the thermal stresses imposed on the surge arresters should be performed to avoid their overloading.

4.3.3 Slow-front overvoltages

4.3.3.1 General

Slow-front overvoltages have front durations of some tens to some thousands of microseconds and tail durations in the same order of magnitude, and are oscillatory by nature. They generally arise from:

- line energization and re-energization;
- faults and fault clearing;
- load rejections;
- switching of capacitive or inductive currents;
- distant lightning strokes to the conductor of overhead lines.

The representative voltage stress is characterized by

- a representative voltage shape, and
- a representative amplitude which can be either an assumed maximum overvoltage or a probability distribution of the overvoltage amplitudes.

The representative voltage shape is the standard switching impulse (time to peak 250 μ s, and time to half-value on the tail 2 500 μ s). The representative amplitude is the amplitude of the overvoltage considered independently from its actual time to peak. However, in some systems in range II, overvoltages with very long fronts may occur and the representative amplitude may be derived by taking into account the influence of the front duration upon the dielectric strength of the insulation.

The probability distribution of the overvoltages without surge arrester operation is characterized by its 2 % value, its deviation and its truncation value. Although not perfectly valid, the probability distribution can be approximated by a Gaussian distribution between the 50 % value and the truncation value, above which no values are assumed to exist. Alternatively, a modified Weibull distribution may be used (see Annex B).

The assumed maximum value of the representative overvoltage is equal to the truncation value of the overvoltages (see 4.3.3.2 to 4.3.3.7) or equal to the switching impulse ~~protective~~ **protection** level of the surge arrester (see 4.3.3.8), whichever is the lower value.

4.3.3.2 Overvoltages due to line energization and re-energization

4.3.3.2.1 General

A three-phase line energization or re-energization produces switching overvoltages on all three phases of the line. Therefore, each switching operation produces three phase-to-earth and, correspondingly, three phase-to-phase overvoltages [1].

In the evaluation of the overvoltages for practical application, several simplifications have been introduced. Concerning the number of overvoltages per switching operation, two methods are in use.

- Phase-peak method: from each switching operation, the highest peak value of the overvoltage on each phase-to-earth or between each combination of phases is included in the overvoltage probability distribution, i.e. each operation contributes three peak values to the representative overvoltage probability distribution. This distribution then has to be assumed to be equal for each of the three insulations involved in each part of insulation, phase-to-earth, phase-to-phase or longitudinal.
- Case-peak method: from each switching operation, the highest peak value of the overvoltages of all three phases to earth or between all three phases is included in the overvoltage probability distribution, i.e. each operation contributes one value to the

representative overvoltage distribution. This distribution is then applicable to one insulation within each type.

The overvoltage amplitudes due to line energization depend on several factors including type of circuit-breaker (closing resistor or not), nature and short-circuit power of the busbar from which the line is energized, the nature of the compensation used and the length of the energized line, type of the line termination (open, transformer, surge arrester), etc.

Three-phase re-energizations may generate high slow-front overvoltages due to trapped charges on the re-energized line. At the time of the re-energization, the amplitude of the overvoltage remaining on the line (due to the trapped charge) may be as high as the temporary overvoltage peak. The discharge of this trapped charge depends on the equipment remaining connected to the line, insulator surface conductivity, conductor corona conditions, and re-closing time.

In normal systems single-phase re-energization (re-closing) does not generate overvoltages higher than those from energization. However, for lines in which resonance or Ferranti effects may be significant, single-phase re-closing may result in higher overvoltages than three-phase energization.

The correct probability distribution of the overvoltage amplitudes can be obtained only from careful simulation of switching operations by digital computation, transient analysers, etc., and typical values such as shown in Figure 1 should be considered only as a rough guide. All considerations relate to the overvoltages at the open end of the line (receiving end). The overvoltages at the sending end may be substantially smaller than those at the open end. For reasons given in Annex C, Figure 1 may be used for both the phase-peak and case-peak methods.

4.3.3.2.2 Phase-to-earth overvoltages

A procedure for the estimation of the probability distribution of the representative overvoltages is given in Annex C.

As a rough guide, Figure 1 shows the range of the 2 % overvoltage values (in p.u. of $U_s \sqrt{2}/\sqrt{3}$) which may be expected between phase and earth without limitation by surge arresters [5]. The data in Figure 1 are based on a number of field results and studies and include the effects of most of the factors determining the overvoltages.

Figure 1 should be used as an indication of whether or not the overvoltages for a given situation can be high enough to cause a problem. If so, the range of values indicates to what extent the overvoltages can be limited. For this purpose, detailed studies would be required.

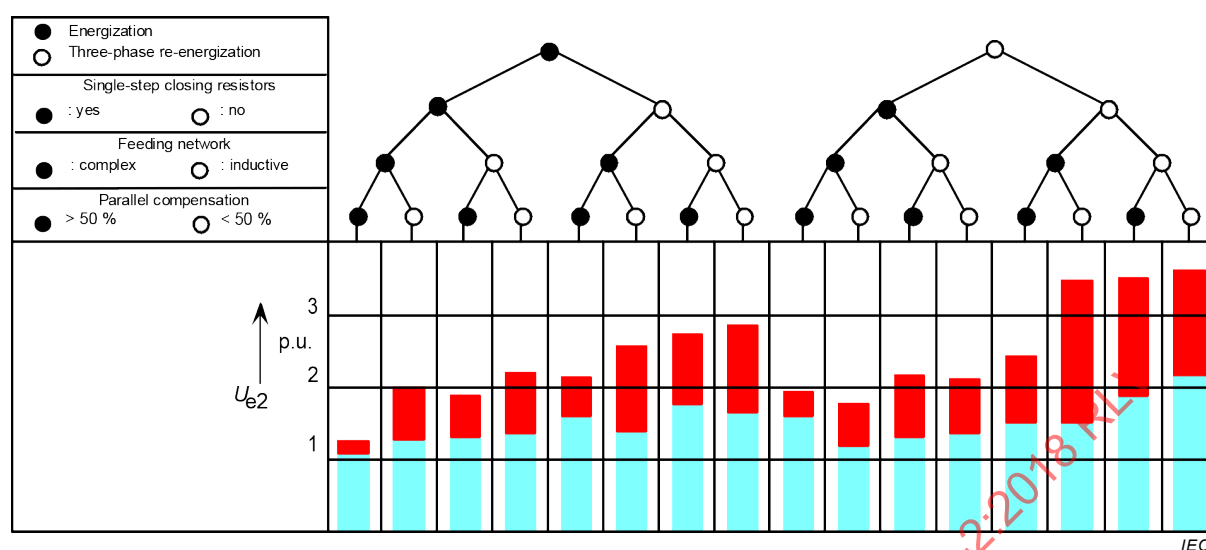


Figure 1 – Range of 2 % slow-front overvoltages at the receiving end due to line energization and re-energization

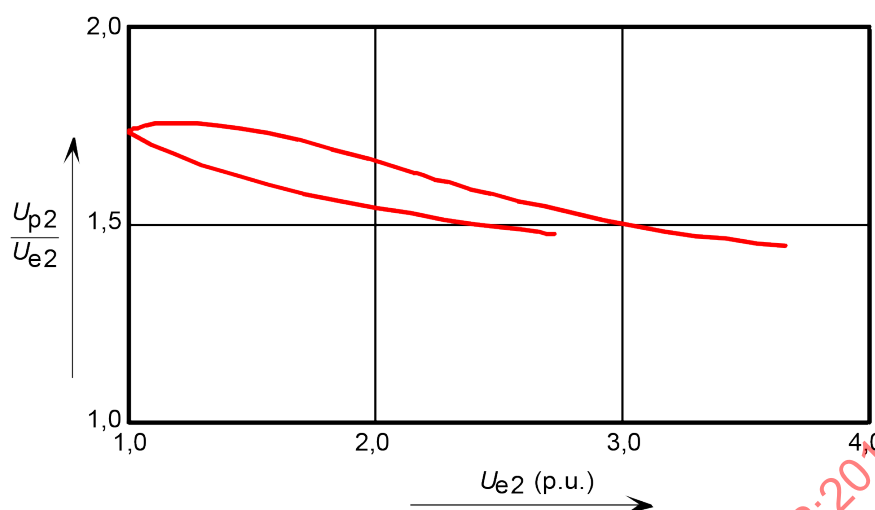
4.3.3.2.3 Phase-to-phase overvoltages

In the evaluation of the phase-to-phase overvoltages, an additional parameter needs to be added. As the insulation is sensitive to the subdivision of a given phase-to-phase overvoltage value into two phase-to-earth components, the selection of a specific instant shall take into account the insulation characteristics. Two instants have been selected [1]:

- instant of phase-to-phase overvoltage peak: this instant gives the highest phase-to-phase overvoltage value. It represents the highest stress for all insulation configurations, for which the dielectric strength between phases is not sensitive to the subdivision into components. Typical examples are the insulation between windings or short air clearances;
- phase-to-phase overvoltage at the instant of the phase-to-earth overvoltage peak: although this instant gives lower overvoltage values than the instant of the phase-to-phase overvoltage peak, it may be more severe for insulation configurations for which the dielectric strength between phases is influenced by the subdivision into components. Typical examples are large air clearances, for which the instant of the positive phase-to-earth peak is most severe, or gas-insulated substations (three-phase enclosed), for which the negative peak is most severe.

The statistical characteristics of the phase-to-phase overvoltages and the relations between the values belonging to the two instants are described in Annex C. It is concluded that for all insulation types, except for air clearances in range II, the representative overvoltage between phases is equal to the phase-to-phase overvoltage peak. For air clearances in range II, and more particularly for system voltages equal to or greater than 500 kV, the representative phase-to-phase overvoltage should be determined from the overvoltage peaks phase-to-earth and phase-to-phase as described in Annex C.

The 2 % phase-to-phase overvoltage value can approximately be determined from the phase-to-earth overvoltage. Figure 2 shows the range of possible ratios between the 2 % values phase-to-phase and phase-to-earth. The upper limit of this range applies to fast three-phase re-energization overvoltages, the lower limit to three-phase energization overvoltages.



NOTE—The upper part of the indicated range may be applied to three-phase re-energization, the lower part to energization.

Figure 2 – Ratio between the 2 % values of slow-front overvoltages phase-to-phase and phase-to-earth

4.3.3.2.4 Longitudinal overvoltages

Longitudinal overvoltages between the terminals during energization or re-energization are composed of the continuous operating voltage at one terminal and the switching overvoltage at the other. In synchronized systems, the highest switching overvoltage peak and the operating voltage have the same polarity, and the longitudinal insulation has a lower overvoltage than the phase-to-earth insulation.

The longitudinal insulation between non-synchronous systems, however, can be subjected to energization overvoltages at one terminal and the normal operating voltage peak of opposite polarity at the other.

For the slow-front overvoltage component, the same principles as for the phase-to-earth insulations apply.

4.3.3.2.5 Assumed maximum overvoltages

If no protection by surge arresters is applied, the assumed maximum energization or re-energization overvoltage is:

- for the phase-to-earth overvoltage: the truncation value U_{et} ;
- for the phase-to-phase overvoltage: the truncation value U_{pt} or, for the external insulation in range II, the value determined according to Annex C, both subdivided into two equal components with opposite polarities;
- for the longitudinal overvoltage: the truncation value U_{et} of the phase-to-earth overvoltage due to energization at one terminal, and the opposite polarity peak of the normal operating voltage at the other terminal.

This definition of the maximum longitudinal overvoltage assumes that power frequencies are synchronized (via a parallel path) at both terminals so that the longitudinal overvoltages due to re-energization need not be considered separately (because the effect of any trapped charge is taken into account by this assumption).

4.3.3.3 Fault and fault-clearing overvoltages

Slow-front overvoltages are generated at fault-initiation and fault-clearing by the change in voltage from operating voltage to temporary overvoltage on the healthy phases and the return from a value close to zero back to the operating voltage on the faulted phase. Both origins cause only overvoltages between phase and earth. The overvoltages between phases can be neglected. Conservative estimates for the assumed maximum value of the representative overvoltage U_{et} are as follows:

- fault initiation $U_{et} = (2k - 1) U_s \sqrt{2}/\sqrt{3}$ (kV crest)

where k is the earth fault factor.

- fault clearing $U_{et} = 2,0 U_s \sqrt{2}/\sqrt{3}$ (kV crest)

In range I, overvoltages caused by earth faults shall be considered for systems with isolated or resonant earthed transformer neutrals in which the earth fault factor is approximately equal to $\sqrt{3}$. For these systems, the insulation co-ordination can be based on the assumed maximum overvoltage and the probability of their amplitudes needs no consideration.

In range II, when the overvoltages due to line energization or re-energization are controlled to values below 2 p.u., fault and fault clearing overvoltages require careful examination if they are not controlled to the same degree.

4.3.3.4 Overvoltages due to load rejection

Slow-front overvoltages due to load rejection are only of importance in systems of range II in which the energization and re-energization overvoltages are controlled to values below 2 p.u. In these cases, they need examination, especially when generator transformers or long transmission lines are involved.

4.3.3.5 Overvoltages due to switching of inductive and capacitive currents

The switching of inductive or capacitive currents can give rise to overvoltages, which may require attention. In particular, the following switching operations should be taken into consideration:

- interruption of the starting currents of motors;
- interruption of inductive currents, for example when interrupting the magnetizing current of a transformer or when switching off a shunt reactor [6];
- switching and operation of arc furnaces and their transformers, which may lead to current chopping;
- switching of unloaded cables and of capacitor banks;
- interruption of currents by high-voltage fuses.

Restrikes of circuit-breakers occurring while interrupting capacitive currents (switching off unloaded lines, cables or capacitor banks) may generate particularly dangerous overvoltages and the use of restrike-free breakers is necessary. Furthermore, when energizing capacitor banks, in particular ungrounded banks, care should be taken to assess the phase-to-phase overvoltages (see also 4.3.4.3).

4.3.3.6 Slow-front lightning overvoltages

In systems with long lines (longer than 100 km), slow-front lightning overvoltages originate from distant lightning strokes to the phase conductor, when the lightning current is sufficiently small so as not to cause a flashover of the line insulation and when the strike occurs at a sufficient distance from the considered location to produce a slow-front.

As lightning currents have times to half-value rarely exceeding 200 µs, overvoltages with high amplitudes and times-to-crest critical for the insulation do not occur. Slow-front lightning overvoltages, therefore, are of minor importance for insulation co-ordination and are usually neglected.

4.3.3.7 Limitation of slow-front overvoltages

The most commonly used method of limiting line switching overvoltages is by the use of closing resistors on line breakers. Other means, like point-on-wave control and varistors across interrupting chambers, can also be used to limit overvoltages due to line energization and inductive or capacitive switching.

Inductive voltage transformers connected to the line terminals effectively reduce the charges trapped on the phases of the line after opening. The slow front overvoltages due to a subsequent three-phase re-energization are thus limited to the level of simple line energization.

The saturation effect of the switching impulse strength has a large impact to the air clearances. Closing or opening resistors, surge arresters and/or controlled switching can reduce switching overvoltages.

4.3.3.8 Surge arrester protection against slow-front overvoltages

Metal-oxide arresters without gaps and specially designed gapped arresters are suitable to protect against slow-front overvoltages in systems with moderate temporary overvoltages, whereas non-linear resistor type arresters operate for slow-front overvoltages only in extreme cases due to the sparkover characteristics of the series gap.

NOTE ~~It should be noted that~~ When the arresters are installed at the ends of long transmission lines for the purpose of limiting slow-front overvoltages, the overvoltages in the middle of the line ~~may~~ can be substantially higher than at the line ends.

As a general rule, it can be assumed that metal-oxide arresters limit the phase-to-earth overvoltage amplitudes (kV peak) to approximately twice the arrester rated voltage (kV RMS). This means that metal-oxide surge arresters are suitable for limiting slow-front overvoltages due to line energization and re-energization and switching of inductive and capacitive currents, but not, in general, overvoltages caused by earth faults and fault clearing, as the expected amplitudes of the latter are too low (exception may be made in the case of faults occurring on series-compensated lines).

Overvoltages originating from line energization and re-energization give currents normally less than about 0,5 kA to 2 kA through the arresters (see IEC 60099-4). In this current range, the knowledge of the exact current amplitude is not so important owing to the extreme non-linearity of the metal-oxide material. The slight dependence on current front times which the metal-oxide surge arresters exhibit is also negligible for slow-front overvoltages and can be neglected. Furthermore, it is not necessary to take separation effects into account within substations. Distant overhead line insulation, however, may be stressed by overvoltages substantially higher than the ~~protective~~ protection level.

Surge arresters are usually installed phase-to-earth and it should be observed that, if metal-oxide arresters are used to limit slow-front overvoltages to a level lower than 70 % of the 2 % value of the uncontrolled overvoltage phase-to-earth, the phase-to-phase overvoltages may reach about twice the phase-to-earth ~~protective~~ protection level of the arrester. The phase-to-phase overvoltage will then consist of two phase-to-earth components with the most frequent subdivision 1:1 [7]. See also 5.3.4.1.

The assumed maximum value of the representative phase-to-earth overvoltage is equal to the ~~protective~~ protection level of the surge arrester: $U_{rp} = U_{ps}$.

For the phase-to-phase overvoltages, it is twice the ~~protective~~ protection level or the truncation value of the phase-to-phase overvoltages determined in Annex C, whichever is the smaller value. If lower phase-to-phase overvoltages are required, additional arresters between phases should be installed.

In all cases, the application of surge arresters to control slow-front overvoltages shall take into account the required duty cycle and energy dissipation requirements in choosing the appropriate surge arrester classification.

4.3.4 Fast-front overvoltages

4.3.4.1 Lightning overvoltages affecting overhead lines

Lightning overvoltages are caused by direct strokes to the phase conductors or by back-flashovers, or are induced by lightning strokes to earth close to the line. Induced lightning surges generally cause overvoltages below 400 kV on the overhead line and are, therefore, of importance only for systems in the lower system voltage range. Owing to the high insulation withstand, back-flashovers are less probable in range II than in range I and are rare on systems at 500 kV and above.

The representative shape of the lightning overvoltage is the standard lightning impulse (1,2/50 μ s). The representative amplitude is either given as an assumed maximum or by a probability distribution of peak values usually given as the peak value dependent on the overvoltage return rate.

4.3.4.2 Lightning overvoltages affecting substations

4.3.4.2.1 General

The lightning overvoltages in substations and their rates of occurrence depend on

- the lightning performance of the overhead lines connected to it,
- the substation layout, size and in particular the number of lines connected to it, and
- the instantaneous value of the operating voltage (at the moment of the stroke).

The severity of lightning overvoltages for the substation equipment is determined from the combination of these three factors, and several steps are necessary to assure adequate protection. The amplitudes of the overvoltages (without limitation by surge arrester) are usually too high to base insulation co-ordination on these values. In some cases, however, in particular with cable connected substations, the self-protection provided by the low surge impedance of the cables may reduce the amplitudes of the lightning overvoltages to suitably low values (see Annex E).

For the phase-to-phase and the longitudinal insulation, the instantaneous power frequency voltage value on the opposite terminals ~~must~~ shall be considered. For the phase-to-phase insulation, it can be assumed that the effects of power-frequency voltage and coupling between the overhead line conductors cancel each other and the opposite terminal can be considered as earthed. For the longitudinal insulation, however, such cancelling effects do not exist and the power-frequency voltage ~~must~~ shall be taken into account.

4.3.4.2.2 Direct strokes

Shielding penetrations occur at a random point on the power-frequency wave. The effect of the power-frequency at the opposite terminal of a longitudinal insulation has to be taken into account by

- calculating the lightning overvoltage return rates for different instantaneous values of the operating voltage,
- evaluating the insulation failure probability for the various subdivisions into components – usually the sum of the two components is the decisive parameter,

- determining the insulation failure rate dependent on the sum of the lightning overvoltage and of the instantaneous value of power-frequency, and
- applying the performance criterion to this expected failure rate to obtain the necessary sum of the two components.

If this sum is subdivided into a lightning impulse component equal to the representative lightning overvoltage phase-to-earth and a power-frequency component, the power-frequency voltage component will be smaller than the operating voltage phase-to-earth peak. It has been found that a factor of 0,7 may be considered suitable. This means that, for shielding penetration, the longitudinal representative overvoltage should be composed of the representative lightning overvoltage to earth at one terminal and 0,7 times the operating voltage phase-to-earth peak with opposite polarity at the other.

4.3.4.2.3 Back flashovers

Back flashovers are most likely to occur on the phase which has the highest instantaneous power-frequency voltage value of opposite polarity. This means that, for substations, the representative longitudinal lightning overvoltage shall be equal to the sum of the representative lightning overvoltage to earth at one terminal and of the operating voltage peak at the other (opposite polarity).

4.3.4.3 Overvoltages due to switching operations and faults

Fast-front switching overvoltages occur when equipment is connected to or disconnected from the system via short connections mainly within substations. Fast-front overvoltages can also occur when external insulation flashes over. Such events can cause particularly severe stresses on nearby internal insulation (such as windings).

Although in general oscillatory, for insulation co-ordination purposes the representative overvoltage shape can be considered to correspond to the standard lightning impulse (1,2/50 μ s). However, special attention should be paid to equipment with windings because of high inter-turn stresses.

The maximum peak overvoltages depend on type and behaviour of the switching equipment. As the overvoltage peak values are usually smaller than those caused by lightning, their importance is restricted to special cases. It is, therefore, technically justified to characterize the amplitude of the representative overvoltage by the maximum following values (in p.u. of $U_s \sqrt{2}/\sqrt{3}$):

- circuit-breaker switching without restrike: 2 p.u.;
- circuit-breaker switching with restrike: 3 p.u.;

NOTE When switching reactive loads, some types of medium voltage circuit breakers tend to produce multiple transient current interruptions resulting in overvoltages up to 6 p.u. unless appropriate protection measures are taken.

- disconnecter switching: 3 p.u.

As simultaneous occurrence of fast-front switching overvoltages on more than one phase is highly improbable, one can assume that phase-to-phase overvoltages higher than phase-to-earth overvoltages do not exist. For the latter, the previously defined assumed maximum values can be used to check the importance of such overvoltages. If they determine the insulation lightning impulse withstand voltage, more careful investigations are recommended.

4.3.4.4 Limitation of fast-front overvoltage occurrences

Lightning overvoltage occurrences can be limited by appropriate design for the overhead lines. Possible design measures for the limitation of lightning overvoltage occurrences are the following:

- for direct lightning strokes to conductors: appropriate earth-wire shielding design;

- for back flashovers: reduction of the tower footing earthing impedance or addition of insulation;
- usage of line surge arresters.

In some cases, earthed crossarms or spark gaps have been used close to substations in an attempt to limit the amplitude of incoming lightning overvoltages. However, such measures tend to increase the likelihood of flashovers near the station with the consequent generation of fast-front surges. Furthermore, special attention should be given to shielding and tower earthing near the station to lower the probability of back flashovers at this location.

Since transmission towers in range II are taller and inter-phase distances are longer than those in range I, direct lightning strokes to phase conductors should be a matter of some concern in range II even though a ground wire is equipped, especially over 550 kV systems.

The severity of fast-front overvoltages generated by switching operations can be limited by the selection of adequate switching equipment (restrike-free interrupters or breakers, low current chopping characteristic, use of opening or closing resistors, point-on-wave control, etc.).

4.3.4.5 Surge arrester protection against fast-front overvoltages

The protection afforded by surge arresters against fast-front overvoltages depends on

- the amplitude and shape of the overvoltage,
- the protection characteristic of the surge arrester,
- the amplitude and shape of the current through the surge arrester,
- the surge impedance and/or capacitance of the protected equipment,
- the distance between arrester and protected equipment including earthing connections (see Figure 3), and
- the number and surge impedance of the connected lines.

For protection against lightning overvoltages, surge arresters with the following nominal discharge currents are generally applied:

- for systems with U_m in range I: 5 kA or 10 kA;
- for systems with U_m in range II: 10 kA or 20 kA.

When currents through the arrester are expected to be higher than its nominal discharge current, it ~~must~~ shall be verified that the corresponding residual voltages still provide a suitable overvoltage limitation.

For the determination of the energy absorption (due to lightning) of surge arresters installed in a substation, it is usually sufficient to assume that the representative amplitude of the prospective lightning overvoltage reaching the substation is equal to the negative 50 % lightning impulse withstand voltage of the overhead line. However, for the total energy absorption, one should consider the possibility that a lightning flash may consist of multiple strokes.

The ~~protective~~ protection characteristics of a surge arrester are only valid at its location. The corresponding overvoltage limitation at the equipment location, therefore, should account for the separation between the two locations. The greater the separation distance of the surge arrester from the protected equipment, the less is its protection efficient for this equipment, and, in fact, the overvoltage applied to the equipment increases above the ~~protective~~ protection level of the arrester with increasing separation distance. Furthermore, if the effect due to the length of the arrester is neglected in the determination of its protection characteristics, this length ~~must~~ shall be added to the length of the connecting leads in the evaluation of the effective overvoltage limitation. For metal-oxide arresters without gaps, the

reaction time of the material itself may be neglected and the arrester length can be added to the connection leads.

For simplified estimation of the representative overvoltage at the protected object, Equation (1) can be used. However, for transformer protection, Equation (1) should be used with caution since a capacitance of more than a few hundred picofarads may result in higher overvoltages.

$$\cancel{U_{rp} = U_{pl} + 2St_s \text{ for } U_{pl} \geq 2St_s} \quad U_{rp} = U_{pl} + 2St_s \text{ for } U_{pl} \geq 2St_s \quad (1)$$

$$\cancel{U_{rp} = 2U_{pl} \text{ for } U_{pl} < 2St_s} \quad U_{rp} = 2U_{pl} \text{ for } U_{pl} < 2St_s \quad (2)$$

where

U_{pl} is the lightning impulse protective level of the arrester (kV);

S is the steepness of the impinging surge (kV/ μ s);

$\cancel{t_s}$ is the travel time of the lightning surge determined as following:

$$\cancel{t_s} = L / c \quad (3)$$

where

c is the velocity of light (300 m/ μ s);

L is the sum of a_1 , a_2 , a_3 , and a_4 (distances from Figure 3 [m]).

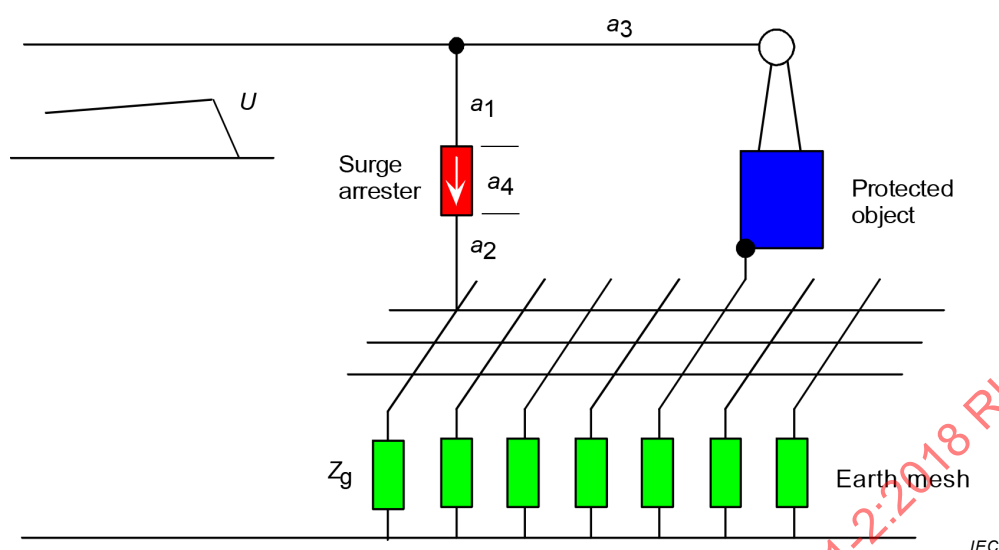
The values of the steepness ~~must~~ shall be selected according to the lightning performance of the overhead lines connected to the station and on the adopted risk of failure in the substation. A complete treatment is given in Annex E.

The probability distribution of the representative lightning overvoltage amplitude at the substation can be determined by transient overvoltage calculations taking into account the lightning performance of the transmission lines, the travelling wave behaviour of overhead lines and substation and the performance of the equipment insulation and of the surge arresters dependent on the overvoltage amplitude and shape. References are given in Annex E.

As a general recommendation, the dependence of the insulation withstand on the overvoltage shape should also be considered in the determination of the representative amplitudes. This, in particular, applies to external insulation and to oil-paper insulation, for which the volt-time curve of the insulation may point to representative amplitudes substantially lower than the overvoltage peak values. For GIS or for solid insulation, this difference is negligible and the amplitude of the representative overvoltage is equal to the overvoltage peak.

A simplified method to estimate the representative lightning overvoltage amplitude probability distribution is given in Annex E. The assumed maximum value of the representative lightning overvoltage amplitude is either the truncation value of the probability distribution or a value obtained from experience in existing systems. Methods for the estimation of these values are also included in Annex E.

Recently, digital simulation is used in general. The numerical modelling of power facilities and equipment has become increasingly precise, enabling accurate calculation for lightning overvoltages. Technical guidance is provided in IEC TR 60071-4.

**Key**

- a_1 length of the lead connecting the surge arrester to the line
- a_2 length of the lead connecting the surge arrester to earth
- a_3 length of the phase conductor between the surge arrester and the protected equipment
- a_4 length of the active part of the surge arrester
- Z_g earthing impedance
- U impinging overvoltage surge

Figure 3 – Diagram for surge arrester connection to the protected object

4.3.4.6 Evaluation method of non-standard lightning overvoltage shape

The "representative overvoltage" stage in the insulation co-ordination procedure is specified to have a standard voltage shape, which is especially meaningful for a lightning impulse in the case of detailed analysis by digital computation. On this subject, recent researches have analysed field surges, clarified insulating characteristics for field real surges in comparison with those for the standard voltage shape in the lightning surge time region, and proposed the overvoltage evaluation method for GIS [14] and transformer [15]. These techniques have been discussed in CIGRE working groups, and adopted in the technical brochures [11], [16], [17].

The decay of the field overvoltage is generally large, making the insulation requirements not as severe as those of the standard voltage shape. Consequently, it could be possible in some cases to use lower withstand voltages (see Annex I).

4.3.5 Very-fast-front overvoltages [13]

Very-fast-front overvoltages (VFFO) originate from disconnector operations or faults within GIS due to the fast breakdown of the gas gap and the nearly undamped surge propagation within the GIS. Their amplitudes are rapidly dampened on leaving the GIS, for example at a bushing, and their front times are usually increased into the range of those of fast-front overvoltages. ~~Very fast-front overvoltages may also occur at medium voltage dry-type transformers with short connections to the switchgear.~~

~~The overvoltage shape is characterized by a fast increase of the voltage nearly to its peak value resulting in a front time below 0,1 μ s. For disconnector operations this front is typically followed by an oscillation with frequencies above 1 MHz. The duration of very fast front overvoltages is less than 3 ms, but may occur several times. The overvoltage amplitude depends on the disconnector construction and on the substation configuration. A limitation of maximum amplitudes to 2,5 p.u. can be assumed to be achievable. The overvoltages may, however, create high local overvoltages in directly connected transformers.~~

~~Due to faults within GIS the connected equipments (e.g. transformer) are stressed by overvoltages. The shape and the amplitude of the overvoltage depends on the kind of connection of the equipment to the GIS and the location of the fault within the GIS. The overvoltages have amplitudes up to 1,6 times the breakdown voltages and contain frequencies up to 20 MHz within the substation.~~

~~On terminals of equipment connected with a short high-voltage overhead line to the GIS, the overvoltage oscillations show frequencies in the range from 0,2 MHz to 2,0 MHz and amplitudes up to 1,5 times the flashover voltage. In this case it is possible to protect the equipment with surge arresters. However, the frequency content of the overvoltages may still cause high internal stresses in transformer windings because of part-winding resonances. Alternative protection methods proved by detailed studies may be necessary. These measures might include changing (lowering) the frequency by installing additional capacitance. However, care must be taken in this approach to ensure that the transformer resonance characteristics are accurately known.~~

~~The representative overvoltage cannot be established because suitable standardizations are not available at present. It is expected, however, that very fast-front overvoltages have no influence on the selection of rated withstand voltages.~~

The overvoltage shape is characterized by a fast increase of the voltage nearly to its peak value resulting in a front time below 0,1 μ s. This front is usually followed by an oscillation with frequencies above 1 MHz. Dominant frequency components may reach up to some tens of MHz.

For disconnector operations the VFFO amplitude depends on the disconnector construction and on the substation configuration. In the most unfavourable case, the maximum VFFO amplitude can reach 2,8 p.u.

VFFO due to faults within GIS can have amplitudes up to 1,6 times the breakdown voltages.

VFFO in UHV systems may be dangerous to the insulation of GIS, transformers and voltage transformers. The shape and the amplitude of the overvoltage depend on the kind of connection of the equipment to the GIS.

A representative overvoltage cannot be established because suitable standardizations are not available. Experience show that very-fast-front overvoltages have no influence on the selection of rated withstand voltages up to system voltages of 800 kV.

Special care has to be taken for very-fast transients in GIS of UHV systems. Due to the decreasing ratio of lightning impulse withstand voltage to the system voltage, VFFO can become the limiting dielectric stress defining the dimensions of GIS. How to handle this situation and mitigation measures in respect to insulation co-ordination are described in Annex J.

5 Co-ordination withstand voltage

5.1 Insulation strength characteristics

5.1.1 General

In all materials, conduction is caused by the migration of charged particles. Conductors have large numbers of relatively free electrons, which will drift in an applied electric field, while ~~insulants~~ insulating media have very few free electrons. When electric stress in an ~~insulant~~ insulating medium is increased to a sufficiently high level, the resistivity along a path through the ~~insulant~~ insulating medium will change from a high value to a value comparable to that of conductors. This change is called breakdown.

Breakdown takes place in three main stages:

- the initial ionization at a point or points;
- the growth of an ionized channel across the gap;
- the bridging of the gap and the transition to a self-sustaining discharge.

A number of factors influence the dielectric strength of the insulation. Such factors include:

- the magnitude, shape, duration and polarity of the applied voltage;
- the electric field distribution in the insulation: homogeneous or non-homogeneous electric field, electrodes adjacent to the considered gap and their potential;
- the type of insulation: gaseous, liquid, solid or a combination of these; the impurity content and the presence of local inhomogeneities;
- the physical state of the insulation: temperature, pressure and other ambient conditions, mechanical stress, etc. The history of the insulation may also have an importance;
- the deformation of the insulation under stress, chemical effects, conductor surface effects, etc.

Breakdown in air is strongly dependent on the gap configuration and on the polarity and wave shape of the applied voltage stress. In addition, relative atmospheric conditions affect the breakdown strength regardless of shape and polarity of applied stress. Relationships for the breakdown strength of air derived from laboratory measurements are referred to as the standard **reference** atmospheric conditions as defined by IEC 60060-1:

- temperature : 20 °C;
- pressure : 1 013 hPa (1 013 mbar);
- absolute humidity : 11 g/m³.

Laboratory measurements have also been made for non-standard conditions including low air density, high relative humidity, contamination, ice and snow, high temperatures and the presence of combustion particles.

For outdoor insulation, the effects of **air density**, humidity, rain, and surface contamination become particularly important. IEC 60060-1 defines test procedures for external insulation in dry and wet conditions. For **internal gas insulation**, such as metal-enclosed gas-insulated switchgear, the effect of the internal pressure and temperature as well as local inhomogeneities and impurities play a significant role.

In liquid insulation, particle impurities, bubbles caused by chemical and physical effects or by local discharges, can drastically reduce the insulation strength. It is important to note also that the amount of chemical degradation of the insulation ~~might~~ **can** tend to increase with time. ~~The same also applies in the case of~~ **can apply** to solid insulation. ~~In these cases, its~~ electric strength ~~might also~~ **can** be affected by mechanical stress.

The breakdown process is also statistical in nature and this should be taken into account. Due to the restoring feature of self-restoring insulation, its statistical response to stresses can be obtained by suitable tests. Therefore, self-restoring insulation is typically described by the statistical withstand voltage corresponding to a withstand probability of 90 %. For non-self-restoring insulation, the statistical nature of the strength cannot usually be found by testing and the assumed withstand voltage deemed to correspond to a withstand probability of 100 % is applied (see definition 3.23 of IEC 60071-1:2006).

Wind has an influence on insulation design, especially in the case of overhead lines employing free swinging insulator strings. Usually, the effect is only important in selecting gap lengths on the basis of power-frequency and switching impulse strengths.

Subclauses 5.1.2 to 5.1.5 give information on the different factors influencing the insulation response. For more detailed information, reference can be made to the CIGRE technical brochure [7 4].

5.1.2 Influence of polarity and overvoltage shapes

5.1.2.1 Influence of overvoltage polarity

In typical electrode geometries encountered in high-voltage applications, for the majority of cases the energized conductor is more highly stressed than the grounded conductor. For air insulation, if the more highly stressed electrode is positively charged, the gap breakdown voltage will be lower than if the more highly stressed electrode is negatively charged. This is because the propagation of ionization phenomena is more readily accomplished under positive stress than negative stress.

Where both electrodes are approximately equally stressed, two discharge processes will be involved, with both positive and negative characteristics. If it is clear which polarity will be more severe for a particular insulation system and gap configuration, the design will be based on that polarity; otherwise both polarities ~~must~~ shall be considered.

5.1.2.2 Influence of overvoltage shape

Under impulse stress, the breakdown voltage also in general depends on the shape of the impulse.

For slow-front impulses, the strength of external insulation depends more on the impulse front than on its tail. The tail becomes especially important only in the case of contamination on the surface of external insulation. The strength of internal insulation is assumed to be affected by the peak value only.

For external insulation, it is typical that for each gap length there is an impulse time-to-peak for which the breakdown voltage is a minimum (the critical time to peak). Usually, the minimum is in the range of times-to-peak for slow-front overvoltages. The larger the gap length, the more pronounced is the minimum. For air gaps in range I, the effect is negligible and can be ignored. For air clearances to be used in range II, this minimum breakdown voltage is, to all intents and purposes, equal to the breakdown voltage at the standard 250 μ s time-to-peak. This means that the use of the withstand voltage of the insulation at the standard voltage shape 250/2 500 μ s results in a conservative insulation design for slow-front overvoltages. For some systems in which slow-front overvoltages have fronts much longer than the standard one, the higher insulation strength at these fronts may be advantageously utilized.

The breakdown voltage of external insulation under lightning impulse stress decreases with increasing tail duration. For withstand voltages, this decrease is neglected, and the breakdown voltage is assumed to be equal to that under the standard lightning impulse 1,2/50 μ s. However, some reduction in the insulation structure may be achieved, for example, in open-air substations protected by surge arresters, when the lightning overvoltage shape and its effect on the insulation strength is taken into account.

The lightning overvoltage shapes are analysed and the insulating characteristics of SF₆ gas and oil-filled transformer elements for these actual surges are clarified to convert them into the standard voltage shape (see 4.3.4.6).

5.1.3 Phase-to-phase and longitudinal insulation

The dielectric strength of phase-to-phase and longitudinal insulation structures depends on the relationship between the two voltage components at the two terminals. This dependence is very important for external insulation in range II or in three-phase metal-enclosed substations.

For external insulation in range II, the response of the insulation to phase-to-phase switching overvoltages depends on the value of α which correlates positive and negative voltage stress components (see Annex C); tests to verify the required withstand voltage shall therefore be so designed as to reflect this phenomenon. The representative overvoltage shape standardized in IEC 60071-1 is a combined overvoltage having two synchronous components of opposite polarity; the positive is a standard switching impulse, while the negative is an impulse with time-to-peak and time-to-half value not shorter than those of the positive component. For insulation affected by the relative value of the two components, therefore, the actual overvoltage amplitude shall be converted into the representative amplitude taking into account the insulation response characteristics (see 4.3.3.2 and Annex C where a particular example is given).

For longitudinal insulation structures, the voltage components are specified by the representative overvoltages (see Clause 4).

The values for the conventional deviation for the phase-to-earth insulation strength given in 5.1.5 may also be applied to the strength of the external phase-to-phase or the longitudinal insulation, when the 50 % flashover voltage is taken as the sum of the components applied to the two terminals.

5.1.4 Influence of weather conditions on external insulation

Flashover voltages for air gaps depend on the moisture content and density of the air. Insulation strength increases with absolute humidity up to the point where condensation forms on the insulator surfaces. Insulation strength decreases with decreasing air density. A detailed description of the effects of air density and absolute humidity is given in IEC 60060-1 for different types of voltage stresses.

When determining the co-ordination withstand voltage, it should be kept in mind that most adverse conditions from the dielectric strength point of view (i.e. low absolute humidity, low air pressure and high temperature) do not usually occur simultaneously. In addition, at a given site, the corrections applicable for humidity and ambient temperature variations cancel each other to all intents and purposes. Therefore, the estimation of the strength can usually be based on the average ambient conditions at the location. Extreme atmospheric conditions on site need special consideration.

For insulators, the possible reduction in the withstand voltage due to snow, ice, dew or fog should be taken into account.

5.1.5 Probability of disruptive discharge of insulation

No method is at present available for the determination of the probability of disruptive discharge of a single piece of non-self-restoring insulation. Therefore, it is assumed that the withstand probability changes from 0 % to 100 % at the value defining the withstand voltage.

For self-restoring insulation, the ability to withstand dielectric stresses caused by the application of an impulse of given shape can be described in statistical terms. The methods to be followed in the determination of the withstand probability curve are given in IEC 60060-1. For a given insulation, and for impulses of given shape and different peak values U , a discharge probability P can be associated with every possible value U , thus establishing a relationship $P = P(U)$. Usually, the function P is monotonically increasing with values of U . The resulting curve can be defined by three parameters:

- a) U_{50} : corresponding to the voltage under which the insulation has a 50 % probability to flashover or to withstand;
- b) Z : the conventional deviation which represents the scatter of flashover voltages. It is defined as the difference between the voltages corresponding to flashover probabilities 50 % and 16 % as shown in Equation (4):

$$Z = U_{50} - U_{16} \quad (4)$$

- c) U_0 U_{spec} : the truncation voltage. The maximum voltage below which a disruptive discharge is no longer possible. The determination of this value, however, is not possible in practical tests.

Usually, the function P is given by a mathematical function (cumulative probability distribution) which is fully described by parameters U_{50} , Z and U_0 U_{spec} . In the traditionally used Gaussian distribution, the value of U_{50} is also the mean, and the conventional deviation is obtained directly from Equation (4). The truncation point is not often considered for the sake of simplicity.

For application of the statistical method for insulation co-ordination for slow-front overvoltages, the use of the modified Weibull cumulative probability distribution given in Equation (5) has advantages with respect to the Gaussian distribution (advantages explained in Annex B). Equation (5) represents a Weibull cumulative function with parameters chosen to match a Gaussian cumulative probability function at the 50 % and 16 % probability of flashover and to truncate the distribution at $U_{50} - NZ$ (see Annex B).

$$P(U) = 1 - 0,5 \left(1 + \frac{x}{N} \right)^\gamma \quad (5)$$

where

x is the number of conventional deviations corresponding to U ;

N is the number of conventional deviations corresponding to the truncation voltage U_0 U_{spec} for which $P(U_0 \text{ } U_{spec}) = 0$.

And

$$x = (U - U_{50}) / Z$$

At one conventional deviation of the Gaussian probability distribution (at $x = -1$), $P(U) = 0,16$ in Equation (5). If $N = 4$ is chosen, then the exact value of γ must shall be 4,83 in Equation (5). Approximating this value to $\gamma = 5$ does not result in any appreciable errors so that the modified Weibull distribution proposed in this document is described in Equation (6).

$$P(U) = 1 - 0,5 \left(1 + \frac{x}{4} \right)^5 \quad (6)$$

Figure 4 illustrates this modified Weibull distribution together with the Gaussian distribution to which it is matched. Figure 5 shows the same distributions on Gaussian probability scales.

For statistical calculations of expected performance in the field, use should be made of detailed data obtained from field or laboratory tests. In the absence of such data, the following values for the conventional deviation derived from a large number of test results are recommended for statistical calculations:

- for lightning impulses: $Z = 0,03 U_{50}$ (kV), and
- for switching impulses: $Z = 0,06 U_{50}$ (kV)

The influence of weather conditions (refer to 5.1.4) is included in the values of derived deviations given above.

In IEC 60071-1, the parameter U_{10} (obtained from Equation (5)) corresponding to the withstand probability 90 % is used to describe the withstand probability distribution together with the deviation:

$$U_{10} = U_{50} - 1,3 Z \quad (7)$$

Annex B contains detailed information and statistical equations to be applied in the context of many identical insulations in parallel being simultaneously stressed.

Annex F contains guidance on the determination of the breakdown strength of air insulation under the different classification of overvoltage.

5.2 Performance criterion

According to definition 3.22 of IEC 60071-1:2006, the performance criterion to be required from the insulation in service is the acceptable failure rate (R_a).

The performance of the insulation in a system is judged on the basis of the number of insulation failures during service. Faults in different parts of the network can have different consequences. For example, in a meshed system, a permanent line fault or an unsuccessful reclosure due to slow-front surges is not as severe as a busbar fault or corresponding faults in a radial network. Therefore, acceptable failure rates in a network can vary from point to point depending on the consequences of a failure at each of these points.

Examples for acceptable failure rates can be drawn from fault statistics covering the existing systems and from design projects where statistics have been taken into account. For apparatus, acceptable failure rates R_a due to overvoltages are in the range of 0,001/year up to 0,004/year depending on the repair times. For overhead lines, acceptable failure rates due to lightning vary in the range of 0,1/100 km/year up to 20/100 km/year (the greatest number being for distribution lines). Corresponding figures for acceptable failure rates due to switching overvoltages lie in the range 0,01 to 0,001 per operation. Values for acceptable failure rates should be in these orders of magnitude.

5.3 Insulation co-ordination procedures

5.3.1 General

5.3.1.1 Overview

The determination of the co-ordination withstand voltages consists of determining the lowest values of the withstand voltages of the insulation meeting the performance criterion when subjected to the representative overvoltages under service conditions.

Two methods for co-ordination of insulation to transient overvoltages are in use: a deterministic and a statistical method. Many of the applied procedures, however, are a mixture of both methods. For example, some factors used in the deterministic method have been derived from statistical considerations or some statistical variations have been neglected in statistical methods.

5.3.1.2 Deterministic method

The deterministic method is normally applied when no statistical information obtained by testing is available on possible failure rates of the equipment to be expected in service.

With the deterministic method,

- when the insulation is characterized by its conventional assumed withstand voltage ($P_W = 100\%$), the withstand value is selected equal to the co-ordination withstand voltage obtained by multiplying the representative overvoltage (an assumed maximum) by a co-ordination factor K_C , accounting for the effect of the uncertainties in the assumptions for the two values (the assumed withstand voltage and the representative overvoltage), and

- when, as for external insulation, the insulation is characterized by the statistical withstand voltage ($P_W = 90\%$), K_C should account also for the difference between this voltage and the assumed withstand voltage.

With this method, no reference is made to possible failure rates of the equipment in service.

Typical examples are:

- insulation co-ordination of internal insulations against slow-front overvoltages, when the insulation is protected by surge arresters;
- surge arrester protection against lightning overvoltages for equipment connected to overhead lines, for which experience with similar equipment is available.

5.3.1.3 Statistical method

The statistical method is based on the frequency of occurrence of a specific origin, the overvoltage probability distribution belonging to this origin and the discharge probability of the insulation. Alternatively, the risk of failure may be determined combining overvoltage and discharge probability calculations simultaneously, shot by shot, taking into account the statistical nature of overvoltages and discharge by suitable procedures, for example using Monte Carlo methods.

By repeating the calculations for different types of insulations and for different states of the network the total outage rate of the system due to the insulation failures can be obtained.

Hence, the application of the statistical insulation co-ordination gives the possibility to estimate the failure frequency directly as a function of the selected system design factors. In principle, even the optimization of the insulation could be possible, if outage costs could be related to the different types of faults. In practice, this is very difficult due to the difficulty to evaluate the consequences of even insulation faults in different operation states of the network and due to the uncertainty of the cost of the undelivered energy. Therefore, it is usually better to slightly overdimension the insulation system rather than optimize it. The design of the insulation system is then based on the comparison of the risks corresponding to the different alternative designs.

5.3.2 Insulation co-ordination procedures for continuous (power-frequency) voltage and temporary overvoltage

5.3.2.1 General

The co-ordination withstand voltage for the continuous (power-frequency) voltage is equal to the highest system voltage for phase-to-phase, and to this voltage divided by $\sqrt{3}$ for phase-to-earth insulations (i.e. equal to the assumed maximum value for the representative voltages given in 4.3.1) with a duration equal to the service life.

With the deterministic method, the co-ordination short-duration withstand voltage is equal to the representative temporary overvoltage. When a statistical procedure is adopted and the representative temporary overvoltage is given by an amplitude/duration distribution frequency characteristic (see 4.3.2), the insulation that meets the performance criterion shall be determined, and the amplitude of the co-ordination withstand voltage shall be equal to that corresponding to the duration of 1 min on the amplitude/duration withstand characteristic of the insulation.

5.3.2.2 Pollution

~~When contamination is present, the response of external insulation to power frequency voltages becomes important and may dictate external insulation design. Flashover of insulation generally occurs when the surface is contaminated and becomes wet due to light rain, snow, dew or fog without a significant washing effect.~~

For standardization purposes, four qualitative levels of pollution are specified. Table 1 gives for each level of pollution a description of some typical corresponding environments. Insulators shall withstand the highest system voltage in polluted conditions continuously with an acceptable risk of flashover. The co-ordination withstand voltages are taken equal to the representative overvoltages and the performance criterion is satisfied choosing a suitable withstand severity of pollution in relation to the site severity. Therefore, the long-duration power-frequency co-ordination withstand voltage shall correspond to the highest system voltage for phase-to-phase insulators and this value divided by $\sqrt{3}$ for phase-to-earth insulators.

An estimate of the pollution level for any specific area may be made according to table 1. For a quantitative evaluation of the site pollution level by measurement, information is available in IEC 815.

Different types of insulator and even different orientations of the same insulator type may accumulate pollution at different rates in the same environment. Further, for the same degree of pollution they may exhibit different flashover characteristics. In addition, variations in the nature of the pollutant may make some shapes of insulator more effective than others. Therefore, for co-ordination purposes, a pollution severity measure should be determined for each type of insulator to be used.

In the case of sites with a high degree of pollution, greasing or washing the insulating surfaces may be considered.

For information, table 1 includes specific creepage distances necessary to withstand the pollution of the four classes, although these distances are more related to insulation design than to insulation co-ordination. Furthermore, IEC 507 correlates to each pollution level of table 1 a range of withstand pollution severities to be undertaken for artificial pollution tests. It remains the domain of the product committees to define testing requirements to verify the withstand of insulators under pollution conditions.

Table 1 – Recommended creepage distances

Pollution level	Examples of typical environments	Minimum nominal specific creepage distance mm/kV ³⁾
I Light	— Areas without industries and with low density of houses equipped with heating plants — Areas with low density of industries or houses but subjected to frequent winds and/or rainfall — Agriculture areas²⁾ — Mountainous areas — All these areas shall be situated at least 10 km to 20 km from the sea and shall not be exposed to winds directly from the sea³⁾	16,0
II Medium	— Areas with industries not producing particularly polluting smoke and/or with average density of houses equipped with heating plants — Areas with high density of houses and/or industries but subjected to frequent winds and/or rainfall — Areas exposed to wind from the sea but not too close to coasts (at least several kilometres distant)³⁾	20,0
III Heavy	— Areas with high density of industries and suburbs of large cities with high density of heating plants producing pollution — Areas close to the sea or in any case exposed to relatively strong winds from the sea³⁾	25,0
IV Very heavy	— Areas generally of moderate extent, subjected to conductive dusts and to industrial smoke producing particularly thick conductive deposits — Areas generally of moderate extent, very close to the coast and exposed to sea-spray or to very strong and polluting winds from the sea	31,0

	~~— Desert areas, characterized by no rain for long periods, exposed to strong winds carrying sand and salt, and subjected to regular condensation~~	
NOTE — This table should be applied only to glass or porcelain insulation and does not cover some environmental situations such as snow and ice in heavy pollution, heavy rain, arid areas, etc. 1) ~~According to IEC 815, minimum creepage distance of insulators between phase and earth related to the highest system voltage (phase-to-phase).~~ 2) ~~Use of fertilizers by spraying, or the burning of crop residues can lead to a higher pollution level due to dispersal by wind.~~ 3) ~~Distances from sea coast depend on the topography of the coastal area and on the extreme wind conditions.~~		

When contamination is present, the response of external insulation to power-frequency voltages becomes important and may dictate external insulation design. Flashover of insulation generally occurs when the surface is contaminated and becomes wet due to light rain, snow, dew or fog without a significant washing effect.

For the purpose of standardization in IEC TS 60815-1, five classes of characterizing site severity are qualitatively defined from very light to very heavy pollution as follows:

- very light;
- light;
- medium;
- heavy;
- very heavy.

Insulators shall continuously withstand the highest system voltage in polluted conditions with an acceptable risk of flashover. The co-ordination withstand voltages are taken equal to the representative overvoltages, and the performance criterion is satisfied choosing a suitable class of site severity. The long-duration power-frequency co-ordination withstand voltage shall correspond to the highest system voltage for phase-to-phase insulators and to this value divided by $\sqrt{3}$ for phase-to-earth insulators.

For the selection of suitable insulators, recommendations are given in IEC TS 60815-1 based on experiences, measurements and testing.

5.3.3 Insulation co-ordination procedures for slow-front overvoltages

5.3.3.1 Deterministic method

The deterministic method involves determining the maximum voltage stressing the equipment and then choosing the minimum dielectric strength of this equipment with a margin that will cover the uncertainties inherent in the determination of these values. The co-ordination withstand voltage is obtained by multiplying the assumed maximum value of the corresponding representative overvoltage by the deterministic co-ordination factor K_{cd} .

For equipment protected by surge arresters, the assumed maximum overvoltage is equal to the switching impulse ~~protective~~ protection level U_{ps} of the arrester. However, in such cases, a severe skewing in the statistical distribution of overvoltages may take place. This skewing is more pronounced the lower the ~~protective~~ protection level, as compared to the amplitudes of the prospective slow-front overvoltages, so that small variations of the insulation withstand strength (or in the value of the arrester ~~protective~~ protection level) can have a large impact on the risk of failure [4]. To cover this effect, it is proposed to evaluate the deterministic co-ordination factor K_{cd} dependent on the relation of the surge arrester switching impulse ~~protective~~ protection level U_{ps} to the 2 % value of the phase-to-earth prospective overvoltages U_{e2} . Figure 6 establishes this dependence.

For equipment not protected by surge arresters, the assumed maximum overvoltage is equal to the truncation value (U_{et} or U_{pt}) according to 4.3.3.2, and the deterministic co-ordination factor is $K_{cd} = 1$.

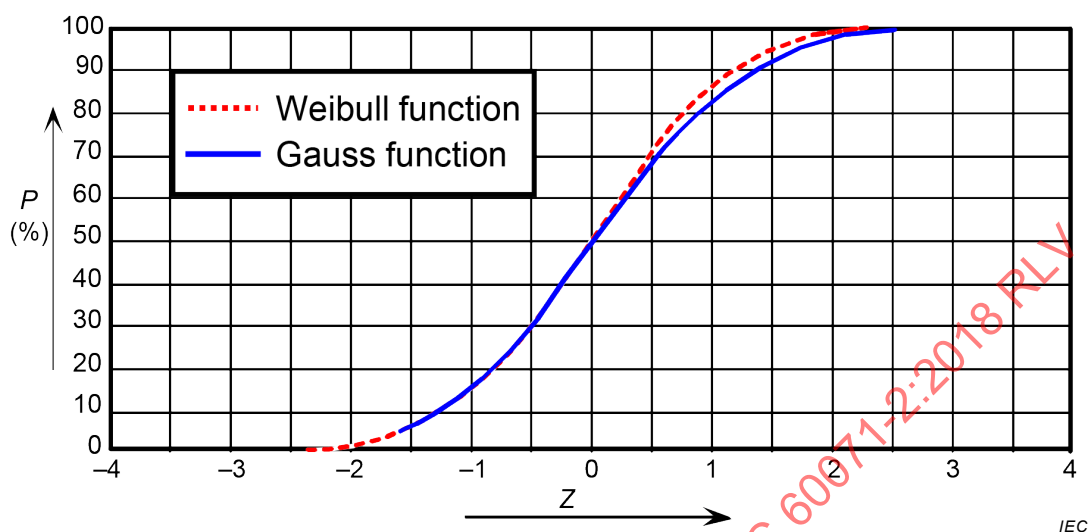


Figure 4 – Distributive discharge probability of self-restoring insulation described on a linear scale

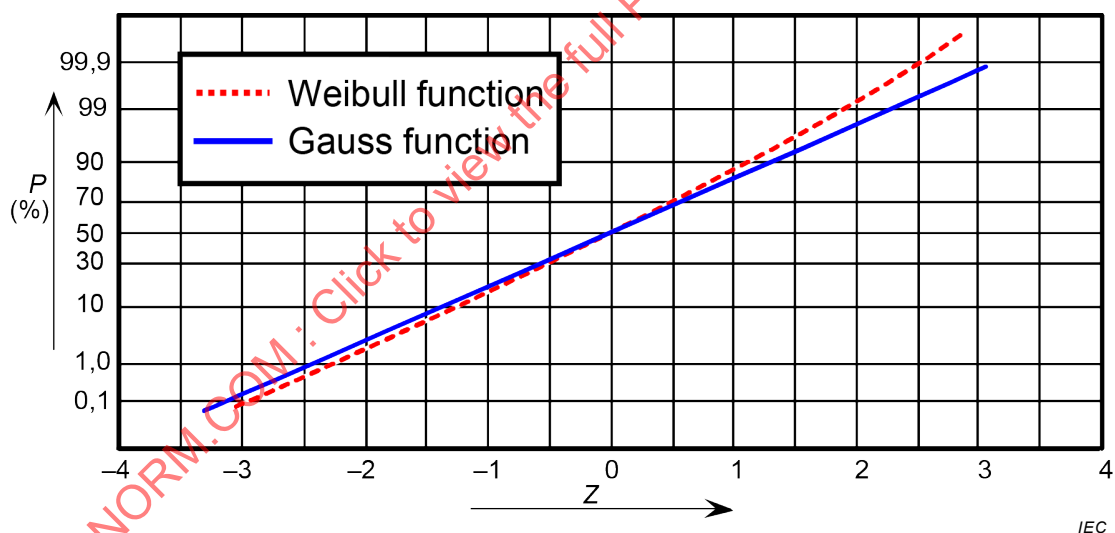
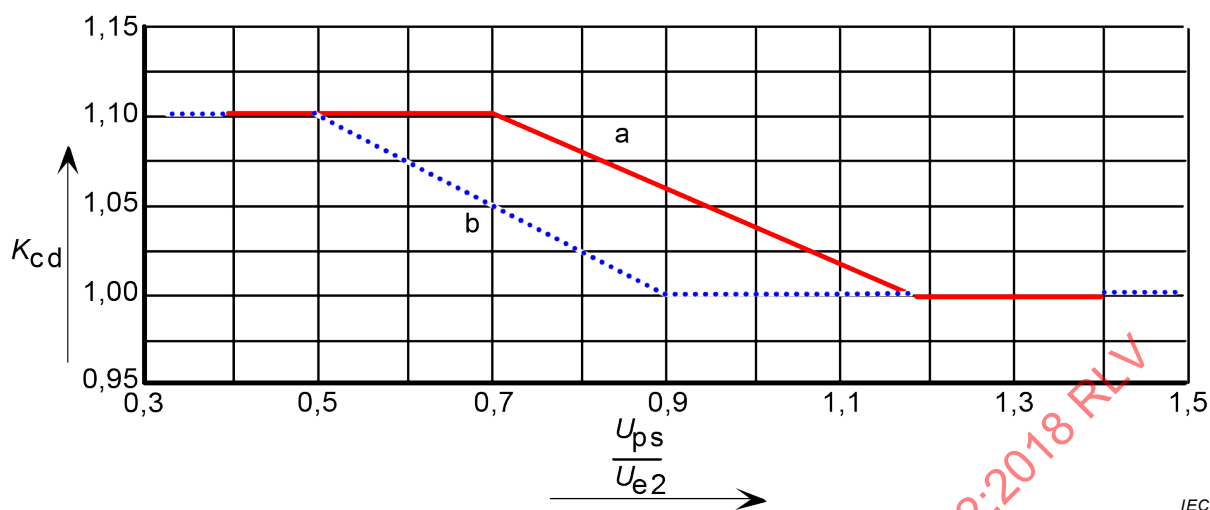


Figure 5 – Disruptive discharge probability of self-restoring insulation described on a Gaussian scale

**Key**

- a co-ordination factor applied to the surge arrester ~~protective~~ protection level to obtain the co-ordination withstand voltage phase-to-earth (applies also to longitudinal insulation);
- b co-ordination factor applied to twice the surge arrester protection level to obtain the co-ordination withstand voltage phase-to-phase.

Figure 6 – Evaluation of deterministic co-ordination factor K_{cd}

5.3.3.2 Statistical method (and corresponding risk of failure)

In applying the statistical method, it is first necessary to establish an acceptable risk of failure, as described in 5.2, based on technical and economic analysis and service experience.

The risk of failure gives the probability of insulation failure. The failure rate is expressed in terms of the expected average frequency of failures of the insulation (e.g. the number of failures per year) as a result of events causing overvoltage stresses. To evaluate this rate, the events giving rise to these overvoltages and their number have to be studied. Fortunately, the types of events that are significant in insulation design are sufficiently few in number to make the method practical.

The statistical method recommended in this document is based on peak value of the surges. The frequency distribution of overvoltages between phase and earth for a particular event is determined from the following assumptions:

- peaks other than the highest one in the shape of any given overvoltage are disregarded;
- the shape of the highest peak is taken to be identical to that of the standard switching impulse;
- the highest overvoltage peaks are taken to be all of the same polarity, namely the most severe for the insulation.

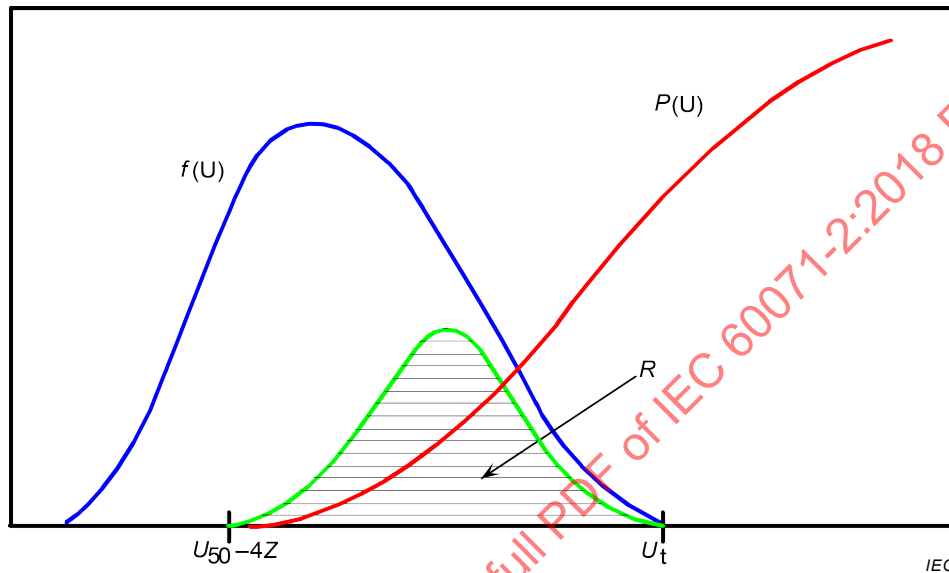
Once the frequency distribution of the overvoltages and the corresponding breakdown probability distribution of the insulation are given, the risk of failure of the insulation between phase and earth can be calculated as follows:

$$R = \int_0^{\infty} f(U) \times P(U) dU \quad (8)$$

where

$f(U)$ is the probability density of overvoltages;

$P(U)$ is the probability of flashover of the insulation under an impulse of value U (see Figure 7).



$$R = \int_{U_{50} - 4Z}^{U_t} f(U) \times P(U) dU$$

where

$f(U)$ is the probability density of overvoltage occurrence described by a truncated Gaussian or a Weibull function;

$P(U)$ is the discharge probability of insulation described by a modified Weibull function;

U_t is the truncation value of the overvoltage probability distribution;

$U_{50} - 4Z$ is the truncation value of the discharge probability distribution.

Figure 7 – Evaluation of the risk of failure

If more than one independent peak occurs, the total risk for a phase can be calculated by taking into account the risk of failures for all peaks. For example, if a switching surge on a particular phase comprises three positive peaks leading to risks of failure R_1 , R_2 and R_3 , the phase-to-earth risk of failure for the switching operation is:

$$R = 1 - (1 - R_1) (1 - R_2) (1 - R_3) \quad (9)$$

If the overvoltage distribution is based on the phase-peak method (see 4.3.3.2.1), and the insulations in the three phases are the same, the total risk of failure is:

$$R_{\text{total}} = 1 - (1 - R)^3 \quad (10)$$

If the case-peak method (see 4.3.3.2.1) is used, the total risk is: $R_{\text{total}} = R$.

NOTE If one of the overvoltage polarities is substantially more severe for the insulation withstand, the risk values may be divided by two.

The risk of failure for the phase-to-earth and the phase-to-phase insulations can be determined separately in this simple way only if the distances between the two are large enough that the flashover to earth and between phases is not based on the same physical event. This is valid if the phase-to-earth and the phase-to-phase insulations have no common electrode. If they have a common electrode, the risk of failure is usually smaller than that calculated separately [6].

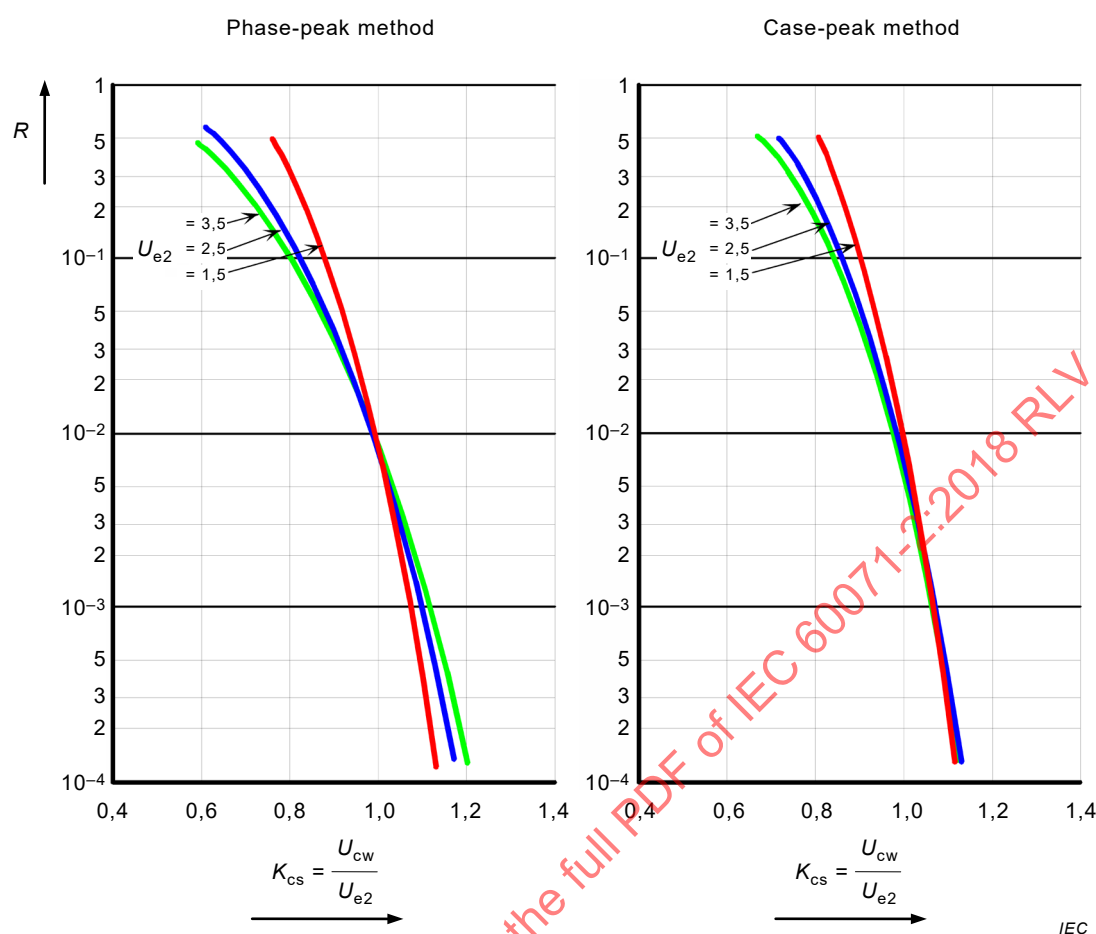
For the important case of the application of the statistical method to many identical parallel insulations, see detailed discussion in Annex B.

Simplified statistical method for slow-front overvoltages

The statistical method based on the amplitudes of the surges can be simplified if it is assumed that one can define the distributions of overvoltage and insulation strength by a point on each of these curves. The overvoltage distribution is identified by the statistical overvoltage, which is the overvoltage having a 2 % probability of being exceeded. The insulation strength distribution is identified by the statistical withstand voltage, which is the voltage at which the insulation exhibits a 90 % probability of withstand. The statistical co-ordination factor (K_{cs}) is then the ratio of the statistical withstand voltage to the statistical overvoltage.

The correlation between the statistical co-ordination factor and the risk of failure appears to be only slightly affected by changes in the parameters of the overvoltage distribution. This is due to the fact that the 2 % value chosen as a reference probability of the overvoltage falls in that part of the overvoltage distribution which gives the major contribution to the risk of failure in the range of risk considered.

Figure 8 shows an example of the relationship between the risk of failure and the statistical co-ordination factor for both the phase-peak and the case-peak methods outlined in Annex C, when the Gaussian distribution is applied for the stress and the modified Weibull distribution is applied for the strength. The curves take into account the fact that the conventional deviation is a function of the 2 % overvoltage value as given in Annex C. Extreme variations in the deviation of the insulation strength, markedly non-Gaussian distribution of overvoltage and, most of all, the shape of the overvoltage may cause the curve to be in error by as much as one order of magnitude. On the other hand, the curves show that a variation of one order of magnitude in the risk corresponds to only a 5 % variation in the electric strength.



Overvoltage parameters: see 4.3.3.2 and Annex C.

Strength parameters: see 5.1.5.

Figure 8 – Risk of failure of external insulation for slow-front overvoltages as a function of the statistical co-ordination factor K_{cs}

5.3.4 Insulation co-ordination procedures for fast-front overvoltages

5.3.4.1 Deterministic method

For fast-front lightning overvoltages, a deterministic co-ordination factor of $K_{cd} = 1$ is applied to the assumed maximum value of the overvoltages. This is because for lightning, the representative overvoltage includes probability effects. For fast-front switching overvoltages, the same relations apply as for slow-front overvoltages (see 5.3.3.1).

5.3.4.2 Statistical method

The statistical method recommended in this document is based on the probability distribution of the representative lightning overvoltages (see Annex E). As the frequency distribution of overvoltages is obtained by dividing their return rate by the total number of overvoltages and the probability density $f(U)$ is the derivative of the result, the risk of failure is calculated by the procedures already outlined in 5.3.3.2. The insulation failure rate is equal to the risk of failure multiplied by the total number of lightning overvoltages.

For internal insulation, the assumed withstand voltage has a withstand probability of 100 % (see definition 3.23 of IEC 60071-1:2006). The withstand probability at higher voltages is assumed to be 0 %. This means that the co-ordination withstand voltage is equal to the representative lightning overvoltage amplitude at a return rate equal to the adopted acceptable failure rate.

NOTE Fast-front overvoltages due to lightning are evaluated without taking into account the instantaneous power-frequency voltage. The combined stresses due to reversal of polarity are therefore neglected. This ~~may~~ can be acceptable provided the power-frequency amplitude is small compared to that of the fast-front overvoltage. It may not be conservative for apparatus with oil paper internal insulation such as transformers in range II and the higher values of U_m in range I. Moreover, the internal (such as turn to turn) voltages in such apparatus due to stresses appearing at the terminals are not strictly considered in insulation co-ordination practice described in this document.

For the external insulation the conventional deviation of the discharge probability is usually small as compared to the dispersion of overvoltages. As a simplification, it can be neglected and the same equation as for the internal insulation applies.

6 Required withstand voltage

6.1 General remarks

The required withstand voltage, to be verified in standard type test conditions and at standard reference atmosphere, is determined taking into account all factors which may decrease the insulation in service, so that the co-ordination withstand voltage is met at the equipment location during the equipment life. To achieve this, two main types of correction factors shall be considered:

- a correction factor associated with atmospheric conditions;
- correction factors (called "safety factors") which take into account the differences between the actual in-service conditions of the insulation and those in the standard withstand tests.

6.2 Atmospheric correction

6.2.1 General remarks

For internal insulation, it may be assumed that the atmospheric air conditions do not influence the insulation properties.

The rules for the atmospheric correction of withstand voltages of the external insulation are specified in IEC 60060-1. These rules are based on measurements in altitudes up to 2 000 m and their application to higher altitudes should be made with care. For insulation co-ordination purposes, the following additional recommendations apply:

- a) for air clearances and clean insulators, the correction shall be carried out for the co-ordination switching and lightning impulse withstand voltages. For insulators requiring a pollution test, a correction of the long duration power-frequency withstand voltage is also necessary;
- b) for the determination of the applicable atmospheric correction factor, it may be assumed that the effects of ambient temperature and humidity tend to cancel each other. Therefore, for insulation co-ordination purposes, only the air pressure corresponding to the altitude of the location need to be taken into account for both dry and wet insulations.

NOTE This assumption can be considered as correct for insulator shapes for which rain does not reduce the withstand voltage to a high degree. For insulators with small shed distance, for which rain causes shed-bridging, this assumption is not completely true.

For further information regarding atmospheric and altitude correction, see Annex H.

6.2.2 Altitude correction

The correction factor K_a is based on the dependence of the atmospheric pressure on the altitude as given in ~~IEC 721-2-3~~ ISO 2533:1975. The coordination withstand voltage U_{cw} has to be multiplied by K_a for the calculation of the required withstand voltage U_{rw} .

The correction factor can be calculated from:

$$K_a = e^{m \times \frac{H}{8150}} \quad (11)$$

where

H is the altitude above sea level (in meters);

m is as follows:

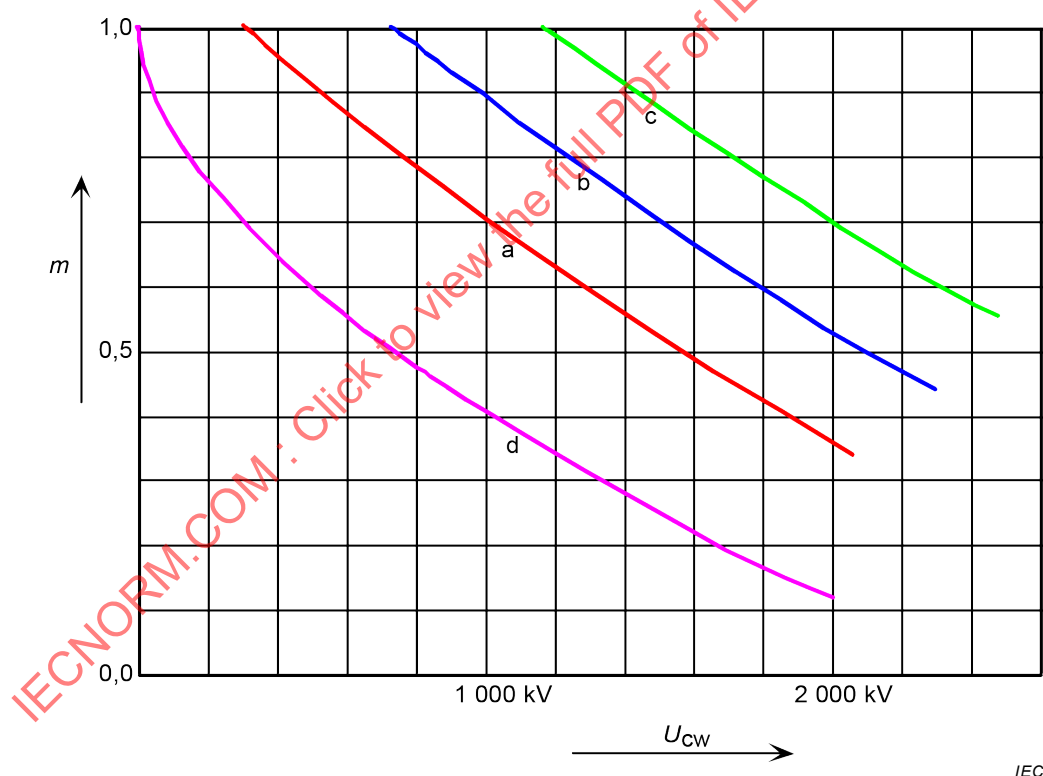
$m = 1,0$ for co-ordination lightning impulse withstand voltages;

m is according to Figure 9 for co-ordination switching impulse withstand voltages;

$m = 1,0$ for short-duration power-frequency withstand voltages of air-clearances and clean insulators.

NOTE The exponent m depends on various parameters, including minimum discharge path which is generally unknown at the specification stage. However, for insulation co-ordination purposes, the conservative estimates of m shown in Figure 9 may be used for the correction of co-ordination switching impulse withstand voltages. The determination of the exponent m is based on IEC 60060-1 ~~in which the given relations are obtained from measurements at altitudes up to 2000 m.~~ In addition, for all types of insulation response, conservative gap factor values have been used (refer to Annex G).

For polluted insulators, the value of the exponent m is tentative. For the purposes of the long duration test and, if required, the short-duration power-frequency withstand voltage of polluted insulators, m may be as low as 0,5 for normal insulators and as high as 0,8 for anti-fog design.



Key

- a phase-to-earth insulation
- b longitudinal insulation
- c phase-to-phase insulation
- d rod-plane gap (reference gap)

For voltages consisting of two components, the voltage value is the sum of the components.

Figure 9 – Dependence of exponent m on the co-ordination switching impulse withstand voltage

6.3 Safety factors

6.3.1 General

The main factors of influence and related operating modes for electrical insulations are indicated in Annex A of IEC 60505:2011. They correspond to the following operational stresses:

- thermal stresses;
- electrical stresses;
- environmental stresses;
- mechanical stresses.

The factors to be applied compensate for

- the differences in the equipment assembly,
- the dispersion in the product quality,
- the quality of installation,
- the ageing of the insulation during the expected lifetime, and
- other unknown influences.

The relative weight of these factors and operating modes may vary between different types of equipment.

6.3.2 Ageing

The electrical insulation of all equipment ages in service owing to one or a combination of thermal, electrical, chemical or mechanical stresses.

For insulation co-ordination purposes, external insulations are not assumed to be subject to ageing. Exceptions are insulations containing organic materials, the ageing of which needs careful investigation, especially when used in outdoor conditions.

For internal insulations, ageing can be significant and should be covered by the safety factors given in 6.3.5.

6.3.3 Production and assembly dispersion

The rated withstand voltages are verified by a type test, often on a representative part of an assembly, or by a test relevant only for a part of the insulation system. As the equipment in service may differ from that in type tests due to different configurations or insulation conditions, the service withstand voltage of the equipment can be lower than the rated value.

For equipment fully assembled in the factory, this dispersion, for insulation co-ordination purposes, is negligibly small. For equipment assembled on site, the actual withstand voltage may be lower than the required withstand voltage, which shall be taken into account in the safety factors given in 6.3.5.

6.3.4 Inaccuracy of the withstand voltage

For external insulation, possible deviations of the test arrangement from the actual service arrangement and influences of the laboratory surroundings shall be taken into account in addition to the statistical inaccuracy involved in the selected type test procedure. Such deviations shall be covered by the safety factors given in 6.3.5.

For internal insulation for which a withstand probability of 100 % is assumed in 3.23 of IEC 60071-1:2006, an impulse type test with three impulses is usually carried out, and the

statistical uncertainty of this test shall be covered by the safety factor as given in 6.3.5 (see also 7.3.2).

6.3.5 Recommended safety factors (K_s)

If not specified by the relevant apparatus committees, the following safety factors should be applied:

- for internal insulation: $K_s = 1,15$;
- for external insulation: $K_s = 1,05$.

~~NOTE — For GIS in range II, higher safety factors may be applicable. In this case, on-site tests may be considered.~~

Safety factors different from the recommended values may be applied according to, as examples, special positive or negative service experience, improvements in technology, higher levels of quality control during manufacturing and assembly especially in higher voltage systems, or exceptionally conservative approaches in system studies.

7 Standard withstand voltage and testing procedures

7.1 General remarks

7.1.1 Overview

Tables 2 and 3 of IEC 60071-1:2006 and IEC 60071-1:2006/AMD1:2010 specify standard withstand voltages U_w for range I and range II, respectively. In both tables, the standard withstand voltages are grouped into standard insulation levels associated with standard values of highest voltage for equipment U_m .

In range I, the standard withstand voltages include the short-duration power-frequency withstand voltage and the lightning impulse withstand voltage. In range II, the standard withstand voltages include the switching impulse withstand voltage and the lightning impulse withstand voltage.

The standard insulation levels given in Tables 2 and 3 of IEC 60071-1:2006 and IEC 60071-1:2006/AMD1:2010 reflect the experience of the world, taking into account modern ~~protective~~ protection devices and methods of overvoltage limitation. The selection of a particular standard insulation level should be based on the insulation co-ordination procedure described in this document and should take into account the insulation characteristics of the particular equipment being considered.

7.1.2 Standard switching impulse withstand voltage

In Table 3 of IEC 60071-1:2006 and IEC 60071-1:2006/AMD1:2010, standard switching impulse withstand voltages associated with a particular highest voltage for equipment have been chosen in consideration of the following:

- a) for equipment protected against switching overvoltages by surge arresters:
 - the expected values of temporary overvoltages;
 - the characteristics of presently available surge arresters;
 - the co-ordination and safety factors between the ~~protective~~ protection level of the surge arrester and the switching impulse withstand voltage of the equipment;
- b) for equipment not protected against switching overvoltages by surge arresters:
 - the acceptable risk of disruptive discharge considering the probable range of overvoltages occurring at the equipment location;
 - the degree of overvoltage control generally deemed economical, and obtainable by careful selection of the switching devices and in the system design.

7.1.3 Standard lightning impulse withstand voltage

In Table 3 of IEC 60071-1:2006/IEC 60071-1:2006/AMD1:2010, standard lightning impulse withstand voltages associated with a particular standard switching impulse withstand voltage have been chosen in consideration of the following.

- a) For equipment protected by ~~close~~ surge arresters, the low values of lightning impulse withstand level are applicable. They are chosen by taking into account the ratio of lightning impulse ~~protective~~ protection level to switching impulse ~~protective~~ protection level likely to be achieved with surge arresters, and by adding appropriate margins.
- b) For equipment not protected by surge arresters (or not effectively protected), only the higher values of lightning impulse withstand voltages shall be used. These higher values are based on the typical ratio of the lightning and switching impulse withstand voltages of the external insulation of apparatus (e.g. circuit-breakers, disconnectors, instrument transformers). They are chosen in such a way that the insulation design will be determined mainly by the ability of the external insulation to withstand the switching impulse test voltages.
- c) In a few extreme cases, provision should be made for a higher value of lightning impulse withstand voltage. This higher value should be chosen from the series of standard values given in 5.6 and 5.7 of IEC 60071-1:2006 and IEC 60071-1:2006/AMD1:2010.

In range I, the standard short-duration power-frequency or the lightning impulse withstand voltage should cover the required switching impulse withstand voltages phase-to-earth and phase-to-phase as well as the required longitudinal withstand voltage.

In range II, the standard switching impulse withstand voltage should cover the required short-duration power-frequency withstand voltage, and the continuous power-frequency voltage if no value is specified by the relevant apparatus committee.

In order to meet these general requirements, the required withstand voltages should be converted to those voltage shapes for which standard withstand voltages are specified using the test conversion factors given in 7.2. The test conversion factors are determined from existing results to provide a conservative value for the rated withstand voltages. They should, therefore, be used only in the specified direction.

IEC 60071-1 leaves it to the relevant apparatus committee to prescribe the long-duration power-frequency test intended to demonstrate the response of the equipment with respect to ageing of internal insulation or to external pollution (see also IEC 60507).

7.2 Test conversion factors

7.2.1 Range I

If adequate factors are not available (or specified by the relevant apparatus committee), suitable test conversion factors to be applied to the required switching impulse withstand voltages are given in Table 1. These factors apply to the required withstand voltages phase-to-earth as well as to the sum of the components of phase-to-phase and longitudinal withstand voltages.

Table 1 – Test conversion factors for range I, to convert required SIWV to SDWV and LIWV

Insulation	Short-duration power-frequency withstand voltage ^a	Lightning impulse withstand voltage
External insulation		
– air clearances and clean insulators, dry:		
• phase-to-earth	$0,6 + U_{rw} / 8\,500$	$1,05 + U_{rw} / 6\,000$
• phase-to-phase	$0,6 + U_{rw} / 12\,700$	$1,05 + U_{rw} / 9\,000$
– clean insulators, wet	0,6	1,3
Internal insulation		
– GIS	0,7	1,25
– liquid-immersed insulation	0,5	1,10
– solid insulation	0,5	1,00
NOTE U_{rw} is the required switching impulse withstand voltage in kV.		
^a The test conversion factors include a factor of $1/\sqrt{2}$ to convert from peak to RMS value.		

7.2.2 Range II

If adequate factors are not available (or specified by the relevant apparatus committee), suitable test conversion factors for the conversion of the required short-duration power-frequency withstand voltage to switching impulses are given in Table 2. They also apply to the longitudinal insulation.

Table 2 – Test conversion factors for range II to convert required SDWV to SIWV

Insulation	Switching impulse withstand voltage
External insulation	
– air clearances and clean insulators, dry	1,4
– clean insulators, wet	1,7
Internal insulation	
– GIS	1,6
– liquid-immersed insulation	2,3
– solid insulation	2,0
NOTE The test conversion factors include a factor of $\sqrt{2}$ to convert from RMS to peak value.	

7.3 Determination of insulation withstand by type tests

7.3.1 Test procedure dependency upon insulation type

The verification of the electric strength of insulation is achieved through tests. The type of test to be selected for a given equipment shall consider the nature of its insulation(s). Subclauses 3.4 and 3.5 of IEC 60071-1:2006 define the sub-division of insulation into self-restoring and non-self-restoring insulation. This constrains the selection of the test procedure to be adopted for a particular equipment from the list provided in 6.3 of IEC 60071-1:2006, and more fully described in IEC 60060-1.

The following information and guidance is given so as to aid the optimum selection of type tests from insulation co-ordination considerations. The fact that much equipment comprises a mixture of both self-restoring and non-self-restoring insulation is taken into account.

7.3.2 Non-self-restoring insulation

With non-self-restoring insulation, a disruptive discharge degrades the insulating property of the insulation, and even test voltages which do not cause a disruptive discharge may affect the insulation. For example, power-frequency overvoltage tests and impulse tests with polarity reversal may initiate treeing in polymeric insulation and give rise to gas generation in liquid and liquid-impregnated insulation. Non-self-restoring insulation is, for these reasons, tested by application of a limited number of test voltages at standard withstand level, i.e. by withstand procedure A, in 7.3.1.1 of IEC 60060-1:2010, in which three impulses are applied for each polarity, and the test is successful if no disruptive discharge occurs.

For insulation co-ordination purposes, equipment which passes this test should be deemed to have an assumed withstand voltage equal to the applied test voltage (i.e. the rated withstand voltage). Since the number of test impulses is limited and no failure is permitted, no useful statistical information regarding the actual withstand voltage of the equipment can be deduced.

Some equipment which contains both non-self-restoring and self-restoring insulation can be regarded, for test purposes, as non-self-restoring if disruptive discharge during the test would produce significant damage to the non-self-restoring insulation part (e.g. transformers tested with bushings having a higher standard impulse withstand voltage).

7.3.3 Self-restoring insulation

With self-restoring insulation, it is possible to apply a large number of test voltages, the number only being limited by testing constraints and not by the insulation itself, even in the presence of disruptive discharges. The advantage of applying many test voltages is that statistical information may be deduced for the insulation withstand. IEC 60060-1 standardizes three alternative methods leading to an estimation of the 90 % withstand voltage. For insulation co-ordination purposes, the up-and-down withstand method with seven impulses per group and at least eight groups is the preferred method of determining U_{50} . U_{10} can be deduced by assuming a value of conventional deviation (see 5.1.5) or the latter may be determined by a multiple level test. For an evaluation of the statistical significance of the test method, reference may be made to Annex A of IEC 60060-1:2010.

7.3.4 Mixed insulation

For equipment which has self-restoring insulation that cannot be tested separately from its non-self-restoring insulation (e.g. bushings and instrument transformers), a compromise in test method ~~must~~ shall be made. This is necessary so as not to damage satisfactory non-self-restoring insulation while, at the same time, seeking to ensure that the test adequately discriminates between satisfactory and unsatisfactory self-restoring insulation. On the one hand, the non-self-restoring insulation part leads to few test voltage applications. On the other hand, the self-restoring insulation part leads to the need of many test voltage applications (for the purpose of selectivity). Experience shows that withstand test procedure B, in 7.3.1.2 of IEC 60060-1:2010 (15 impulses, up to two disruptive discharges permitted on self-restoring parts), is an acceptable compromise.

Its selectivity may be indicated as the difference between actual withstand levels which would result in probabilities of passing the test of 5 % and 95 %. Refer to Table 3.

Table 3 – Selectivity of test procedures B and C of IEC 60060-1

IEC test procedure	Number of impulses	% probability for passing test at U_{10}	Withstand level for 95 % probability to pass the test	Withstand level for 5 % probability to pass the test	Selectivity
B	15/2	82	$U_{5,5}$ ($U_w + 0,32 Z$)	U_{36} ($U_w - 0,92 Z$)	1,24 Z
C	3 + 9	82	$U_{4,6}$ ($U_w + 0,40 Z$)	U_{63} ($U_w - 1,62 Z$)	2,02 Z

Thus, an equipment tested using procedure B, which is on the borderline of being acceptable (rated and tested at its U_{10}), has a probability of passing the test of 82 %. A better equipment, having a withstand voltage U_{10} higher than the standard value U_w by 0,32 Z (rated and tested at its $U_{5,5}$), has a 95 % probability of passing the test. A poor equipment, having a withstand voltage lower than the standard value U_w by 0,92 Z (rated and tested at its U_{36}), has a 5 % probability of passing the test. This selectivity of test (1,24 Z) may be further quantified by assuming values for Z as 3 % and 6 % of U_{50} for lightning and switching impulses respectively. (It should be noted that Z cannot be determined from the test.) The selectivity of the 15/2 test is further illustrated in Figure 10 in comparison to the ideal test.

An alternative to the above test procedure is withstand test procedure C, in 7.3.1.3 of IEC 60060-1:2010, which is a modification of USA practice. In this procedure, three test impulses are applied and up to one disruptive discharge is permitted across self-restoring insulation, in which case a further nine impulses are applied and the test requirements are satisfied if no further disruptive discharge occurs. The selectivity of this procedure is compared with that of the 15/2 test in Table 3 and also in Figure 10.

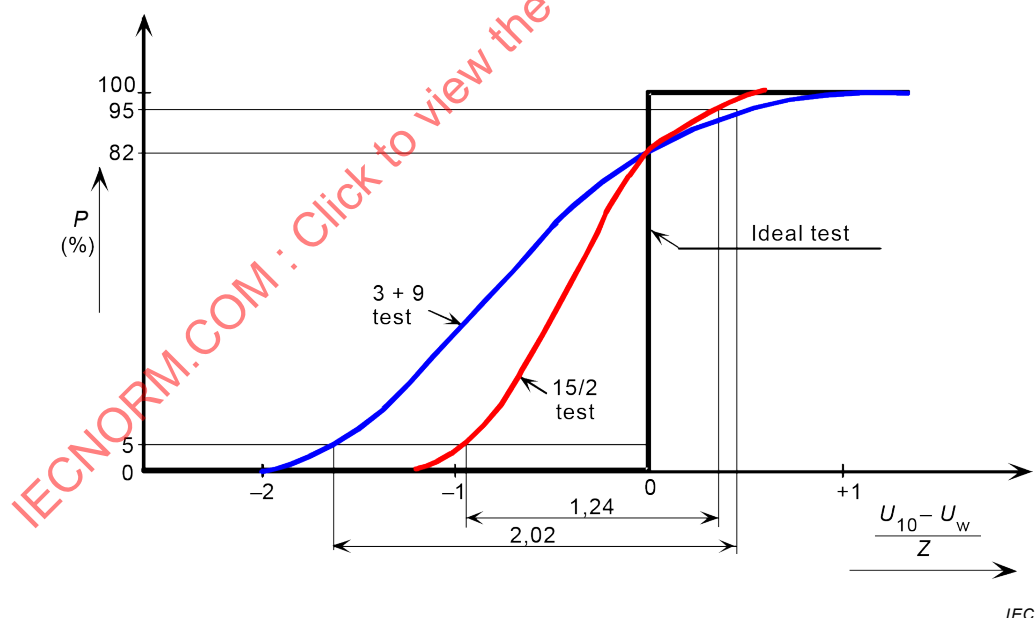


Figure 10 – Probability P of an equipment to pass the test dependent on the difference K between the actual and the rated impulse withstand voltage

7.3.5 Limitations of the test procedures

Since the recovery of insulation from a disruptive discharge is a time-dependent process, an adequate time interval between test voltage applications ~~must~~ shall be permitted for the self-restoring insulation to fully recover its electric strength. Apparatus committees should specify the limits of acceptability (if any) of time intervals between test voltage applications which are dependent upon the type of insulation. Considerations should also be given to the possible

degradation of the non-self-restoring insulation by the repeated application of test voltages even without the occurrence of a disruptive discharge.

7.3.6 Selection of the type test procedures

In view of the foregoing, the following recommendations are made for tests performed for insulation co-ordination purposes:

- self-restoring insulation should be tested with the up-and-down withstand method (one of the methods described in withstand test procedure D, in 7.3.1.4 of IEC 60060-1:2010);
- non-self-restoring insulation should be tested with the three impulse withstand test (withstand test procedure A, in 7.3.1.1 of IEC 60060-1:2010);
- in general, equipment which comprises both self-restoring and non-self-restoring insulation (i.e. mixed insulation) should be tested with the 15/2 test (withstand test procedure B, in 7.3.1.2 of IEC 60060-1:2010). When, however, the risk of tree propagation in the non-self-restoring insulation is of prime concern, and the number of voltage applications is considered excessive, the 3 + 9 test (test procedure C, in 7.3.1.3 of IEC 60060-1:2010) is an acceptable alternative;
- also, where power-frequency tests are required for insulation co-ordination purposes, the short-duration power-frequency withstand tests (IEC 60071-1) should be applied to the insulation, whether self-restoring, non-self-restoring, or mixed.

7.3.7 Selection of the type test voltages

7.3.7.1 General

For equipment containing only external air insulation, the test is performed with the standard withstand voltage applying the atmospheric correction factors specified in IEC 60060-1.

For equipment containing only internal insulation, the test is performed with the ~~uncorrected~~ standard withstand voltage **only (without applying the atmospheric correction factors specified in IEC 60060-1).**

For equipment containing both internal and external insulation, the atmospheric correction factor should be applied and the test carried out with the corrected value, provided that the corrected factor is between 0,95 and 1,05. When the correction factor is outside this range, the alternatives listed below are acceptable for insulation co-ordination purposes.

7.3.7.2 Test voltage of the external insulation higher than that of the internal insulation (atmospheric correction factor > 1,05)

The external insulation can only be correctly tested when the internal insulation is oversized. If not, the internal insulation should be tested with the standard value and, for the external insulation, the following alternatives may be considered by the technical apparatus committees or by agreement:

- ~~test of~~ the external insulation **should only be tested** on dummies;
- interpolation between existing results;
- estimation of the withstand voltages from the dimensions.

In general, a test of the external insulation is not necessary if the air clearances are equal to or larger than those given in IEC 60071-1.

For wet tests on vertical insulators, the insulator shape should meet certain additional requirements. Until supporting information is available, these requirements may be considered as being fulfilled if the insulator shape meets requirements of IEC **TS 60815-1**.

For power-frequency tests under wet conditions, no additional test of the external insulation is necessary if the clearances are larger than the rated power-frequency withstand voltage divided by 230 kV/m and the insulator shape meets the requirements of IEC TS 60815-1.

7.3.7.3 Test voltage of the external insulation lower than that of the internal insulation (atmospheric correction factor < 0,95)

The internal insulation can only be correctly tested when the external insulation is oversized. If not, the external insulation should be tested with the corrected values and, for the internal insulation, the following alternatives may be considered by the technical apparatus committees or by agreement:

- test of the internal insulation with one polarity (usually negative) impulse only;
- test of the internal insulation increasing the external insulation strength, for example by corona control electrodes of different gap sizes. The strengthening measure should not affect the behaviour of the internal insulation.

8 Special considerations for overhead lines

8.1 General remarks

Although the insulation co-ordination procedure for overhead line insulation follows the general philosophy of insulation co-ordination, the following special considerations shall be taken into account.

- Where the design employs free-swinging insulators, the dielectric strength of air clearances should take into account conductor movement.
- Insulator standards specify the dimensions of insulator units without making reference to a highest voltage for equipment or a highest system voltage. Consequently the insulation co-ordination procedure terminates with the determination of the required withstand voltage U_{rw} . The selection of a rated voltage in IEC 60071-1 is not necessary, and Tables 2 and 3 of IEC 60071-1:2006 and IEC 60071-1:2006/AMD1:2010 do not apply.
- The insulation performance of overhead lines has a large impact on the insulation performance of substations. The transmission line outage rate due to lightning primarily determines the frequency of re-energization operations, and the lightning performance rate close to the substation determines the frequency of fast-front overvoltages impinging on the substation.

8.2 Insulation co-ordination for operating voltages and temporary overvoltages

The operating voltage and the temporary overvoltages determine the required insulator string length and the shape of the insulator unit for the pollution site severity. In directly earthed neutral systems with earth fault factors of 1,3 and below, it is usually sufficient to design the insulators to withstand the highest system voltage phase-to-earth. For higher earth fault factors and especially in isolated or resonant earthed neutral systems, consideration of the temporary overvoltages may be necessary.

Where consideration ~~must~~ shall be given to free-swinging insulators, the clearances should be determined under extreme swing conditions.

8.3 Insulation co-ordination for slow-front overvoltages

8.3.1 General

Slow-front overvoltages of interest for overhead lines are earth-fault overvoltages, energization and re-energization overvoltages. When establishing the acceptable failure rates it should be taken into account that

- an insulation failure due to earth-fault overvoltages causes a double phase-to-earth fault, and

- an insulation failure due to re-energization overvoltages causes an unsuccessful reclosure.

8.3.2 Earth-fault overvoltages

Earth-fault overvoltages should be taken into account in systems with high earth fault factors, i.e. for distribution lines or transmission lines in resonant earthed-neutral systems. The acceptable failure rates for these lines shall be selected in the order of magnitude of their two-phase lightning outage rate. As a guide, acceptable failure rates between 0,1 and 1,0 flashover/year are typical.

Special considerations are necessary for lines in range II where energization and re-energization overvoltages are normally controlled to low amplitudes, since in this case the slow-front overvoltage generated by earth faults may be more severe.

8.3.3 Energization and re-energization overvoltages

Energization overvoltages are of interest for all overhead lines, but specially in range II. Suitable acceptable failure rates are in the order of 0,005 to 0,05 flashover/year.

Re-energization overvoltages require attention for transmission lines when fast three-phase reclosing is applied (because of trapped charges). Acceptable failure rates of 0,005 to 0,05 flashover/year may be suitable.

Re-energization overvoltages can be disregarded when single-phase reclosing is used on transmission lines or for distribution lines in which the distribution transformers remain connected during the operation.

Slow-front overvoltages are one of the factors determining the air clearances and, for some type of insulators, the insulator fittings. Usually their importance is restricted to transmission lines in the higher system voltage range of 123 kV and above. Where free-swinging insulators are applied, air clearances for slow-front overvoltages are generally determined assuming moderate (mean) swing conditions. For distribution lines, the clearances are generally determined by the insulator (see 8.2) and slow-front overvoltages need not be considered.

8.4 Insulation co-ordination for lightning overvoltages

8.4.1 General

The lightning performance of overhead lines depends on a variety of factors, among which the most important are

- the lightning ground flash density,
- the height of the overhead line,
- the conductor configuration,
- the protection by shield wires,
- the tower earthing,
- the insulation strength, and
- the use of line surge arresters.

8.4.2 Distribution lines

For distribution lines, it should be assumed that each direct lightning flash to the line causes a flashover between phases with or without a flashover to earth. Protection by shield wires is useless because tower earthing and insulation strength cannot economically be improved to such a degree that back flashovers are avoided. The lightning performance of distribution lines, therefore, is largely determined by the ground flash density and the line height.

For distribution lines with unearthed crossarms (wood-pole lines), induced overvoltages from nearby strokes to earth have no importance. However, the high dielectric strength to earth causes overvoltage surges with high amplitudes impinging on the substation and, in such cases, consideration should be given for the appropriate choice of substation surge arresters (energy requirements).

For distribution lines with earthed crossarms, induced overvoltages may affect the required lightning impulse strength of the overhead line insulation.

8.4.3 Transmission lines

For transmission lines above 72,5 kV, induced voltages can be neglected and only direct flashes to the line determine the lightning performance. A general guide for a suitable target performance rate cannot be given because this rate would largely depend on the consequences of a lightning outage and the cost to improve shielding, earthing and insulation strength. It is possible, however, to design for a lower outage rate for the line section in front of the substation than for the rest of the line, in order to reduce the amplitudes and frequency of the overvoltage surges impinging on the substation and also to reduce the probability of occurrence of short-line faults (see IEC ~~56~~ 62271-100).

9 Special considerations for substations

9.1 General remarks

9.1.1 Overview

The voltage stresses which can arise in a substation as shown in Figure 11 are described in the following subclauses 9.1.2 to 9.1.5.

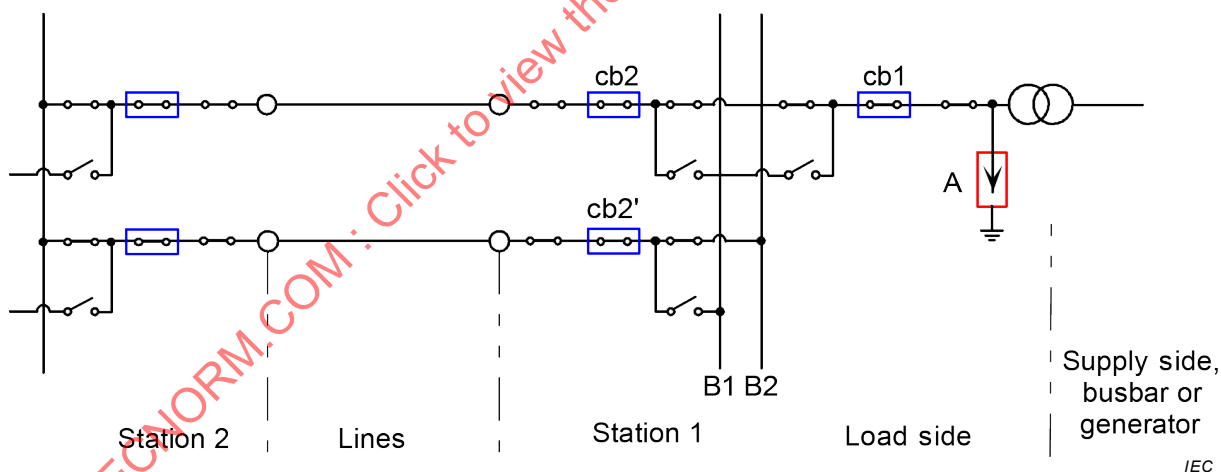


Figure 11 – Example of a schematic substation layout used for the overvoltage stress location ~~(see 7.1)~~

9.1.2 Operating voltage

It is assumed to be equal to the highest system voltage. All parts of the substation are equally stressed.

9.1.3 Temporary overvoltage

Earth faults on the load side stress all parts of one phase of the substation equally.

Load rejection overvoltages may arise in the substation mainly due to a fault in the distant substation (station 2). Depending on the protection scheme, either all or some parts between

circuit-breaker cb2 and the transformer will be stressed. For a fault in the substation itself (station 1), only the parts between circuit-breaker cb1 and the transformer are subjected to load rejection overvoltages.

Longitudinal overvoltage stresses may exist at circuit-breaker cb1 during synchronization if the transformer is connected to a generator. When busbar B2 is operating in a different system, the longitudinal insulation of the busbar disconnectors may be subjected to the operating voltage on busbar B2 and the load rejection overvoltage on busbar B1 in phase opposition.

9.1.4 Slow-front overvoltages

Overvoltages due to line energization or re-energization can have the high amplitudes of the receiving end only between the line entrance and the circuit-breaker cb2. The rest of the substation is subjected to the overvoltages at the sending end.

Overvoltage due to faults and fault clearing may occur in all parts.

9.1.5 Fast-front overvoltages

Lightning overvoltages may arise at all parts of the station; however, with different amplitudes depending on the distance to the arrester.

Fast-front switching overvoltages occur only on the switched section of the station (e.g. on busbar B2) or at one of the breakers, when they are switched by one of the busbar disconnectors.

The different steps of insulation co-ordination are shown in three selected examples in Annex G.

As the specification of suitable long-duration power-frequency test voltages is left to the technical apparatus committees, the verification of the required long-duration power-frequency withstand voltages is omitted from the examples.

NOTES

1 At the initial stage, only one line ~~may~~ can be in service and temporary overvoltages due to load rejection after an earth-fault ~~need consideration~~ should be considered.

2 When the transformers are energized via a long line, slow-front overvoltages ~~may~~ can also stress transformer and busbar.

3 In GIS, very-fast-front overvoltages due to disconnector operations ~~may need consideration~~ should be considered.

9.2 Insulation co-ordination for overvoltages

9.2.1 Substations in distribution systems with U_m up to 36 kV in range I

9.2.1.1 General

For equipment in this voltage range, IEC 60071-1 specifies standard rated short-duration power-frequency and lightning impulse withstand voltages.

As a general guide, it can be assumed that in the distribution voltage range the required switching impulse withstand voltages phase-to-earth are covered by the standard short-duration power-frequency withstand voltage. The required switching impulse withstand voltages phase-to-phase, however, have to be considered in the selection of the standard lightning impulse withstand voltage, or the short-duration power-frequency withstand voltage.

Provided that the slow-front phase-to-phase overvoltages have been accommodated, equipment designed to the lower standard lightning impulse withstand voltage values from IEC 60071-1:2006, Table 2, may be suitable for installations such as the following:

- a) systems and industrial installations not connected to overhead lines;
- b) systems and industrial installations connected to overhead lines only through transformers where the capacitance to earth of cables connected to the transformer low-voltage terminals is at least 0,05 μF per phase; when the cable capacitance to earth is insufficient, additional capacitors should be added on the transformer side of the switchgear, as close as possible to the transformer terminals, so that the combined capacitance to earth of the cables plus the additional capacitors is at least 0,05 μF per phase;
- c) systems and industrial installations connected directly to overhead lines, when adequate overvoltage protection by surge arresters is provided.

In all other cases, or where a very high degree of security is required, equipment designed to the higher rated lightning impulse withstand voltage value should be used.

9.2.1.2 Equipment connected to an overhead line through a transformer

Equipment connected to the low-voltage side of a transformer supplied on the high-voltage side from an overhead line is not directly subjected to lightning or switching overvoltages originating on the overhead line. However, due to electrostatic and electromagnetic transference of such overvoltages from the high-voltage ~~side~~ winding to the low-voltage winding of the transformer, such equipment can be subjected to overvoltages which ~~must~~ **shall** be taken into account in the insulation co-ordination procedure with the possible application of ~~protective~~ **protection** devices.

Analytical expressions for the electrostatic and electromagnetic terms of the transferred voltage are given in Annex D.

9.2.1.3 Equipment connected to an overhead line through a cable

Insulation co-ordination, in this case, is not only concerned with the protection of the substation equipment, but also of the cable.

When a lightning surge propagating along an overhead line impinges on a cable, it breaks up into a reflected wave and a transmitted wave, where the transmitted wave amplitude is substantially decreased as compared to that of the impinging surge. Subsequent reflections at each end of the cable, however, usually result in a substantial increase in the voltage along the cable above this initial value. In general, the higher standard rated lightning impulse withstand voltages from IEC 60071-1:2006, Table 2, should be selected and surge arresters installed at the line-cable junction. When wood poles are used in the overhead line and when only one line may be connected to the substation, additional arresters may be required at the cable entrance of the substation.

9.2.2 Substations in transmission systems with U_m between 52,5 kV and 245 kV in range I

For equipment in this voltage range, IEC 60071-1 specifies standard rated short-duration power-frequency and lightning impulse withstand voltages.

As a general guide, it can be assumed that in the transmission voltage range within range I, the required switching impulse withstand voltages phase-to-earth are covered by the standard short-duration power-frequency withstand voltage. The required switching impulse withstand voltages phase-to-phase, however, have to be considered in the selection of the lightning impulse withstand voltage or standard short-duration power-frequency withstand voltage for the equipment at the line entrance, or additional phase-to-phase switching impulse tests may be necessary for three-phase equipment.

For the selection of the lightning impulse withstand voltage, many considerations for the distribution voltage range also apply to the transmission voltage range within range I. However, as the variety of equipment and locations is not as great, it is recommended that the insulation co-ordination procedure be carried out for a number of representative substation-overhead line combinations using at least the simplified procedures described in Annex E.

9.2.3 Substations in transmission systems in range II

For equipment in this voltage range, IEC 60071-1 specifies standard rated switching and lightning impulse withstand voltages.

In this voltage range, the use of the statistical methods of insulation co-ordination should generally be applied. The frequency of overvoltages for both switching operations or faults and lightning events should be examined, carefully considering the location of the equipment in the substation (e.g. to distinguish between equipment at the sending or receiving end of energized lines). Furthermore, the deterministic insulation co-ordination method based on temporary overvoltages may result in standard withstand voltages that are too conservative and more accurate procedures should be applied, which take into account the actual overvoltage duration and the power-frequency voltage-time withstand characteristic of the insulation.

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Annex A **(normative)**

Clearances in air to assure a specified impulse withstand voltage installation

In complete installations (e.g. substations) which cannot be tested as a whole, it is necessary to ensure that the dielectric strength is adequate.

The switching and lightning impulse withstand voltages in air at standard atmosphere shall be equal to, or greater than, the standard switching and lightning impulse withstand voltages as specified in this standard. Following this principle, minimum clearances have been determined for different electrode configurations. The minimum clearances specified are determined with a conservative approach, taking into account practical experience, economy, and size of practical equipment in the range below 1 m clearance.

These clearances are intended solely to address insulation co-ordination requirements. Safety requirements may result in substantially larger clearances.

Tables A.1, A.2 and A.3 are suitable for general application, as they provide minimum clearances ensuring the specified insulation level.

These clearances may be lower if it has been proven by tests on actual or similar configurations that the standard impulse withstand voltages are met, taking into account all relevant environmental conditions which can create irregularities on the surface of electrodes, for example rain, pollution. The distances are therefore not applicable to equipment which has an impulse type test included in the specification, since mandatory clearance might hamper the design of equipment, increase its cost and impede progress.

The clearances may also be lower, where it has been confirmed by operating experience that the overvoltages are lower than those expected in the selection of the standard withstand voltages or that the gap configuration is more favourable than that assumed for the recommended clearances.

Table A.1 correlates the minimum air clearances with the standard lightning impulse withstand voltage for electrode configurations of the rod-structure type and, in addition for range II, of the conductor-structure type. They are applicable for phase-to-earth clearances as well as for clearances between phases (see note under table A.1).

Table A.2 correlates the minimum air clearances for electrode configurations of the conductor-structure type and the rod-structure type with the standard switching impulse withstand voltage phase-to-earth. The conductor-structure configuration covers a large range for normally-used configurations.

Table A.3 correlates the minimum air clearances for electrode configurations of the conductor-conductor type and the rod-conductor type with the standard switching impulse withstand voltage phase-to-phase. The unsymmetrical rod-conductor configuration is the worst electrode configuration normally encountered in service. The conductor-conductor configuration covers all symmetrical configurations with similar electrode shapes on the two phases.

The air clearances applicable in service are determined according to the following rules:

A.1 Range I

The air clearance phase-to-earth and phase-to-phase is determined from table A.1 for the rated lightning impulse withstand voltage. The standard short-duration power frequency withstand voltage can be disregarded when the ratio of the standard lightning impulse to the standard short-duration power frequency withstand voltage is higher than 1,7.

A.2 Range II

The phase-to-earth clearance is the higher value of the clearances determined for the rod-structure configuration from table A.1 for the standard lightning impulse, and from table A.2 for the standard switching impulse withstand voltages respectively.

The phase-to-phase clearance is the higher value of the clearances determined for the rod-structure configuration from table A.1 for the standard lightning impulse and from table A.3 for the standard switching impulse withstand voltages respectively.

The values are valid for altitudes which have been taken into account in the determination of the required withstand voltages (see 4.3.2).

The clearances necessary to withstand the standard lightning impulse withstand voltage for the longitudinal insulation in range II can be obtained by adding 0,7 times the maximum operating voltage phase-to-earth peak to the value of the standard lightning impulse voltage and by dividing the sum by 500 kV/m.

The clearances necessary for the longitudinal standard switching impulse withstand voltage in range II are smaller than the corresponding phase-to-phase value. Such clearances usually exist only in type tested apparatus and minimum values are therefore not given in this guide.

Table A.1 — Correlation between standard lightning impulse withstand voltages and minimum air clearances

Standard lightning impulse withstand voltage kV	Minimum clearance mm	
	Rod-structure	Conductor-structure
–20	–60	
–40	–60	
–60	–90	
–75	–120	
–95	–160	
–125	–220	
–145	–270	
–170	–320	
–250	–480	
–325	–630	
–450	–900	
–550	1100	
–650	1300	
–750	1500	
–850	1700	1600
–950	1900	1700
1050	2100	1900
1175	2350	2200
1300	2600	2400
1425	2850	2600
1550	3100	2900
1675	3350	3100
1800	3600	3300
1950	3900	3600
2100	4200	3900

NOTE — The standard lightning impulse is applicable phase-to-phase and phase-to-earth.
 For phase-to-earth, the minimum clearance for conductor-structure and rod-structure is applicable.
 For phase-to-phase, the minimum clearance for rod-structure is applicable

Table A.2 — Correlation between standard switching impulse withstand voltages and minimum phase-to-earth air clearances

Standard switching impulse withstand voltage kV	Minimum phase-to-earth mm	
	Conductor-structure	Rod-structure
–750	1600	1900
–850	1800	2400
–950	2200	2900
1050	2600	3400
1175	3100	4100
1300	3600	4800
1425	4200	5600
1550	4900	6400

Table A.3 — Correlation between standard switching impulse withstand voltages and minimum phase-to-phase air clearances

Standard switching impulse withstand voltage			Minimum phase-to-phase clearance mm	
Phase-to-earth kV	Phase-to-phase value Phase-to-earth value	Phase-to-phase kV	Conductor-conductor parallel	Red-conductor
750	1,5	1125	2300	2600
850	1,5	1275	2600	3100
850	1,6	1360	2900	3400
950	1,5	1425	3100	3600
950	1,7	1615	3700	4300
1050	1,5	1575	3600	4200
1050	1,6	1680	3900	4600
1175	1,5	1763	4200	5000
1300	1,7	2210	6100	7400
1425	1,7	2423	7200	9000
1550	1,6	2480	7600	9400

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Annex A (informative)

Determination of temporary overvoltages due to earth faults

The earth fault factor is at a given location of a three-phase system, and for a given system configuration, the ratio of the highest RMS phase-to-earth power frequency voltage on a healthy phase during a fault to earth affecting one or more phases at any point on the system to the RMS phase-to-earth power frequency voltage which would be obtained at the given location in the absence of any such fault (see definition 3.15 of IEC 60071-1:2006).

The earth fault factor is calculated using the complex impedances Z_1 and Z_0 of the positive and zero sequence systems, taking into account the fault resistance R . The following applies:

$Z_1 = R_1 + jX_1$: resistance and reactance of positive and negative sequence system;

$Z_0 = R_0 + jX_0$: resistance and reactance of zero sequence system;

(the earth fault factors are calculated for the location of the fault).

NOTE It should be observed that in extended resonant-earthed networks, the earth fault factor ~~may~~ can be higher at other locations than the fault.

Figure A.1 shows the overall situation for $R_1 \ll X_1$ and $R = 0$

The range of high values for X_0/X_1 positive and/or negative, apply to resonant earthed or isolated neutral systems.

The range of low values of positive X_0/X_1 are valid for earthed neutral systems.

The range of low values of negative X_0/X_1 , shown hatched, is not suitable for practical application due to resonant conditions.

For earthed neutral systems, Figure A.2 to Figure A.5 show the earth fault factors as a family of curves applicable to particular values of R_1/X_1 .

The curves are divided into regions representing the most critical conditions by the following methods of presentation:

- Maximum voltage occurs on the phase which leads the faulted phase, during a phase-to-earth fault.
- Maximum voltage occurs on the phase which lags the faulted phase, during a phase-to-earth fault.
- Maximum voltage occurs on the unfaulted phases, during a phase-to-earth fault.

The curves are valid for fault resistance values giving the highest earth fault factors.

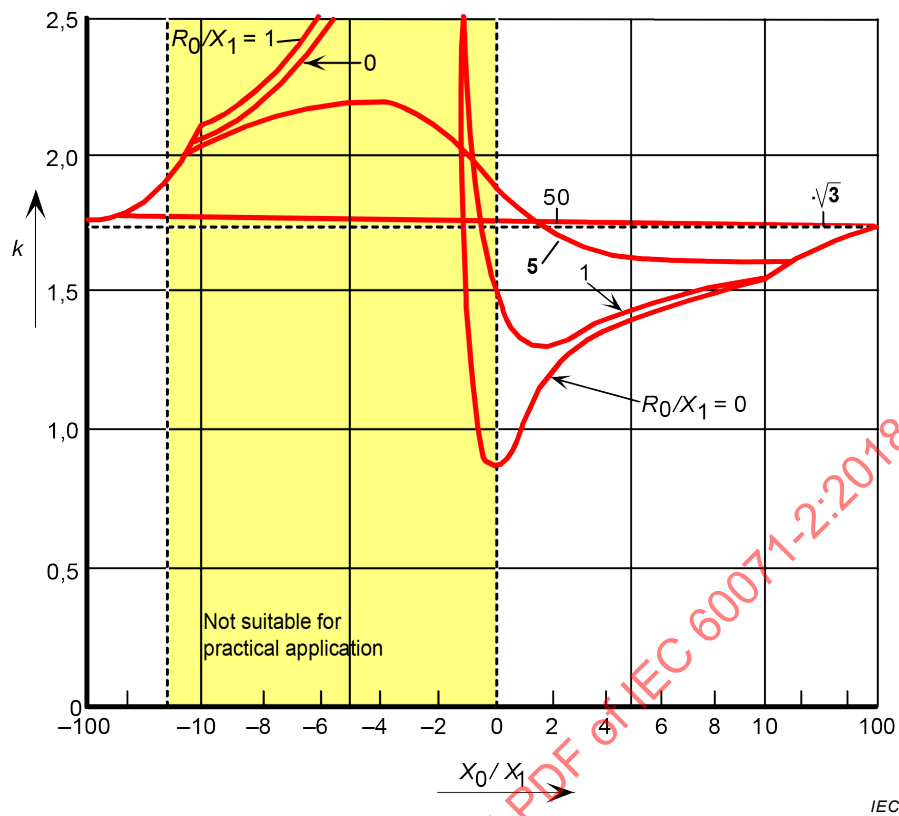


Figure A.1 – Earth fault factor k on a base of X_0/X_1 for $R_1/X_1 = R = 0$

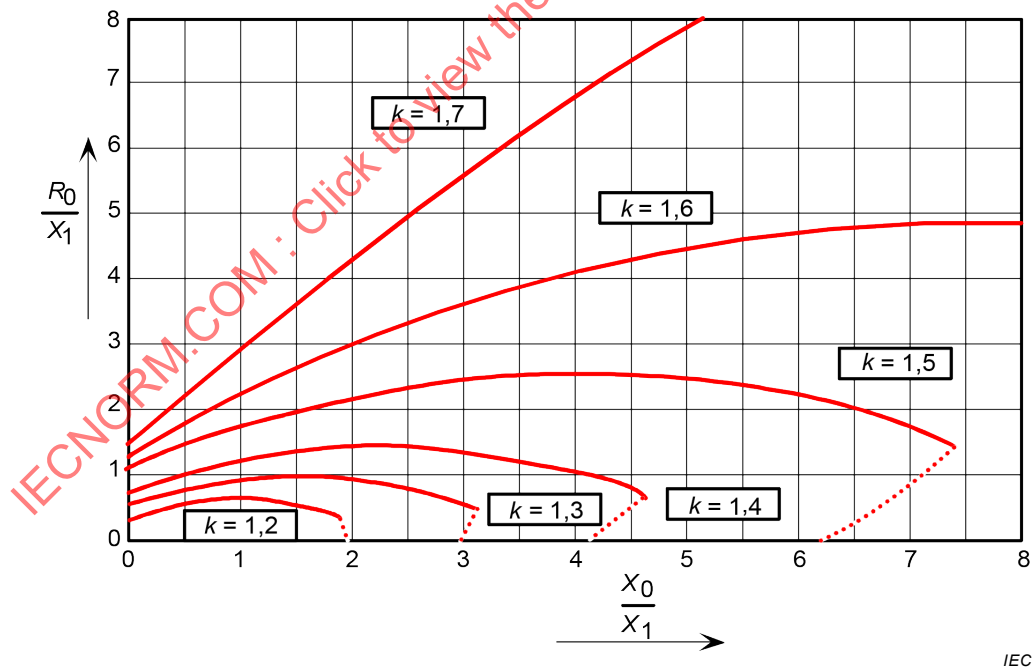


Figure A.2 – Relationship between R_0/X_1 and X_0/X_1 for constant values of earth fault factor k where $R_1 = 0$

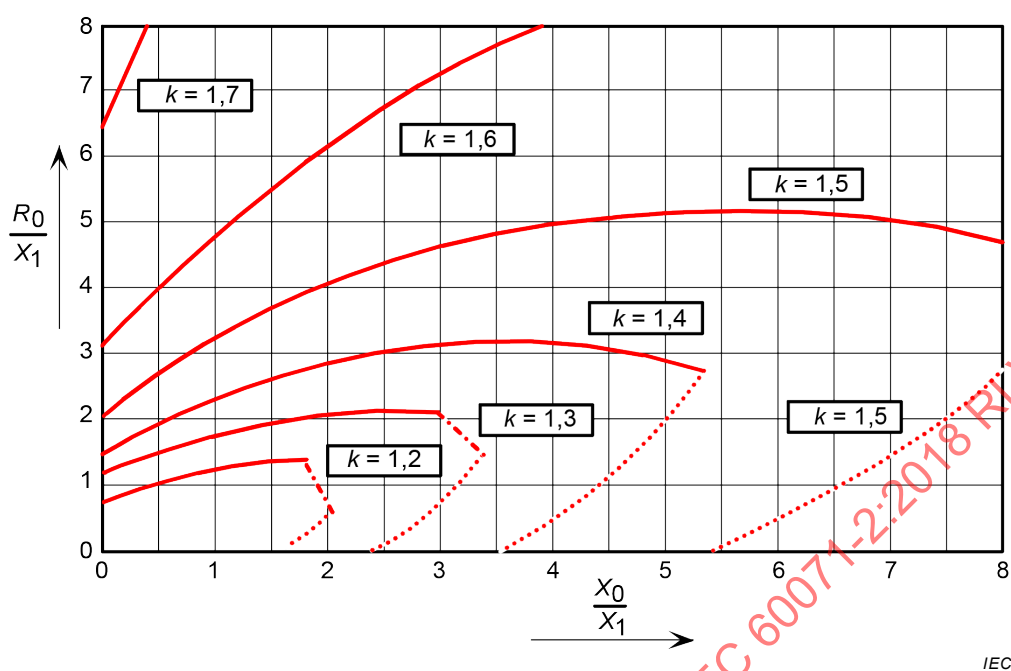


Figure A.3 – Relationship between R_0/X_1 and X_0/X_1 for constant values of earth fault factor k where $R_1 = 0,5 X_1$

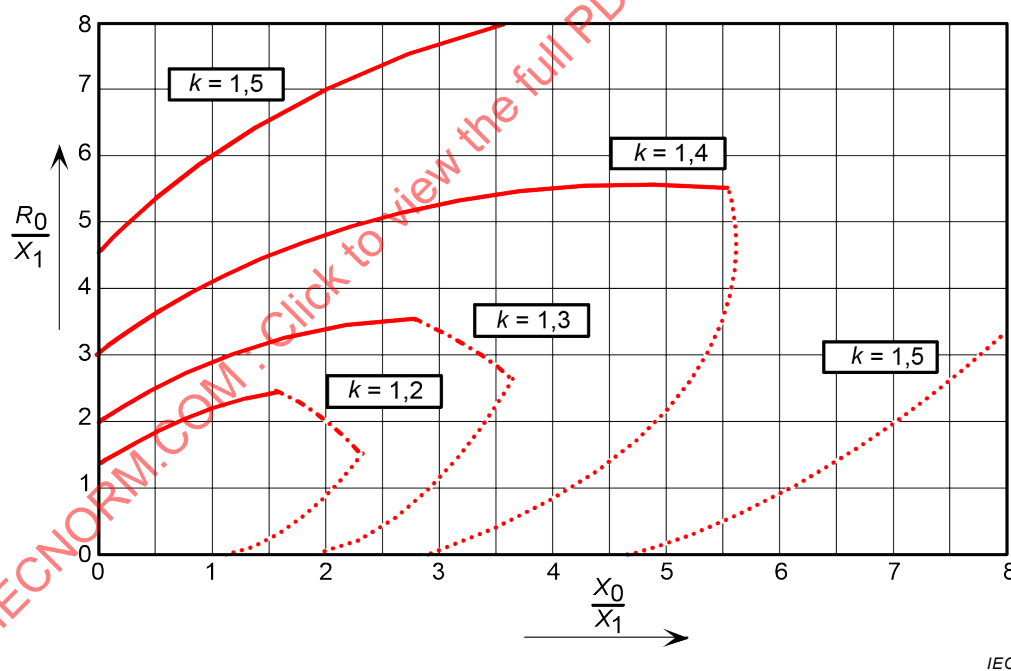


Figure A.4 – Relationship between R_0/X_1 and X_0/X_1 for constant values of earth fault factor k where $R_1 = X_1$

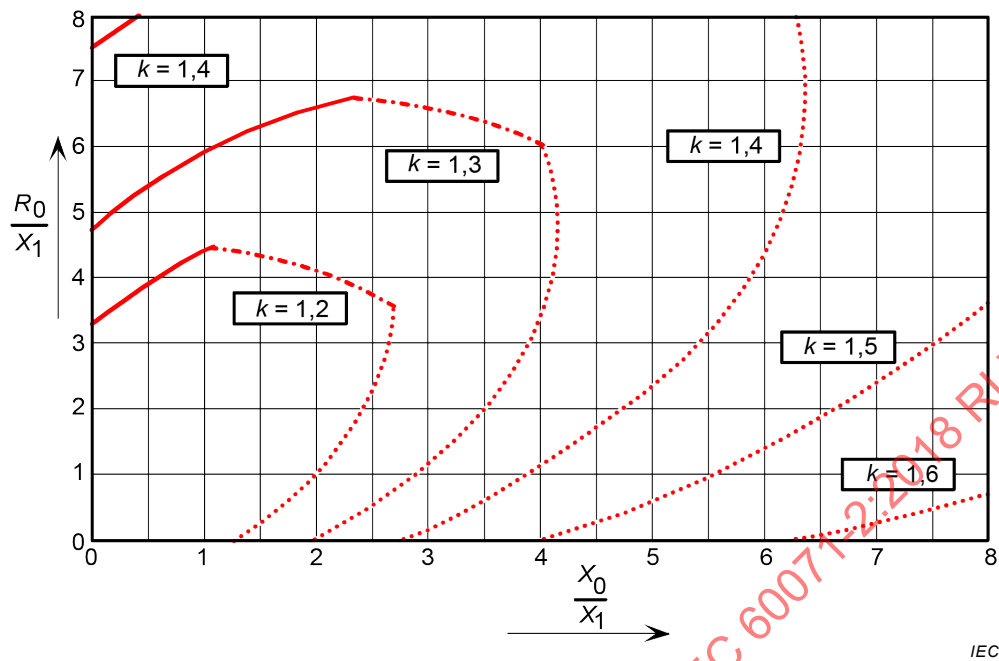


Figure A.5 – Relationship between R_0/X_1 and X_0/X_1 for constant values of earth fault factor k where $R_1 = 2X_1$

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Annex B (informative)

Weibull probability distributions

B.1 General remarks

In the vast majority of literature dealing with external insulation, the disruptive discharge probability of the insulation as function of the peak value of the applied voltage $P(U)$ is represented by a Gaussian cumulative frequency distribution which is given by the following expression:

$$P(U) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^x e^{-\frac{1}{2}y^2} dy \quad (\text{B.1})$$

And

$$x = (U - U_{50}) / Z$$

where

U_{50} is the 50 % discharge voltage ($P(U_{50}) = 0,5$);

Z is the conventional deviation according to IEC 60061-1.

A fundamental observation, however, is that there is no physical support to the adoption of this function for $P(U)$. An evidence of this lack of support is that physically no discharge can occur below a minimum value of U . The function is therefore truncated at (U_0 $U_{\text{spec}} = U_{50} - 3 Z$) or at (U_0 $U_{\text{spec}} = U_{50} - 4 Z$), so that $P(U) = 0$ for $U \leq U_0$ U_{spec} . The main reason why Equation (B.1) was adopted is because it fitted reasonably well with the experimental results.

Also, the cumulative frequency distribution of the overvoltages is usually described by a Gaussian cumulative function $F(U)$ which is often truncated at ($U_{\text{et}} = U_{e50} + 3 S_e$) or at ($U_{\text{pt}} = U_{p50} + 3 S_p$) in order to represent an upper assumed limit for the overvoltages.

In order to account for these facts, this document recommends the use of Weibull probability functions both for the overvoltages and for the disruptive discharge of self-restoring insulation, because it offers the following advantages:

- the truncation values U_0 U_{spec} and U_{et} are mathematically included in the Weibull expression;
- the functions are easily evaluated by pocket calculators;
- the inverse functions $U = U(P)$ and $U_e = U_e(F)$ can be expressed mathematically and are easily evaluated by pocket calculators;
- the modified Weibull expressions are defined by the same parameters characterizing the two truncated Gaussian expressions: (U_{50} , Z and U_0 U_{spec}) for $P(U)$, and for example (U_{e2} , S_e and U_{et}) for $F(U_e)$;
- the disruptive discharge probability function of several identical insulations in parallel has the same expression as that of one insulation and its characteristics can be easily determined from those of the single insulation.

Annex B describes the derivation of the two modified functions from the Weibull cumulative probability distribution with three parameters, to be used for the representation of the disruptive discharge probability function of external insulation under switching and lightning impulses, and of the cumulative probability distribution of the peak values of the overvoltages occurring in a system.

B.2 Disruptive discharge probability of external insulation

The general expression for the Weibull distribution is:

$$P(U) = 1 - e^{-\left(\frac{U-\delta}{\beta}\right)^\gamma} \quad P(U) = 1 - e^{-\left(\frac{U-U_0}{\beta}\right)^\gamma} \quad (\text{B.2})$$

where

U_0 is the truncation value;

β is the scale parameter;

γ is the shape parameter.

This expression can be suitably modified for the description of the discharge probability of an insulation with a truncated discharge probability by substituting the truncation value U_0 and the scale factor β :

$$U_0 = U_{50} - N Z \quad (\text{B.3})$$

$$\beta = N Z (\ln 2)^{-\frac{1}{\gamma}} \quad (\text{B.4})$$

which leads to the modified Weibull function:

$$P(U) = 1 - 0,5^{\left(1 + \frac{U-U_{50}}{ZN}\right)^\gamma} \quad (\text{B.5})$$

in which the constant N is equal to the number of conventional deviations below U_{50} corresponding to the truncation voltage ($P(U) = 0$) and the exponent is determined by the condition that ($P(U_{50} - Z) = 0,16$) resulting in:

$$\gamma = \frac{\ln\left[\frac{\ln(1 - 0,16)}{\ln 0,5}\right]}{\ln(1 - (1/N))} \quad (\text{B.6})$$

For external insulation, it is assumed that no discharge is possible (withstand probability = 100 %) at a truncation value ($U_0 = U_{\text{spec}} = U_{50} - 4 Z$), i.e. for $N = 4$. Introducing $N = 4$ in Equation (B.6) results in an exponent of $\gamma = 4,80$, which can be approximated to $\gamma = 5$ without any significant error.

Introducing the normalized variable ($x = (U - U_{50}) / Z$) as for the Gaussian function, the adopted modified Weibull flashover probability distribution is then:

$$P(U) = 1 - 0,5^{\left(1 + \frac{x}{4}\right)^5} \quad (\text{B.7})$$

Figure 5 illustrates this modified Weibull distribution together with the Gaussian distribution to which it is matched. Figure 6 shows the same distributions on Gaussian probability scales.

If the same overvoltage stresses simultaneously M identical parallel insulations, the resulting flashover probability of the parallel insulations $[P'(U)]$ is given by Equation (B.8):

$$P'(U) = 1 - [1 - P(U)]^M \quad (\text{B.8})$$

Combining Equations (B.7) and (B.8), the flashover probability for M parallel insulations is:

$$P'(U) = 1 - 0,5^{M \left(1 + \frac{x}{4}\right)^5} \quad (\text{B.9})$$

Introducing the normalized variable ($x_M = (U - U_{50M})/Z_M$), the Equation (B.9) can be expressed as following:

$$P'(U) = 1 - 0,5^{\left(1 + \frac{x_M}{4}\right)^5} \quad (\text{B.10})$$

From Equations (B.9) and (B.10) is obtained:

$$1 + \frac{x_M}{4} = \sqrt[5]{M} \left(1 + \frac{x}{4}\right) \quad (\text{B.11})$$

In general, if the risk of failure of one insulation (R) is small (such as 10^{-5}), then the risk of failure of M identical parallel insulations stressed simultaneously can be approximated as the product of M and R .

Replacing in Equation (B.11) x and x_M by their respective extended definition, and because at the truncation point ($U_{50} - 4Z = U_{50M} - 4Z_M = U_0 = U_{\text{spec}}$), the following relationships are obtained:

$$Z_M = \frac{Z}{\sqrt[5]{M}} \quad U_{50M} = U_{50} - 4Z \left(1 - \frac{1}{\sqrt[5]{M}}\right) \quad (\text{B.12})$$

These relationships are shown in Figure B.1 which gives the withstand characteristic of M parallel identical insulations related to the withstand characteristic of one insulation.

For example, applying preceding formulas for $M = 200$:

$$U_{50(200)} = U_{50} - 2,6Z$$

$$U_{10(200)} = U_{50(200)} - 1,3 Z_{200} = U_{50} - 3,1Z$$

As another example, for 100 parallel insulations, each one with $U_{50} = 1\,600$ kV and $Z = 100$ kV, then $Z_M = 100 / (100)^{1/5} = 39,8$ kV and $U_{50M} = 1359,2$ kV. Table B.1 completes this example giving the values of U and U_M for various flashover probabilities $P(U)$.

**Table B.1 – Breakdown voltage versus cumulative flashover probability –
Single insulation and 100 parallel insulations**

P(U) (%)	50	16	10	2	1,	0,1	0 ^a
U (kV)	1 600	1 500	1 475	1 400	1 370	1 310	1 200
U _M (kV)	1 359	1 319	1 308	1 280	1 268	1 244	1 200
^a The truncation value remains constant.							

Calculation of the risk of failure

To calculate the risk of failure for the preceding example, assume $U_{e2} = 1\,200$ kV and $S_e = 100$ kV. Then, for one insulator:

$$K_{cs} = U_{10} / U_{e2} = 1\,475 / 1\,200 = 1,23$$

and $R = 10^{-5}$

For 100 identical parallel insulations:

$$K_{cs} = 1\,308 / 1\,200 = 1,09$$

and $R = 10^{-3}$ (to compare to Figure 8)

As an approximation, one could calculate the risk of failure of M parallel insulations using the following equation, for $R < 0,1$:

$$R = M \Phi \left[\frac{U_{e50} - U_{50}}{\sqrt{S_e^2 + Z^2}} \right] \quad (\text{B.13})$$

where

M is the number of simultaneously stressed insulations;

Φ is the untruncated Gaussian integral function;

U_{e50} is the mean value of the overvoltage distribution, obtained as $U_{e2} - 2S_e$ according to Annex C (kV);

U_{50} is the 50 % flashover voltage determined as withstand voltage divided by $(1 - 1,3Z)$ (kV);

S_e is the conventional deviation of the overvoltage probability distribution (kV);

Z is the conventional deviation of the flashover probability (kV).

Then

$$R = 100 \Phi ((1\,000 - 1\,600) / 140) = 100 \Phi (-4,3) = 100 (10^{-5}) = 10^{-3}$$

which is the same result as above. For low risk values, the use of this equation may be too conservative.

B.3 Cumulative frequency distribution of overvoltages

To represent the cumulative frequency of overvoltages with a modified Weibull function, it is sufficient to change the sign of the voltages within the exponent of Equation (C.2) to take into

account that the function shall be truncated for high-voltage values. For example, for phase-to-earth overvoltages:

$$F(U_e) = 1 - e^{-\left(\frac{U_{et} - U_e}{\beta}\right)^\gamma} \quad (B.14)$$

With the assumptions made in Annex C that the truncation value ($U_{et} = U_{e50} + 3 S_e$) and the 2 % value is equal to ($U_{e2} = U_{e50} + 2,05 S_e$), the exponent of Equation (B.6) becomes $\gamma = 3,07$, which can be approximated to $\gamma = 3$. The scale parameter with these assumptions becomes $\beta = 3,5 S_e$ to be used in Equation (B.14).

Alternatively, the frequency distribution of overvoltage can be expressed in a form similar to Equation (B.5) for the disruptive discharge:

$$F(U_e) = 1 - 0,5 \left[1 - \frac{1}{3} \left(\frac{U_e - U_{e50}}{S_e} \right) \right]^3 \quad (B.15)$$

With these factors, both equations (B.14) and (B.15) yield a probability of 2,2 % at the 2 % value, which is considered as sufficiently accurate.

If the case-peak method and the phase-peak method (for definition see 4.3.3.2.1) are compared, and the overvoltages at the three phases are statistically independent, then the probability distribution is:

$$F_{c-p} = 1 - (1 - F_{p-p})^3 = 1 - e^{-3 \left(\frac{U_{et} - U}{B} \right)^\gamma} \quad (B.16)$$

where c – p and p – p refer to the case-peak and phase-peak method, respectively, and with the parameters $\gamma = 3$ et $\beta = 3,5 S_e$.

This means that the parameters β for the two methods follow the relation:

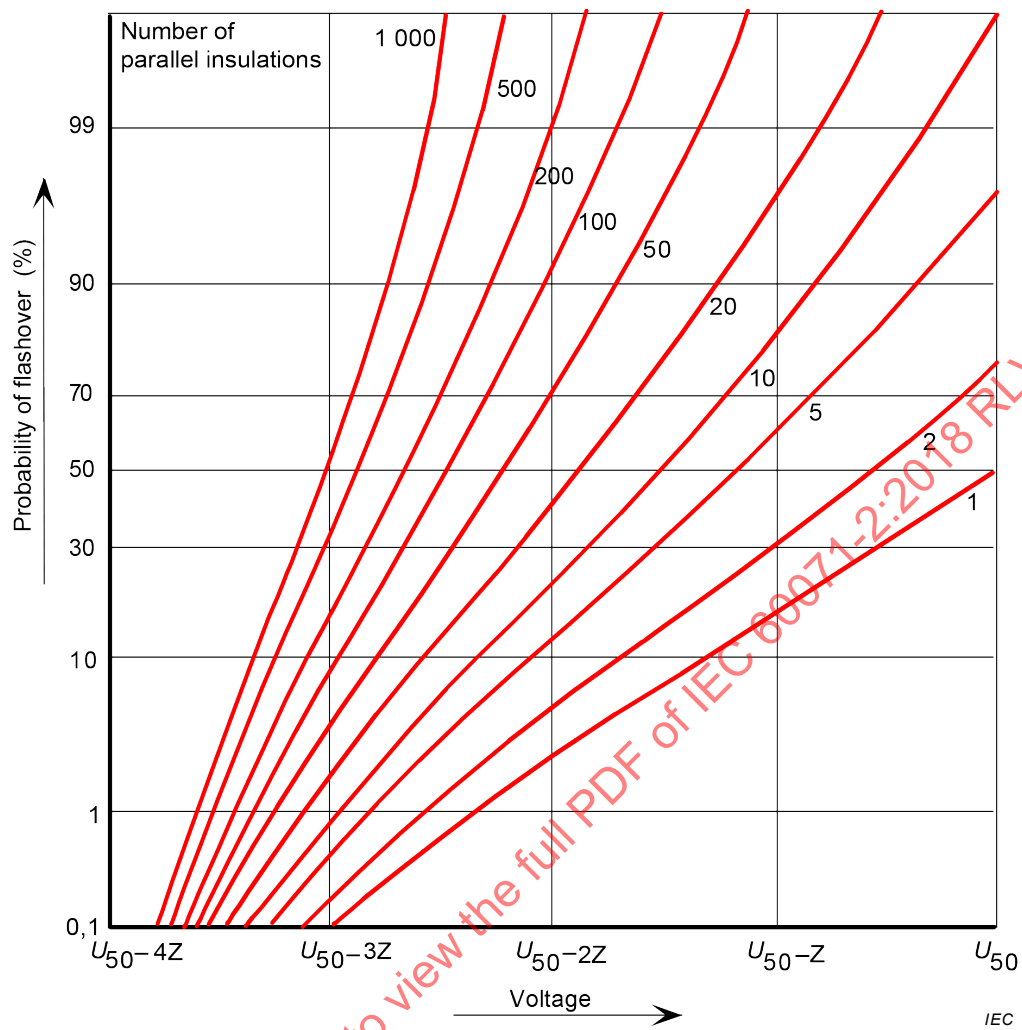
$$\beta_{c-p} = 3^{-1/3} \beta_{p-p} = 0,69 \beta_{p-p} \quad (B.17)$$

and consequently, the relation between the deviations is:

$$S_{c-p} = 0,69 S_{p-p} \quad (B.18)$$

and, as the truncation value should be the same for both methods:

$$u_{e2c-p} = 1,08 u_{e2p-p} - 0,08 \quad (B.19)$$



U_{50} : 50 % flashover voltage of a single gap

Z: conventional deviation of a single gap

Figure B.1 – Conversion chart for the reduction of the withstand voltage due to placing insulation configurations in parallel

Annex C (informative)

Determination of the representative slow-front overvoltage due to line energization and re-energization

C.1 General remarks

The determination of the overvoltages due to energization and re-energization, the insulation response under these overvoltages and the consequences for the insulation co-ordination procedure for a phase-phase-earth insulation configuration have been investigated by CIGRE study committee 33 and been published [1], [6], [7], [8]. Although the principles reported there are still valid, their application has turned out to be complicated. Annex C, therefore, summarizes the results and introduces the simplifications which are considered necessary for the use of this document. ~~For an explanation of the results, reference is made to the relevant ELECTRA publication.~~

The principles are derived for the phase-peak method (defined in 4.3.3.2.1) in the evaluation of the overvoltages. The results and, in particular, the obtained simplifications, however, are also valid when the case-peak method is used

C.2 Probability distribution of the representative amplitude of the prospective overvoltage phase-to-earth

From the 2 % overvoltage values phase-to-earth (U_{e2} values from Figure 1), the representative probability distribution can be estimated:

Phase-peak method:

- 2 % value: U_{e2} ;
- deviation: $\sigma_e = 0,25 (U_{e2} - 1)$; (C.1)

- truncation value: $U_{et} = 1,25 U_{e2} - 0,25$; (C.2)

- it can be noted that if ($U_{e2} = U_{e50} + 2\sigma_e$), then ($U_{et} = U_{e50} + 3\sigma_e$).

Case-peak method:

- 2 % value: U_{e2} ;
- deviation: $\sigma_e = 0,17 (U_{e2} - 1)$; (C.3)

- truncation value: $U_{et} = 1,13 U_{e2} - 0,13$. (C.4)

As shown in Annex B, for the same switching operation, the truncation values obtained for the two methods are the same. Consequently, the 2 % values and the deviations ~~must~~ shall differ.

Correct values for both methods can be obtained from studies. However, in view of the dispersion of the results, Figure 1 can be used for both methods.

C.3 Probability distribution of the representative amplitude of the prospective overvoltage phase-to-phase

In general, the insulation characteristic ~~must~~ shall be taken into account in the evaluation of a three-phase overvoltage in order to determine the most critical instant from the overvoltage

shape (see Clause C.4). This most critical instant is sufficiently defined by one of the three following instants.

1) Instant of the positive peak of the phase-to-earth overvoltage

At this instant, the overvoltages are described by

- the positive peak at each terminal,
- the highest negative component from the two neighbouring terminals, given the highest stress between phases, and
- the lowest negative component from the two neighbouring terminals.

2) Instant of the negative peak of the phase-to-earth overvoltage

This instant is equivalent to the instant of the positive peak with reversed polarities.

3) Instant of the peak of the phase-to-phase overvoltage

At this instant the overvoltages are described by

- the phase-to-phase overvoltage peak between each couple of terminals,
- the positive and negative component of this overvoltage, and
- the component at the third terminal to earth.

In all instants, the third component is small. The overvoltage, therefore, can be described by two components on two phases with the third phase earthed. The probability distribution of the overvoltages is bivariate, because both components vary. In a bivariate probability distribution the usually used single voltage value is replaced by combinations of overvoltages, which all have the same probability density. These combinations form curves, which are ellipses, when Gaussian distributions are used to approximate the probability distribution of the components, with the special case of circles if the dispersions of the two distributions are equal. If Weibull distributions are used, the curves are similar to ellipses or circles.

Besides being the curve of constant probability density, a further characteristic of the curve is that each tangent to them defines a composite phase-to-phase overvoltage of constant probability. Figure C.1 shows an example from [7] corresponding to a tangent probability of 2 % for the three instants mentioned above. According to the evaluation of overvoltages only one of the three curves corresponds to the most critical instant for the insulation and only this curve is representative for the overvoltages.

In order to simplify and to take into account instants between the three selected ones, it is proposed in [7] to represent the three curves by a circle given in Figure C.2. This circle is fully defined by the positive and the equal negative peak of the phase-to-earth overvoltages and the peak of the phase-to-phase overvoltage. The circle has its centre at:

$$U_c^+ = U_c^- = \frac{U_p - \sqrt{2}U_e}{2 - \sqrt{2}} \quad (C.5)$$

and a radius:

$$R_u = \frac{2U_e - U_p}{2 - \sqrt{2}} \quad (C.6)$$

where the phase-to-earth overvoltage U_e and the phase-to-phase overvoltage U_p correspond to the same considered probability.

The phase-to-phase overvoltage probability distribution can be estimated as (refer to Figure 1 and Figure 2):

Phase-peak method:

- 2 % value: $U_{p2};$
- deviation: $\sigma_p = 0,25 (U_{p2} - 1,73);$ (C.7)
- truncation value: $U_{pt} = 1,25 U_{p2} - 0,43.$ (C.8)

Case-peak method:

- 2 % value: $U_{p2};$
- deviation: $\sigma_p = 0,17 (U_{p2} - 1,73);$ (C.9)
- truncation value: $U_{pt} = 1,14 U_{p2} - 0,24.$ (C.10)

C.4 Insulation characteristic

In the evaluation of three-phase overvoltages, the basic insulation characteristics have to be taken into account in order to determine the instant of the overvoltage transient which is most critical for the insulation (see 5.1.2). Figure C.3 shows two-phase terminals and the earth terminal of a complete insulation configuration in which the third phase is disregarded for simplification reasons. For the description of the dielectric strength of such a configuration two methods have been used.

- The positive component belonging to a given discharge probability is reported dependent on the negative component. With this description, an insulation characteristic is obtained as shown in Figure C.4 a) for the 50 % discharge probability.
- The total discharge voltage equal to the sum of the two components corresponding to a given discharge probability is reported dependent on a ratio α :

$$\alpha = U^- / (U^+ + U^-) = 1 / [1 + (U^+ / U^-)] \quad (C.11)$$

where

- U^+ is the positive component;
- U^- is the negative component.

The example of Figure C.4 a) then results in the dependency shown in Figure C.4 b).

The insulation characteristic is divided into three ranges (as shown in Figure C.4). Range "a" is the range of discharges from the positive terminal to earth. The negative component has little or no influence on the discharge probability. In range "b" the discharges occur between the terminals and the discharge probability depends on both components (α shall to be taken into account). Range "c" corresponds to range "a" for the discharges from the negative terminal to earth.

The discharge voltages in ranges "a" and "c" can be determined with the opposite terminal earthed, i.e. with a voltage component equal to zero. In range "b", however, the ratio of the components (or the ratio α) influences the result. This part of the insulation characteristic, which is responsible for the phase-to-phase flashover depends on the electrode configuration and the physical discharge process. Two different kinds of electrode configurations are of interest.

- Electrode configurations in which the discharges phase-to-earth and the discharges phase-to-phase occur at different parts of the configuration, for example when the radius of the electrodes is large compared to their clearance. The discharge between phases is exclusively determined by the total voltage between phases. The insulation characteristic

in range b decreases at 45° in Figure C.4 a) or is constant in Figure C.4 b). Such configurations exist in three-phase power transformers or in GIS.

- Electrode configurations in which the discharges phase-to-earth and the discharges phase-to-phase occur at the same part of the configuration. For these the insulation characteristic depends on the discharge process.

According to the discharge process, three groups can be distinguished.

a) Configurations with homogeneous or quasi-homogeneous electric field

The discharge voltage is equal to the corona inception voltage and the insulation characteristic can be obtained by field calculations. Such insulation configurations exist in three-phase enclosed GIS.

In spite of this, as the electrode dimensions are large compared to the clearances, the dielectric field between the phases is little influenced by the earth terminal and, therefore, determined by the total voltage. The insulation characteristic in range "b" is decreasing with about 45° in Figure C.4 a) and constant in Figure C.4 b).

b) Short air clearances with inhomogeneous electric field

The discharge voltage is substantially higher than the corona inception voltage. This discharge process corresponds to a streamer discharge, as a leader does not develop owing to the short air clearance. The discharge probability is determined by the sum of the two components, which means that the insulation characteristic in range "b" decreases with 45° in Figure C.4 a) or is constant in Figure C.4 b). The air clearances in range I of IEC 60071-1 can be associated with this group;

c) Long air clearances

In addition to the conditions mentioned for short air clearances, leader formation from the positive terminal takes place. This means that the dielectric field around the positive terminal is decisive and the positive component has a higher influence on the discharge than the negative. The insulation characteristic decreases by less than 45° [6]. Air clearances in range II of IEC 60071-1 can be associated with this group.

In summary, the insulation characteristic of a two-phase insulation configuration is described by

- the positive switching impulse withstand voltage phase-to-earth (range "a" in Figure C.4),
- the negative switching impulse withstand voltage phase-to-earth (range "c" in Figure C.4), and
- the insulation characteristic between phases (range "b" in Figure C.4) which can be described, for the representation of Figure C.4 a), by:

$$U^+ = U_0^+ - BU^- \quad (\text{C.12})$$

or, for the representation in Figure C.4 b), by:

$$U^+ + U^- = \frac{U_0^+}{1 - \alpha(1 - B)} \quad (\text{C.13})$$

The value of the constant B is:

In range I: all insulation types: $B = 1$;

In range II:

- internal insulation: $B = 1$;
- external insulation: $B < 1$.

Figure C.5 gives the angle ϕ ($B = \tan \phi$) dependent on the ratio of D/H_t .

IEC 60071-1 defines the representative overvoltage between phases as consisting of two components with equal amplitude and opposite polarity. This overvoltage is situated on the line $U^+ = U^-$ or $\alpha = 0,5$. The most critical stress on the insulation configuration depends on the insulation characteristic and, in particular, on the inclination B mentioned in Equation (C.12). The most critical stress is given by the voltage component at which the characteristic is tangent to the circle proposed as a simplification to describe the overvoltages. Figure C.2 shows that the most critical stress does not correspond with the representative overvoltage, if the inclination B is smaller than 1. In this case, the representative overvoltage ~~must~~ shall be increased in order to test at $\alpha = 0,5$. This results in a new value for the phase-to-phase representative overvoltage U_{p2re} given by:

$$U_{p2re} = 2 (F_1 U_{p2} + F_2 U_{e2}) \quad (C.14)$$

The deviation value S_{pre} and the truncation value U_{ptre} are respectively given by Equations (C.15) and (C.16):

$$S_{pre} = 2 (F_1 S_p + F_2 S_e) \quad (C.15)$$

$$U_{ptre} = 2 (F_1 U_{pt} + F_2 U_{et}) \quad (C.16)$$

where:

$$F_1 = \frac{1}{2 - \sqrt{2}} \left[1 - \frac{\sqrt{1+B^2}}{1+B} \right]$$

$$F_2 = \frac{1}{2 - \sqrt{2}} \left[2 \frac{\sqrt{1+B^2}}{1+B} - \sqrt{2} \right]$$

If $B = 1$, i.e. for internal insulation and external insulations in range I, the representative phase-to-phase overvoltage is equal to the probability distribution of the phase-to-phase overvoltages. If $B < 1$, the representative phase-to-phase overvoltage varies between the phase-to-phase overvoltages for $B = 1$ and twice the phase-to-earth overvoltages for $B = 0$.

C.5 Numerical example

A phase-phase-earth insulation configuration typical for a system with $U_m = 765$ kV (1 p.u. = 625 kV) has an insulation strength between phases described by a constant $B = 0,6$. This results in the constants $F_1 = 0,463$ and $F_2 = 0,074$.

With the following phase-to-earth overvoltage parameters (phase-peak):

- $U_{e2} = (1,98 \text{ p.u.}) = 1\,238 \text{ kV};$
- $S_e = (0,25 \text{ p.u.}) = 156 \text{ kV};$
- $U_{et} = (2,225 \text{ p.u.}) = 1\,391 \text{ kV};$

the following phase-to-phase overvoltage parameters are derived:

- $U_{p2} = (3,366 \text{ p.u.}) = 2\,104 \text{ kV};$
- $S_p = (0,42 \text{ p.u.}) = 263 \text{ kV};$
- $U_{pt} = (3,778 \text{ p.u.}) = 2\,361 \text{ kV}.$

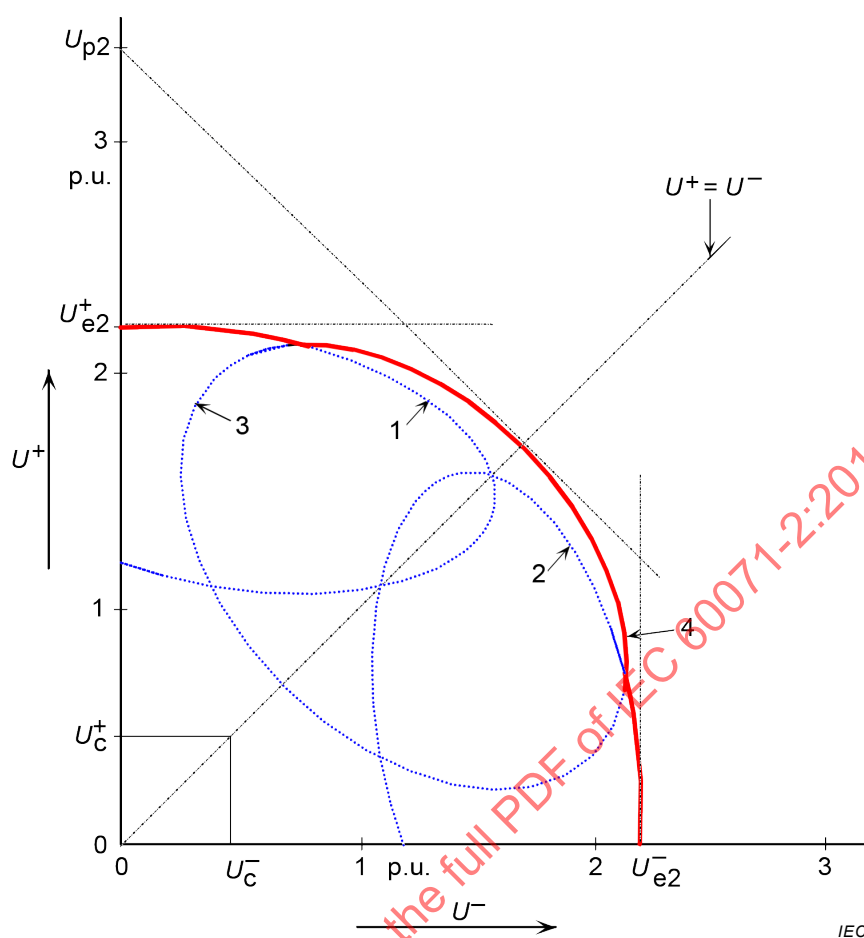
The representative overvoltage amplitude phase-to-earth is equal to the phase-to-earth overvoltage. The representative overvoltage amplitude phase-to-phase is derived from Equations (C.14) to (C.16) with the above-given constants:

- $U_{p2re} = (3,41 \text{ p.u.}) = 2\,131 \text{ kV};$
- $S_{pre} = (0,44 \text{ p.u.}) = 266 \text{ kV};$
- $U_{ptre} = (3,828 \text{ p.u.}) = 2\,392 \text{ kV}.$

The required withstand voltages for $K_{cs} = 1,15$ are then:

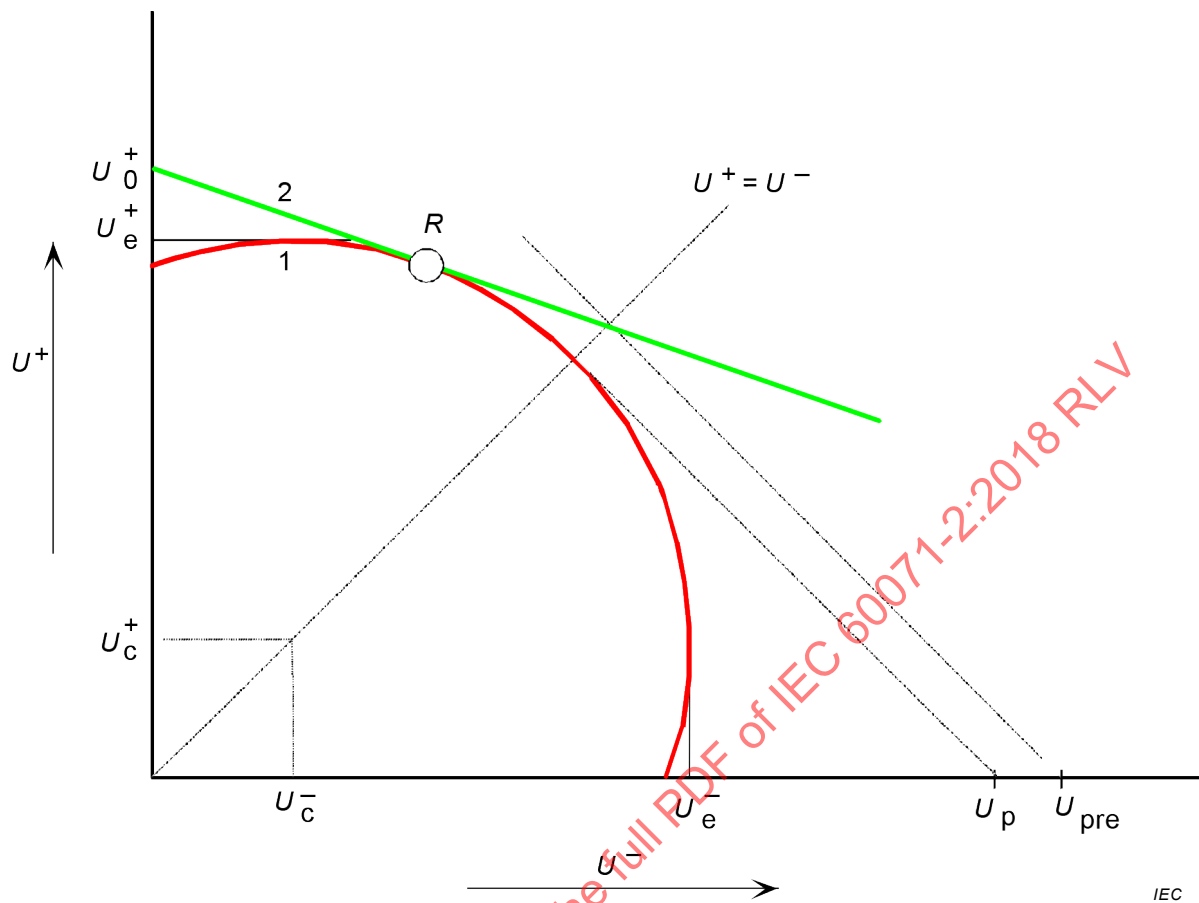
- phase-to-earth: $U_w = U_{e2} \times 1,15 = 1\,424 \text{ kV};$
- phase-to-phase (nominal): $U_w = U_{p2} \times 1,15 = 2\,420 \text{ kV};$
- phase-to-phase (derived): $U_w = U_{p2re} \times 1,15 = 2\,451 \text{ kV}.$

In IEC 60071-1:2006 and IEC 60071-1:2006/AMD1:2010, Table 3, provides standard withstand voltages of 1 425 kV phase-to-earth and 2 422 (1 425 × 1,7) kV phase-to-phase. While these values would adequately cover the nominal required withstand voltages, they would not cover the derived phase-to-phase required withstand voltage U_{p2re} of 2 451 kV. Therefore, the next highest standard withstand voltages of 1 550 kV phase-to-earth and 2 480 (1 550 × 1,6) kV phase-to-phase ~~must~~ shall be selected, and the insulation ~~is to be~~ shall tested with positive and negative switching impulses of equal magnitude.

**Key**

- 1 overvoltage at the instant of the positive phase-to-earth overvoltage peak
- 2 overvoltage at the instant of the negative phase-to-earth overvoltage peak
- 3 overvoltage at the instant of the phase-to-phase overvoltage peak
- 4 proposed simplification covering all instants

Figure C.1 – Example for bivariate phase-to-phase overvoltage curves with constant probability density and tangents giving the relevant 2 % values



Key

- 1 simplified overvoltage circle as given by the values for the phase-to-earth overvoltage $U_e^+ = U_e^-$ and for the phase-to-phase for the considered probability
- 2 50 % flashover characteristic of the insulation
- R most critical overvoltage stress

Figure C.2 – Principle of the determination of the representative phase-to-phase overvoltage U_{pre}

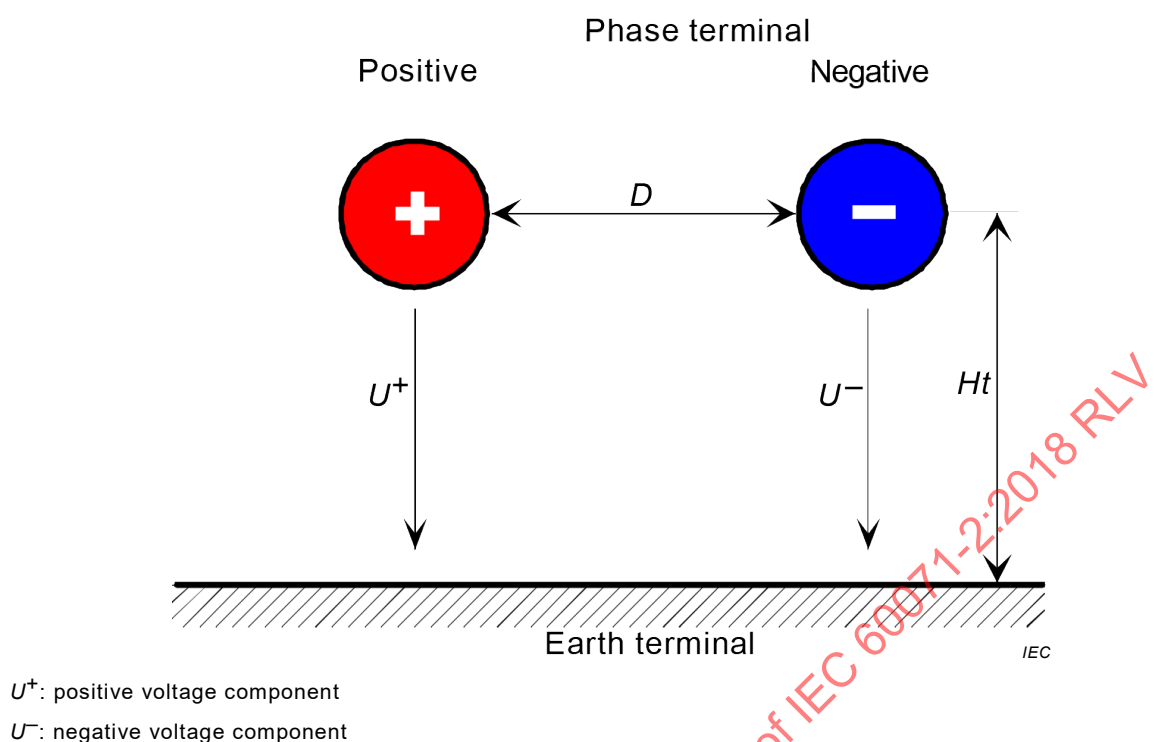
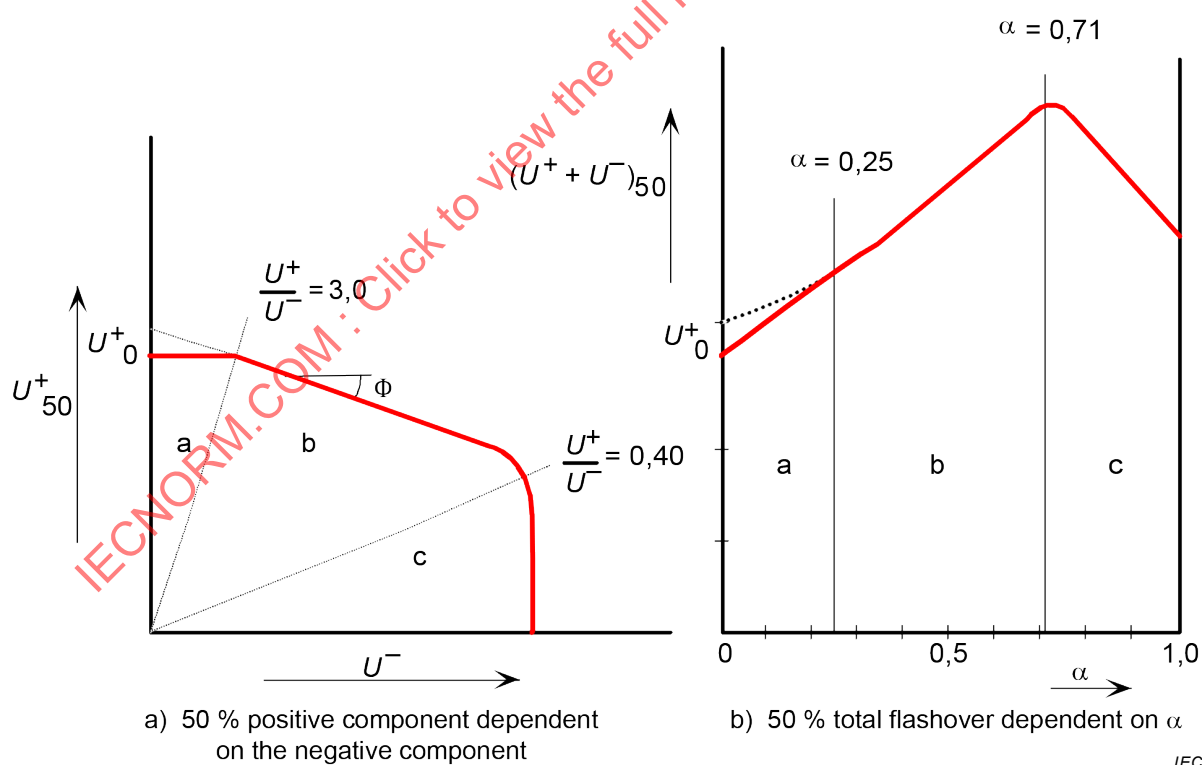


Figure C.3 – Schematic phase-phase-earth insulation configuration



Key

range a: flashover from positive phase terminal to earth

range b: flashover between phase terminals

range c: flashover from negative phase terminal to earth

Figure C.4 – Description of the 50 % switching impulse flashover voltage of a phase-phase-earth insulation

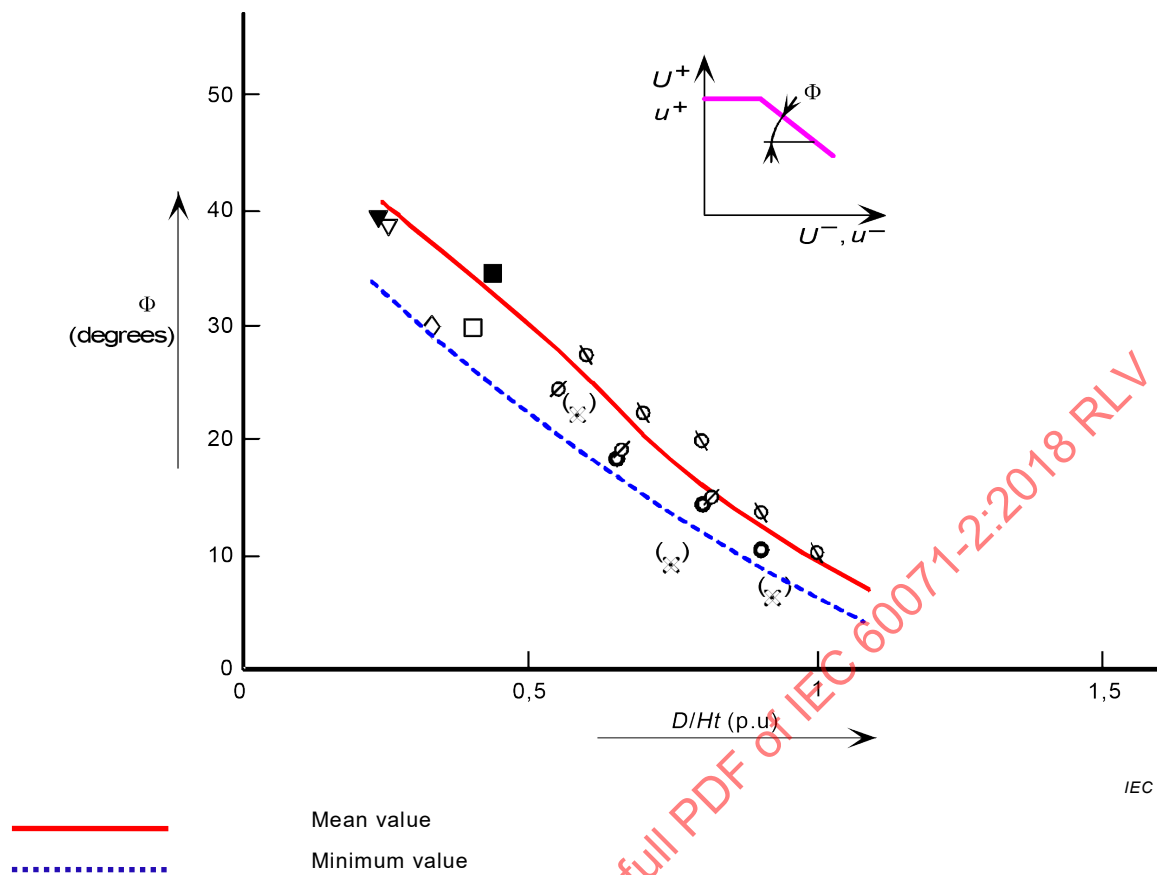


Figure C.5 – Inclination angle of the phase-to-phase insulation characteristic in range "b" dependent on the ratio of the phase-phase clearance D to the height H_t above earth

Annex D (informative)

Transferred overvoltages in transformers

D.1 General remarks

In some cases, the voltages and surges transferred through the transformer can be decisive when the overvoltage protection of the transformer is designed. A transformer connected to a high rating generator or motor with common circuit-breaker and protection is an example of such a case. Special cases are transformers whose one winding is permanently or occasionally (due to e.g. circuit-breaker operations) disconnected from the network.

The surges can be transferred through the transformer from one winding system to another. In certain cases the surge can be transferred also between the phases, which can increase the stress in an adjacent phase which is already being subjected to a direct surge. Problems are experienced with (for example) vacuum circuit-breaker switching a motor and in GIS with surges generated by disconnector operations.

The voltages transferred through the transformers are mainly fast-front or slow-front overvoltages. The transfer mode depends upon associated rates of change. In principle, the following transfer modes can come into question:

- electrostatic or capacitive transfer;
- oscillatory transfer through natural oscillations of primary and/or secondary circuits of the transformer (the earth capacitances and the self-inductances of the windings form the oscillation circuits);
- normal electromagnetic transfer which depends primarily on the turns ratio, leakage inductance and loading impedance of the transformer.

The oscillatory component is damped and superimposed on the electromagnetic transferred component. The oscillatory component is usually small and of secondary importance, if it is not magnified by resonance effects. Therefore, this transferring mechanism is not considered further here.

The transferred surge has usually both the capacitively and inductively transferred components which superimpose to the power-frequency voltage. The eventual voltage rise due to an earth fault have to be included in the power-frequency voltage. The capacitively transferred component lays typically in megahertz range and is seen first in the transferred surge. The inductively transferred component comes after the capacitive one. Its shape and amplitude change in time because the distribution of the voltage along the primary winding is time-dependent.

A special case of surge transference is the capacitively transferred neutral potential rise during earth faults and other unsymmetrical events in transformers where the turns ratio between the high-and low-voltage windings is exceptionally high (e.g. generator transformers or a transformer with a tertiary winding) and where the capacitance of the low-voltage side is low.

The magnitude of the transferred voltages depends on the construction of the transformer (especially the construction of the windings – disc, interleaved winding, etc. – and their order around the core legs as well as the leakage inductances), damping of the winding, capacitances of the transformer, turns (transformation) vector group, connection to the network, etc. In addition, the shape of the incoming surge has an important role.

Some of the constructional factors influencing the magnitude of transferred surges are difficult to calculate. Therefore, the most practical method to get a quantitative estimate for the

magnitude of these surges is to measure them, for example with recurrent surge measurement.

The following explains only the most important features of the overvoltage transference through transformers. Equations presented can be used only as a rough estimation of the surge magnitudes. "Primary" and "secondary" terms are used independently of the number of windings and in the direction of normal power transmission so that the surges come in the primary winding and are transferred from there to the secondary winding.

D.2 Transferred temporary overvoltages

The unsymmetry in the primary phase-to-earth voltages can cause phase-to-earth overvoltages in the secondary side if the secondary winding is with an isolated neutral and has a remarkably low rated voltage in respect to the primary winding. The most common cause of voltage unsymmetry is the earth fault. The magnitude of the transferred temporary overvoltage depends on the primary voltage during the earth fault, capacitance ratio of the transformer and on the eventual additional capacitors connected to the secondary side.

The maximum phase-to-earth overvoltage can be estimated from:

$$U_{2e} = \frac{C_{12}}{C_{12} + C_2} U_{1e} + \frac{U_{2N}}{\sqrt{3}} \quad (\text{D.1})$$

where

- U_{2e} is the secondary overvoltage caused by the earth fault in the primary;
- U_{1e} is the voltage in the neutral point of the primary winding during the earth fault;
- $U_{2N} / \sqrt{3}$ is the rated phase-to earth voltage in the secondary side;
- C_{12} is the capacitance between primary and secondary windings;
- C_2 is the phase-to-earth capacitance of the secondary winding and equipments connected to it.

The required capacitance values are obtained from the routine test protocols of the transformer.

The voltages should rigorously be added vectorially; however, arithmetic addition as given yields conservative results.

Too high overvoltages can occur if the phase-to-earth capacitance of the secondary winding is too low. For example, the standard power-frequency withstand voltages can be exceeded in the case of 110 kV transformers if the rated secondary voltage is 10 kV or less.

Another case leading to excessive capacitively transferred overvoltages is when the secondary winding with an isolated neutral is totally disconnected from the network during an earth fault on the primary side.

The magnitude of these overvoltages can be reduced with the help of additional capacitances which are connected between phase and earth in all phases on the secondary side. Often a capacitor of 0,1 μF is enough.

D.3 Capacitively transferred surges

Capacitively transferred surges are usually critical only when they are transferred from the high-voltage side to the low-voltage side.

The capacitively transferred surge can originate from the potential rise of the primary winding caused by incoming fast-front or slow-front overvoltages. They transfer to the secondary through the winding capacitance as in the case of unbalanced primary voltages but an important difference is caused by the fact that in the case of rapid primary voltage variations only those parts of the windings which are near the terminals take part in the surge transference. Therefore, in a general case, the distributed nature of the capacitances should be recognized by noting that the surge capacitance of a transformer winding is calculated from the distributed series and earth capacitances (C_s and C_e respectively) by:

$$C_{1in} = \sqrt{C_s C_e} \quad (D.2)$$

The value of C_e can be measured but the value of C_s has to be estimated on the basis of the construction of the windings. Therefore, only the manufacturer can give the value of the capacitance C_s .

NOTE The validity of the above calculation of C_{1in} is based on the assumption of a high initial distribution constant of the windings [9]. When high-voltage windings with much higher series capacitances (low distribution constant) are used, this approximation will be less accurate.

The surge capacitances form a capacitive divider (refer to Figure D.1) which can be used in the rough estimation of the magnitude of the capacitively transferred surges. When the effect of the power-frequency voltage is encountered, the resulting initial voltage spike on the open secondary side is given by:

$$U_{T2} = g d_r h U_{T1} \quad (D.3)$$

where

h is the power-frequency voltage factor.

And the dividing ratio of the divider (d_r) is:

$$g d_r = C_{1in} / (C_{1in} + C_{3in})$$

The dividing ratio $g d_r$ can range from 0,0 to at least 0,4. It can be estimated from the data available from the manufacturer of the transformer or measured by low-voltage impulse test. Delta connection of the low-voltage winding with a star connected high-voltage winding results in a further reduction in the value of parameter $g d_r$.

The value of the factor h depends on the class of the voltage stress and on the type of transformer windings connections:

- for slow-front overvoltages, it is correct to assume $h = 1$ (no matter what the windings connections are);
- for fast-front overvoltages, $h > 1$ shall be used;
 - for star/delta or delta/star connections, $h = 1,15$ (rough estimate);
 - for star/star or delta/delta connections, $h = 1,07$ (rough estimate).

In the case of fast-front overvoltages, the value of U_{T1} can be the ~~protective~~ protection level of the arresters connected on the primary side. In the case of slow-front overvoltages, the value of U_{T1} can be the peak value of the phase-to-earth voltage stress (assuming the arresters will not react).

The magnitudes of capacitively transferred surges are damped due to the losses in the windings. This effect, as well as the load connected to the transformer, effectively reduces the magnitude of the capacitive spikes. Usually, these overvoltage spikes are critical only in the case of transformers with large step-down ratios and when only a small capacitance is connected to the secondary. Critical situations can arise if the incoming surge has a great

steepness or is chopped. Arresters connected to the secondary effectively limit the magnitudes of the capacitively transferred voltages. The protection can be further improved with additional capacitors, especially in the case of equipment which do not tolerate voltages with fast rising fronts (e.g. generators and motors) or if the capacitive ratio of the transformer is unfavourable, because otherwise the surge arresters on the secondary side might operate too frequently.

D.4 Inductively transferred surges

Inductive transfer of surges is usually the most important transfer mode and takes place already on moderate rates of voltage changes. Usually, an inductive surge transfer is associated with the transient behaviour of the surge voltages and currents in the primary winding when the initial distributions change in an oscillatory fashion towards the final voltage and current distributions. This means that the transferred surge is composed of several components which oscillate with different frequencies.

In this transfer mode, the transformer operates essentially in its normal mode and conventional power-frequency methods apply in the analysis of the magnitudes and shapes of the surges. Consequently, the derivation of equivalent circuits and equations for the voltage components is quite easy but, on the other hand, the determination of the values of the needed transformer parameters is complicated. Therefore, only simple approximative equations are often used for the determination of surge magnitudes. Consequently, direct measurements can give more reliable and accurate information on the magnitudes of the inductively transferred surges.

The magnitudes of the inductively transferred surges depend on

- the magnitude of the primary voltage (including the arrester operation),
- the duration of the incoming surge,
- the characteristics of the transformer (number of windings and turns ratio, short-circuit impedances, vector group),
- the surge impedances of the lines connected to the secondary, and
- the characteristics of the load.

The surge induced on the secondary side of a transformer may be estimated with the help of Equation (D.4):

$$U_{T2} = h q J w_{21} U_{T1} \quad (\text{D.4})$$

where

h is the factor defined under Equation (D.3);

q is the response factor of the secondary circuit to the transferred surge;

J is the factor dependent on the connection of the windings;

w_{21} is the ratio of transformer secondary to primary phase-to-phase voltage.

The response factor q basically determines the amplitude of the oscillation. The magnitude of q depends on the leakage inductance of the secondary winding, on the load connected to it as well as on the rate of rise of the incoming surge. Also, the order of the windings around the core legs influences (even reducing the value of q like the load in other windings) and makes the predetermination of q difficult.

In the following, some values are given to illustrate the situation in the case of transformers with disc windings. Manufacturers should be contacted in the case of transformers with other winding types.

Some typical values for q can be defined as following:

- if the transformer is connected to an overhead line without appreciable load, the value of q varies for fast-front surges from 0,3 to 1,3 when the rated voltage of the secondary winding varies from 245 kV to 36 kV;
- for switching surges on a similar system without appreciable load, the usual value is $q < 1,8$;
- if the transformer is connected to a cable, the usual value is $q < 1,0$, both for the fast-front and the slow-front surges.

Clearly higher values of q can result in the case of a three-winding transformer. Even values exceeding 1,7 to 2,0 have been recorded for such transformers.

Values of J for a surge on one phase only and for equal surges of opposite polarity on two phases are shown in Figure D.2 for eight different three-phase connections of the transformer. The figure is based on the assumption that the system voltage ratio is unity.

Inductively transferred surges from the high-voltage winding to the low-voltage one can be critical if

- the secondary voltage winding is not connected to the network,
- the secondary winding has a low rated voltage but a high rated power (e.g. generator transformers), and
- the winding is the tertiary of a three-winding transformer.

Inductively transferred surges can be dangerous for the phase-to-phase insulation of the delta-connected secondary windings, although all terminals of the transformer are equipped with surge arresters connected between phases and earth. Therefore, arresters connected between phases can also be necessary. High overvoltages can occur when the surge is transferred from the low-voltage winding to the high-voltage one, especially if resonance type voltage rises are caused.

The protection between phases and earth as well as between phases should be studied case by case. Necessary information should be required from the transformer manufacturer. Surge arresters connected between all phases and earth and also between the phases (when needed, e.g. star/delta connected transformers) usually give an adequate protection. Adding of extra capacitors does not usually reduce the inductively transferred overvoltages.

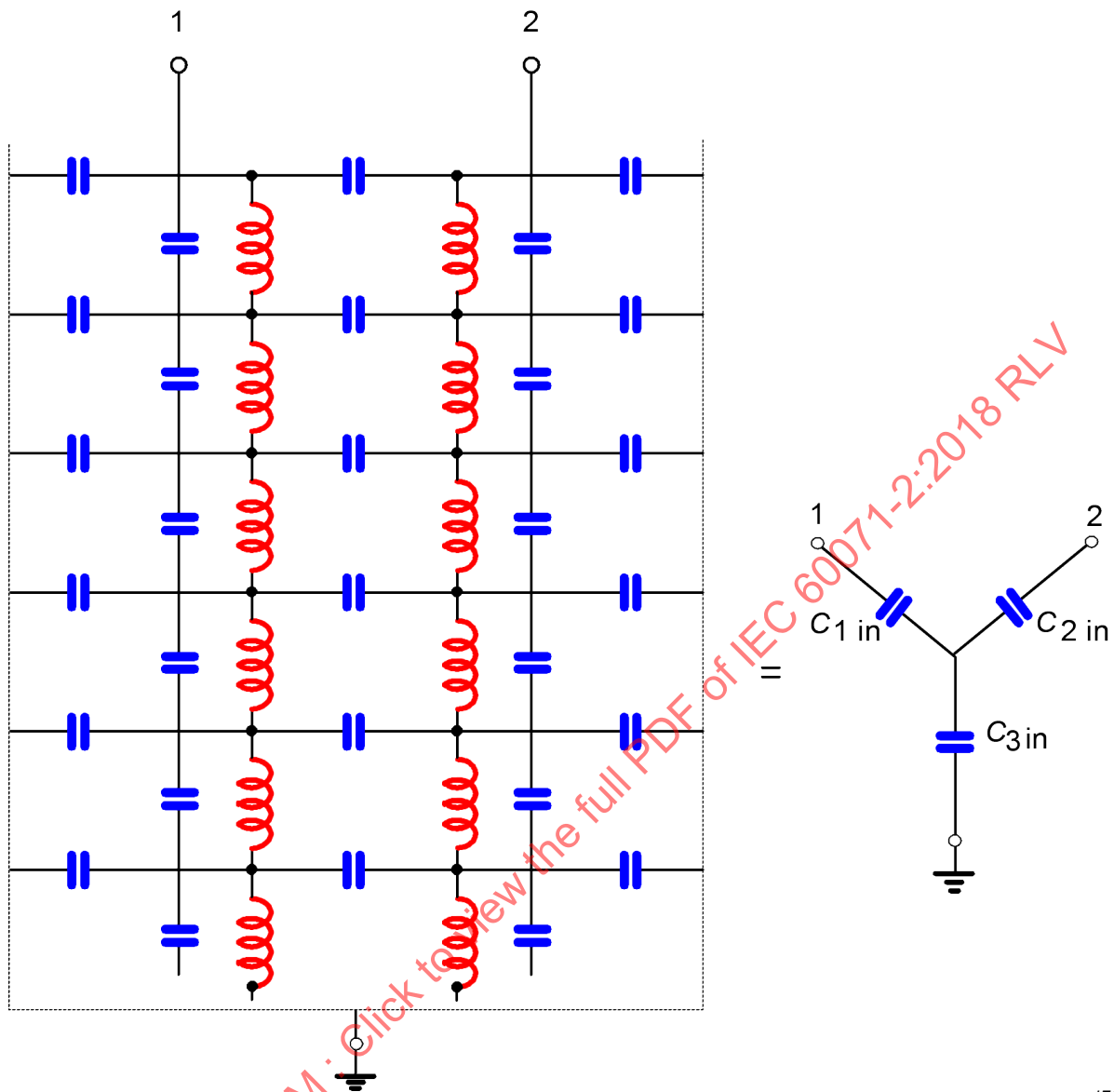


Figure D.1 – Distributed capacitances of the windings of a transformer and the equivalent circuit describing the windings

Case	Transformer connexion			Surge on one phase only $U_A = 1, U_B = U_C = 0$		Surges of opposite polarity on 2 phases $U_A = 1, U_B = -1, U_C = 0$	
	Higher-voltage winding	Lower-voltage winding	Tertiary	Higher-voltage winding	Lower-voltage winding	Higher-voltage winding	Lower-voltage winding
1	Y(e)	y(e)	(-, y)				
2	Y(e)	y(i)	(-, y)				
3	Y(e)	d	(-, y, d)				
4	Y(i)	y(e, i)	(-, y, d)				
5	Y(i)	d	(-, y, d)				
6	Y(i)	z(e, i)	(-, y, d)				
7	D	y(e, i)	(-, y, d)				
8	D	d	(-, y, d)				

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Key

Y,y star-connected windings

D,d delta-connected windings

z Z-connected windings

 U_A, U_B, U_C overvoltage amplitudes at the high-voltage terminals A, B, C**Figure D.2 – Values of factor J describing the effect of the winding connections on the inductive surge transference**

Annex E (informative)

Lightning overvoltages

E.1 General remarks

The overvoltages in substations depend on amplitude and shape of the overvoltage impinging on the substation from the overhead line conductor as well as on the travelling wave behaviour of the substation itself. The frequency with which such impinging overvoltages occur is given by the lightning performance of the overhead line connected to the substation. For substations or parts of a substation to which no surge arrester is connected, the most important parameter is the amplitude of the impinging overvoltage; for substations protected by surge arresters, it is its steepness and the separation distance between surge arrester and the equipment under consideration.

The steepness of an impinging overvoltage surge is reduced mainly by corona damping effects on the overhead line [9]. This means that the steepness of the impinging surge can be only sufficient to cause a certain overvoltage amplitude if the lightning stroke hits the overhead line within a certain distance from the substation (see Clause E.2 for detailed explanations). For further strokes the steepness will be too low, irrespective of the amplitude of the surge.

The knowledge of this limit distance is of primary importance. In detailed digital overvoltage calculations using transient programs the overhead line should be carefully simulated over this distance. Recommendations for the necessary parameters to be included in such calculations are given in [9]. Furthermore, all simplifications which take into account the frequency of occurrence of the overvoltage amplitudes are based on similar considerations.

E.2 Determination of the limit distance (X_p)

E.2.1 Protection with arresters in the substation

E.2.1 contains more detailed information on surge arrester protection discussed in 4.3.4.5.

When more than one overhead line is connected to the substation, the original steepness (S) of the impinging surge can be divided by the number of lines (n). However, it is emphasized that the number of lines should correspond to the minimum number which reasonably remain in service taking into account possible outages during lightning storms.

Allowing for the fact that the steepness of the impinging surge reduces inversely with the travel distance on the overhead line, the steepness S of the impinging surge to be used in Equation (1) is approximately equal to:

$$S = 1 / (n K_{co} X) \quad (\text{E.1})$$

where

n is the number of overhead lines connected to the substation; if multi-circuit towers are involved and double-system back flashovers have to be taken into account, it is recommended to divide the number by two;

K_{co} is the corona damping constant according to Table E.1 ($\mu\text{s}/(\text{kV}\cdot\text{m})$);

X is the distance between struck point of lightning and substation (m).

NOTE Equation (E.1) has been derived with the assumption that the distances between the protected object and the connection points of the overhead lines result in travel times of less than half the front time of the impinging

surge. The lead between object and connection point, therefore, can be neglected in an approximate estimation. This approach is justified for determination of the limit distance in Equation (E.2) because here low steepnesses of the impinging surge are relevant. For the calculation of actual overvoltages resulting from an assumed impinging surge, this simplification may be not conservative.

The use of this steepness value in Equation (1) does not yield sufficiently accurate results for the calculation of overvoltage at the equipment. However, it is sufficient (and conservative) to estimate the limit distance X_p by:

$$X_p = -2T_s / [nK_{co} (U - U_{pl})] \quad (E.2)$$

where

U is the lowest considered overvoltage amplitude;

T_s is the longest travel time between any point in the substation to be protected and the closest arrester (μs);

U_{pl} is the lightning impulse ~~protective~~ protection level of the arrester.

For distances larger than X_p the steepness will be reduced such that the overvoltage at the equipment will in general be smaller than the assumed value U .

Table E.1 – Corona damping constant K_{co}

Conductor configuration	K_{co} $\mu s/(kV \cdot m)$
Single conductor	$1,5 \times 10^{-6}$
Double conductor bundle	$1,0 \times 10^{-6}$
Three or four conductor bundle	$0,6 \times 10^{-6}$
Six or eight conductor bundle	$0,4 \times 10^{-6}$

E.2.2 Self-protection of substation

Self-protection of the substation exists when the lightning overvoltage impinging the substation from the overhead line is decreased below the co-ordination withstand voltage by the reflections within the substation itself without any action of arresters. The fundamental requirement is that the number of lines connected to the substation is sufficiently large.

The necessary number of lines can be estimated by:

$$n \geq 4 \left[(U_{50}^- / U) \right] - 1 \quad (E.3)$$

where

n is the number of overhead lines;

U_{50}^- is the 50 % lightning impulse flashover voltage of the line insulation, negative polarity;

U is the overvoltage amplitude considered.

In addition, the impinging surge ~~must~~ shall not cause too high overvoltages before the reflections from the additional lines act to decrease them. This requirement is fulfilled if the steepness of the impinging surge is so small due to corona damping effects on the line that the substation can be considered as a lumped element. This can be considered as valid when the lightning struck-point is beyond the limit distance:

$$X_p \geq 4 (-T_s / K_{co} U) \quad (E.4)$$

Where

t_s is the travel time to the most distant point from the substation busbar (μs).

An appreciable self-protection effect may be present in the case of GIS or cable-connected substations for which the reflections at the line entrance already decrease the overvoltage below the permitted value. This can be assumed as valid if:

$$U > (6Z_s / (Z_s + Z_L))U_{50}^- \quad (\text{E.5})$$

where

Z_s is the surge impedance of the substation;

Z_L is the surge impedance of the overhead line.

However, the distance between the lightning struck-point to the substation entrance may not be so small that the reflection from the substation interferes with the lightning. For this reason the following minimum limit distance is applicable:

- for shielding failures: $X_p = 1$ span;
- for back flashovers: $X_p = 2$ towers.

E.3 Estimation of the representative lightning overvoltage amplitude

E.3.1 General

As the full travelling wave calculation including the simulation of the overhead line performance is extremely difficult, a simplified procedure has been proposed in [9]. This procedure consists in calculating a lightning current with the desired return rate and calculating the overvoltage by travelling wave calculations in the substation including a short-line section equivalent circuit.

E.3.2 Shielding penetration

The lightning current determining the impinging surge is determined from the shielding penetration rate within the limit distance and its probability to be exceeded:

$$F(I) = F(I_m) + (R_t / R_p) \quad (\text{E.6})$$

where

$F(I_m)$ is the lightning current probability corresponding to the maximum shielding current;

R_t is the considered return rate;

R_p is the shielding penetration rate withing the limit distance.

NOTE The shielding penetration rate can be obtained from the shielding failure flashover rate by:

$$R_p = \frac{R_{sf}}{F(I_{cr}) - F(I_m)} \quad (\text{E.7})$$

where

R_{sf} is the shielding failure flashover rate;

$F(I_{cr})$ is the probability corresponding to the current causing line insulation flashover at negative polarity.

The currents corresponding to the probabilities can be obtained from the lightning stroke current probability distribution in the shielding failure range ~~to be found in publications~~.

The amplitude of the impinging overvoltage surge is determined by Equation (E.8), and its steepness may be assumed to correspond to Equation (E.9):

$$U_l = Z_L I / 2 \quad (\text{E.8})$$

$$S = 1 / (K_{co} X_T) \quad (\text{E.9})$$

where

$$X_T = X_P / 4.$$

Its time to half-value should be 140 µs. If peak values higher than 1,6 times the negative flashover voltage of the line insulation are obtained, an impinging surge with this peak value should be used.

The impinging voltage surge is used to perform a travelling wave calculation within the substation and the representative overvoltages are obtained for this return rate for the various locations.

NOTE For some conductor bundles, the corona inception voltage can be very high, and the assumption of a linearly rising front ~~may~~ can lead to an underestimation of the overvoltages. For such cases, a more suitable representation of the impinging surge front is recommended.

E.3.3 Back flashovers

The lightning current determining the design impinging surge is determined from the number of flashes to the overhead line tower and earth-wires within the limit distance and its probability to be exceeded is:

$$F(N) = R_t / R_f \quad (\text{E.10})$$

where

R_t is the considered return rate;

R_f is the flashing rate within the limit distance.

The voltage created at the tower footing impedance by this current is determined by its time response and current dependence. When the extension of the tower footing is within a radius of 30 m, the time response can be neglected and the tower footing impedance is:

$$R_{hc} = \frac{R_{lc}}{\sqrt{1 + \frac{I}{I_g}}} \quad (\text{E.11})$$

where

R_{lc} is the low current resistance;

I_g is the limit current (kA).

The limit current I_g represents the soil ionization and is evaluated by:

$$I_g = \frac{1}{2\pi} \frac{E_0 \rho}{R_{lc}^2} \quad (\text{E.12})$$

where

ρ is the soil resistivity (Ω·m);

E_0 is the soil ionization gradient (recommended value: 400 kV/m).

The amplitude of the design impinging surge is then given as:

$$U_1 = \frac{(1 - c_f) R_{lc} I}{\sqrt{1 + \frac{I}{I_g}}} \quad (\text{E.13})$$

where

c_f is the coupling factor between earth-wire and phase conductor.

Typical values of c_f are:

- $c_f = 0,15$ for single earth-wire lines;
- $c_f = 0,35$ for double earth-wire lines.

If amplitudes higher than 1,6 times the negative flashover voltage of the line insulation are obtained, an impinging surge with this amplitude should be used.

The design impinging surge has an exponentially decreasing tail with a time constant τ given by Equation (E.14) and a linear increasing front whose steepness S is given by Equation (E.15):

$$\tau = \frac{Z_e L_{sp}}{R_{lc} c} \quad (\text{E.14})$$

where

Z_e is the earth-wire surge impedance (typical values are 500 Ω for single earth-wire lines and 270 Ω for double earth-wire lines);

L_{sp} is the span length (m);

c is the light velocity (recommended value: 300 m/ μ s).

$$S = 1 / (K_{co} X_T) \quad (\text{E.15})$$

where

K_{co} is given by Equation (E.1);

X_T is given by Equation (E.9).

For travelling wave calculations in the considered substation, a single conductor of the length X_T and surge impedance equal to that of the phase conductors is connected to the substation. A voltage source with the internal impedance of the low current footing resistance R_{lc} is placed at the end of the conductor. It produces a voltage with the shape parameters of the impinging surge.

If the impinging surge amplitude is higher than 1,6 times the positive 50 % lightning impulse flashover voltage, the simplifications are no longer applicable and more careful studies may be recommendable. The same applies for tower footing extensions larger than 30 m in radius.

Two dependencies of the representative overvoltage amplitude on the return rate are obtained, one for shielding failures and one for back flashovers. The overall dependency is obtained by adding the return rates for a constant amplitude.

NOTE For some conductor bundles the corona inception voltage can be very high and the assumption of a linearly rising front ~~may~~ can lead to an underestimation of the overvoltages.

For such cases, a more suitable representation of the impinging surge front ~~is recommended~~ **should be adopted**.

E.4 Simplified method

A further simplification to the procedures described in Clauses E.2 and E.3 is to apply the basic principles given there, but to adopt the following assumptions:

- all lightning events within a certain distance from the substation cause higher overvoltages at the protected equipment than an assumed value, and all events outside this distance lower values;
- the overvoltage at the equipment can be calculated according to Equation (1) and Equation (E.1).

As mentioned already, both assumptions are not strictly valid. Firstly, not all events within a certain distance are equally severe. They depend on the lightning current or on the amplitude of the impinging overvoltage surge. Secondly, the overvoltages may be higher than that calculated with Equations (1) and (E.1). However, current practice of equipment protection by surge arresters has shown that both inaccuracies sufficiently cancel each other.

As regards the distance X to be applied in Equation (E.1), it has been shown that back flashovers do not occur at a tower close to the substation owing to the substation earth. The minimum value of X is one overhead line span length. The representative steepness S_{rp} to be applied in Equation (1), therefore, is equal to:

$$S_{rp} = 1 / [K_{co}(L_{sp} + L_t)] \quad (E.16)$$

And the overhead line section in which the lightning flashover rate is equal to the desired return rate [8] is **equal to**:

$$L_t = (R_t / R_{km})$$

where

R_t is the adopted overvoltage return rate (1/year);

R_{km} is the overhead line outage rate per year for a design corresponding to the first kilometre in front of the station (see Equation (E.16)) [usual unit: 1/(100 km·year); recommended unit: 1/(m·year)].

NOTE The equation is derived from the observation that back-flashovers do not occur at the tower close to the substation owing to the good substation earthing and that shielding failures do not occur in the first span of the overhead line. Therefore, there is a minimum travel length of the impinging surge which results in a maximum possible steepness. The analytical expression used in Equation (E.16) is an approximation to this observation. Alternatively, instead of the sum, the higher value of the span length or the length L_t can be used.

Thus, introducing S_{rp} in Equation (1) and putting $A = 2 / (K_{co} c)$ for transmission lines, the dependence of the representative lightning overvoltage on the return rate is obtained by:

$$U_{rp} = U_{pl} + \frac{A}{n} \frac{L}{L_{sp} + L_t} \quad (E.17)$$

where

U_{rp} is the representative lightning overvoltage amplitude (kV);

A is a factor given in Table E.2 describing the lightning performance of the overhead line connected to the station;

U_{pl} is the lightning impulse protection level of the surge arrester (kV);

n is the minimum of lines connected to the substation ($n = 1$ or $n = 2$);

L is the separation distance: $L = a_1 + a_2 + a_3 + a_4$ as shown on Figure 3 (m);

L_{sp} is the span length (m);

L_t is the overhead line length with outage rate equal to adopted return rate (m).

The co-ordination withstand voltage is obtained by replacing L_t by the line length L_a which yields an outage rate equal to the acceptable failure rate R_a :

$$L_a = R_a / R_{km} \quad (\text{E.18})$$

where

L_a is the overhead line section with outage rate equal to acceptable failure rate;

R_a is the acceptable failure rate for equipment.

And the co-ordination lightning impulse withstand voltage (U_{cw}) is equal to:

$$U_{cw} = U_{pl} + \frac{A}{n} \frac{L}{L_{sp} + L_a} \quad (\text{E.19})$$

For transmission lines, the factors A are obtained from Table E.2 and the corona damping constants K_{co} from Table E.1. For distribution systems, lightning overvoltages are usually multiphase and current sharing of the phase conductors has to be considered. For steel towers, the flashovers of more than one tower during a lightning stroke lead to a further reduction of the lightning overvoltages. For these lines, the factor A has been matched with the service practice.

GIS are, in general, better protected than open-air substations owing to a surge impedance much lower than that of the overhead lines. A generally valid recommendation for the estimation of the amelioration obtained for GIS as compared to open-air substations cannot be made. However, the use of the Equation (E.19) for the open-air substation results in conservative estimates of the co-ordination lightning impulse withstand voltage or of the protective protection range and a reduction of the ratio A/n to half the value used for outdoor stations is still suitable.

Table E.2 – Factor A for various overhead lines

Type of line	A (kV)
Distribution lines (phase-phase flashovers):	
– with earthed crossarms (flashover to earth at low voltage)	900
– wood-pole lines (flashover to earth at high voltage)	2 700
Transmission lines (single-phase flashover to earth)	
– single conductor	4 500
– double conductor bundle	7 000
– four conductor bundle	11 000
– six and eight conductor bundle	17 000
NOTE Values in this table are applicable in Equations (E.17) and (E.19).	

E.5 Assumed maximum value of the representative lightning overvoltage

For new stations, where lightning insulation performance of existing stations is known, the assumed maximum value of the representative overvoltage may be estimated by:

$$\frac{U_{rp2}}{U_{pl2}} = 1 + \left[\frac{n_1}{n_2} \frac{L_2}{L_1} \frac{U_{pl1}}{U_{pl2}} \left(\frac{U_{rp1}}{U_{pl1}} - 1 \right) \right] \quad (\text{E.20})$$

where

U_{rp} is the assumed maximum representative overvoltage;

U_{pl} is the lightning impulse ~~protective~~ protection level of the surge arrester;

n is the minimum number of in-service overhead lines connected to the station;

And L is as follows (see Figure 3):

$$L = a_1 + a_2 + a_3 + a_4$$

The index 1 refers to the situation for which service experience has been satisfactory, and the index 2 to the new station situation.

Alternatively, the assumed maximum value can be obtained by assuming the return rate in Equation (E.16) equal to zero, thus leading to $L_t = 0$, and:

$$U_{rp} = U_{pl} + \frac{A}{n} \frac{L}{L_{sp}} \quad (\text{E.21})$$

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Annex F (informative)

Calculation of air gap breakdown strength from experimental data

F.1 General

The intent of Annex F is not to provide the apparatus committees with a method to calculate air clearances. The purpose is rather to provide help to the user to estimate the size of equipment and the dielectric strength of air gaps for the purpose of determining the atmospheric correction factor.

It ~~must~~ **shall** be noted that the equations provided here are based on experimental data and for the purposes of insulation co-ordination. For distances greater than 1 m, they can be assumed to give an approximate fit to these experimental results.

~~The user who is tempted to use these formulae to verify the minimum clearances given in annex A or to justify a deviation from those values given in annex A should do so with caution. The values given in annex A do not correspond to U_{50} but to withstand conditions and embody additional considerations including feasibility, economy, experience and environmental conditions (pollution, rain, insects, etc.).~~

Discrepancies may be particularly significant for distances less than 1 m where the accuracy of the given equations is questionable.

F.2 Insulation response to power-frequency voltages

For air gap breakdown under power-frequency voltage, the lowest withstand voltage is obtained for the rod-plane gap configuration. The 50 % breakdown voltage for a rod-plane gap may be approximated by the following equation, for air gaps d up to 3 m:

$$U_{50RP} = 750 \sqrt{2} \ln (1 + 0,55 d^{1,2}) \text{ (kV crest, m)} \quad (\text{F.1})$$

The peak value of U_{50RP} under power-frequency voltage is about 20 % to 30 % higher than the corresponding value under positive switching impulse at critical front time. Withstand can be taken to be 90 % of U_{50} , based on an assumed conventional deviation of 3 % of U_{50} .

The influence of gap configuration on the strength is generally lower under power-frequency than under switching impulse:

- it is quite small for gaps up to about 1 m clearance;
- for gaps larger than 2 m, the strength can be evaluated according to the following equation (applicable to dry conditions):

$$U_{50} = U_{50RP} (1,35 K - 0,35 K^2) \quad (\text{F.2})$$

where

K is the gap factor (determined from switching impulse tests) as shown in Table F.1;

- for gaps between 1 m and 2 m, Equation (F.1) can be used with the knowledge that the results will be conservative.

When insulators are present, the flashover voltage can substantially decrease with respect to the reference case (the same air gap without insulators), especially in conditions of high humidity.

In general, discharges under power-frequency voltage and normal operating conditions and under temporary overvoltages will be caused by exceptional reductions in insulation withstand strength due to the severe ambient conditions or by aging of the insulation properties of the equipment.

The influence of rain on air gaps is negligible, especially for configurations presenting the lowest strength. However, rain can reduce the external dielectric strength of insulators, especially for post insulators with small distance between sheds. The degree of reduction depends on the rain rate, the insulator configuration and the conductivity of water.

Rain, together with pollution, can drastically reduce the insulation strength. The worst condition is usually caused by fog or light rain together with the polluted insulators (see 5.3.2.2). These conditions may in fact dictate the external insulation design. Comparative insulation contamination levels can be simulated by the equivalent salt deposit density (ESDD) in grams per square metre of NaCl. ESDD relates the steady-state conductivity of dissolved contaminant to an equivalent amount of dissolved NaCl. The determination of the ESDD requires an analysis of either performance of existing insulation in the area or statistical data gathered from on-site investigations.

Analysis of existing performance may be the more desirable but may not provide sufficient information if existing insulation never suffers pollution flashovers.

Analysis of statistical data requires several years of on-site monitoring as data is gathered by direct measurement of ESDD from washdown of exposed insulators or by other methods, for example leakage current measurement, chemical analysis or conductivity measurements.

NOTE The applicability of the concept of ESDD to non-ceramic insulators is not clear. The present research indicates that the phenomenon of surface hydrophobicity may can be more important. The user is advised to use caution.

The statistical description of ambient conditions usually requires a greater amount of data. The statistical description of aging is even more difficult. Therefore, statistical procedures are not recommended in this document for estimation of the insulation response at power-frequency voltages.

F.3 Insulation response to slow-front overvoltages

Under stress from slow-front surges, a given self-restoring insulation exhibits an appreciably lower withstand voltage than under fast-front surges of the same polarity. As a result of numerous switching impulse tests, air gaps can be characterized by the minimum strength observed for the critical time-to-crest, as a function of the geometrical characteristics of the air gap which are mainly the gap spacing d and the electrode configuration. Among the different gaps of spacing d , the positively stressed rod-plane gap has the lowest strength and is used as a reference. For rod-plane gaps of length up to 25 m, experimental data for positive-polarity critical-front-time strength can be reasonably approximated by [10] [11]:

$$U_{50RP} = 1\,080 \ln(0,46 d + 1) \text{ (kV crest, m)} \quad (\text{F.3})$$

For standard switching impulses, the following equation provides a better approximation [11] [12]:

$$U_{50RP} = 500 d^{0,6} \text{ (kV crest, m)} \quad (\text{F.4})$$

Equations (F.3) and (F.4) are applicable to sea-level ($H = 0$). Therefore, correction for altitude is required ~~(according to 4.2.2)~~ when applying the insulation co-ordination procedure.

Insulators in the air gap generally decrease the breakdown strength, for positive slow-front impulses. For dry cap and pin insulators, the influence is small but can be important for post insulators.

For other gap configurations, a gap factor as described in Table F.1 is applied as follows:

$$U_{50} = K U_{50RP} \quad (\text{F.5})$$

Note that for $K \geq 1,45$, the breakdown voltage under negative polarity may become lower than that for positive polarity.

For phase-to-phase configurations, a similar gap factor may be applied. In this case however, the gap factor is influenced not only by the gap configuration, but also by the ratio α defined as the peak negative component divided by the sum of the peak negative and positive components (see Annex C).

Table F.2 gives typical values of gap factor for usual phase-to-phase gap geometries for $\alpha = 0,5$ and $\alpha = 0,33$.

NOTE For any given gap configuration, actual gap factors can only be determined accurately by testing.

F.4 Insulation response to fast-front overvoltages

Under fast-front impulse stress, the negative polarity breakdown strength of a rod-plane gap configuration is much higher than that with positive polarity stress. Furthermore, the gap strength when plotted against the gap clearance is non-linear with negative polarity while it is linear with positive polarity. For standard lightning impulses applied to rod-plane gaps from 1 m up to 10 m, the experimental data for positive polarity strength may be approximated by:

$$U_{50RP} = 530 d \text{ (kV crest, m)} \quad (\text{F.6})$$

In general, the gap factors applicable to switching impulse are not directly useable for lightning impulse strength. However, experimental results have shown that for positive polarity the breakdown gradient for a general air gap in per unit of the breakdown gradient for a rod-plane gap increases linearly with switching impulse gap factor for positive impulse stress. The gap factor K_{ff}^+ for fast-front lightning impulses of positive polarity can be approximated in terms of the switching impulse gap factor as follows:

$$K_{ff}^+ = 0,74 + 0,26 K \quad (\text{F.7})$$

For the purpose of estimating the breakdown strength of overhead line insulator strings for negative polarity, in order to determine the magnitude of surges impinging on a substation, the following equation may be used:

$$U_{50} = 700 d \text{ (kV crest, m)} \quad (\text{F.8})$$

The formulas (F.6) and (F.8) are applicable to sea-level ($H = 0$). Therefore, correction for altitude is required ~~(according to 4.2.2)~~ when applying the insulation co-ordination procedure.

For configurations such as conductor-upper structure and conductor-crossarm, the influence of the insulators on the strength is negligible so that the strength of these configurations is close to that of air gaps.

For other unusual configurations and particularly when large clearances are involved (like in range II), specific testing is advised for accurate results. For these configurations, the presence of insulators between the electrodes can play an important role on the discharge process, thus also heavily affecting the value of U_{50} . The degree of influence depends on insulator type (capacitance between units, distance between metal parts along the insulator set). A lower influence is to be expected for insulators with few metal parts (e.g. post insulators, long rod, composite). The generalization of the results similar to that made for configurations without insulators is not easy when cap and pin insulators are included in the gap. It can be stated however that the influence of cap and pin insulators is reduced when the stress on the first insulator at both extremities of the string is reduced using shielding rings. It is also reduced for more practical configurations with insulators at both extremities less stressed than in the case of rod-plane gaps.

For air gaps, the conventional deviation is about 3 % of U_{50} under positive impulses and about 5 % of U_{50} under negative impulses. When insulators are present, the conventional deviation is increased reaching a maximum of 5 % to 9 % in connection with cases presenting the largest reduction of U_{50} . In other cases, a value close to that of air gaps is applicable.

The influence of rain on a flashover voltage is generally secondary, both in the case of air gaps and insulator strings.

For fast-front overvoltages, the time-to-breakdown is markedly influenced by the amplitude of the applied impulse relative to the breakdown voltage. For impulses close to the value of U_{50} , flashover occurs on the tail of the standard impulse. As amplitude is increased, time to flashover decreases giving rise to the well-known volt-time curve.

Table F.1 – Typical gap factors K for switching impulse breakdown phase-to-earth (according to [1] and [4])

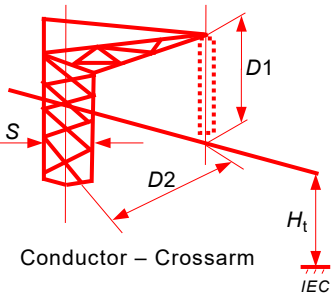
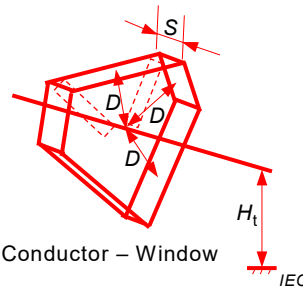
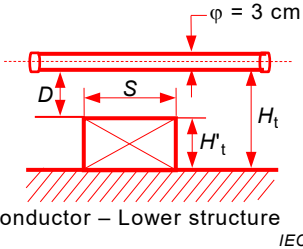
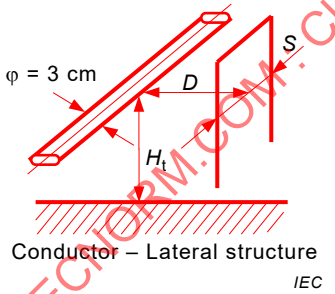
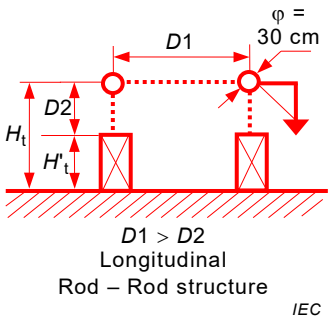
Gap type	Parameters	Typical range	Reference value	
 Conductor – Crossarm IEC	K	1,36 to 1,58	1,45	
	$D2 / D1$	1 to 2	1,5	
	$H_t / D1$	3,34 to 10	6	
	$S / D1$	0,167 to 0,2	0,2	
 Conductor – Window IEC	K	1,22 to 1,32	1,25	
	H_t / D	8 to 6,7	6	
	S / D	0,4 to 0,1	0,2	
 Conductor – Lower structure IEC	K	1,18 to 1,35	1,15 Conductor-plane	1,47 Conductor-rod
	H'_t / H_t	0,75 to 0,75	0	0,909
	H'_t / D	3 to 3	0	10
	S / D	1,4 to 0,05	-	0
 Conductor – Lateral structure IEC	K	1,28 to 1,63	1,45	
	H_t / D	2 to 10	6	
	S / D	1 to 0,1	0,2	
 $D1 > D2$ Longitudinal Rod – Rod structure IEC	K	1,03 to 1,66	1,35	
	H'_t / H_t	0,2 to 0,9	0	
	$D1 / H_t$	0,1 to 0,8	0,5	

Table F.2 – Gap factors for typical phase-to-phase geometries

Configuration	$\alpha = 0,5$	$\alpha = 0,33$
Ring-ring or large smooth electrodes	1,80	1,70
Crossed conductors	1,65	1,53
Rod-rod or conductor-conductor (along the span)	1,62	1,52
Supported busbars (fittings)	1,50	1,40
Asymmetrical geometries	1,45	1,36
NOTE According to [1] and [4].		

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Annex G (informative)

Examples of insulation co-ordination procedure

G.1 Overview

The insulation co-ordination procedure includes determining the voltage stresses from all origins on equipment and the corresponding electric strength required based on acceptable margins of protection or acceptable levels of performance. These margins (or levels) are mostly empirical.

As described in Figure 1 of IEC 60071-1:2006, there are in fact four main steps in this insulation co-ordination procedure, which can be identified as follows:

- step 1: determination of the representative overvoltages (U_{rp});
- step 2: determination of the co-ordination withstand voltages (U_{cw});
- step 3: determination of the required withstand voltages (U_{rw});
- step 4: determination of the standard withstand voltages (U_w).

These main steps, with associated links connecting them, will be illustrated in some examples contained in Annex G. Not only will the required standard withstand voltages be determined but also the calculation related to phase-to-ground and phase-to-phase clearances will be illustrated, as applicable.

The representative overvoltages are not, strictly speaking, the overvoltages that occur in the system but are overvoltages that represent the same electric stress on the equipment as the actual overvoltages. Thus, if the assumed actual overvoltage has a shape different from the test shape, the representative overvoltage may have to be modified accordingly so that the tests truly verify the insulation strength.

In matching the voltage stresses with the electric strength, one has to take into account the various types of voltage stresses and the corresponding response of the insulation. This involves making a distinction between self-restoring (external) insulation and non-self-restoring (internal) insulation. For non-self-restoring insulation, the stress-strength co-ordination is made using deterministic methodology whereas for self-restoring insulation a statistical methodology can be used where this is convenient. The following examples attempt to present all these considerations.

G.2 Numerical example for a system in range I (with nominal voltage of 230 kV)

G.2.1 General

The system analysed corresponds to that shown in Figure 11. The process of insulation co-ordination is applied to station 1 assumed to be a new station.

For equipment in range I, IEC 60071-1 specifies short-duration power-frequency and lightning impulse withstand voltages.

The evaluation of the required slow-front (switching) withstand voltages is followed by their conversion into equivalent power-frequency and fast-front (lightning) withstand voltages. The example showed in Clause G.2 includes such a conversion procedure.

For normal systems in range I, the insulation co-ordination procedure leads to the general philosophy of specifying one standard insulation level (a set of standard withstand voltages) applicable phase-to-phase and phase-to-earth.

This is illustrated in the first part of the example (G.2.2) where no "abnormal" operating condition is considered.

However, as a second part of the example (G.2.3), to show the importance of considering stresses from all origins and their influence on this general philosophy, such special operating conditions (consisting of capacitor switching at station 2) are considered.

In the third part of this example (G.2.4), flow charts summarize intermediate and final results obtained along the different steps of the insulation co-ordination procedure.

For the purpose of this example, one will assume the following basic data:

- the highest system voltage is $U_s = 245$ kV;
- the pollution level is heavy (refer to 5.3.2.2);
- the altitude is $H = 1\,000$ m.

G.2.2 Part 1: no special operating conditions

G.2.2.1 Step 1: determination of the representative overvoltages – values of U_{rp}

G.2.2.1.1 Power-frequency voltage

For the insulation co-ordination procedure, the most important reference voltage is the maximum continuous operating voltage U_s . For the system analysed, while the nominal voltage is 230 kV, the value of U_s is confirmed to be 245 kV (RMS, phase-to-phase). The system, including compensation, is designed to operate at or below this limit. Obviously, the installed equipment should have a U_m equal to or greater than U_s .

The new station 1 is to be located adjacent to a major thoroughfare where salt, spread on the road in winter, can be expected to lead to heavy pollution. Because of this environment, the performance requirements of external insulation at power-frequency will be met by specifying an artificial pollution test corresponding to pollution level ~~III of table 1~~ "heavy" in 5.3.2.2. According to ~~the same table~~ IEC TS 60815-1, the minimum creepage distance recommended for insulators is 25 mm/kV.

G.2.2.1.2 Temporary overvoltages

One source of temporary overvoltages is earth faults (refer to 4.3.2.2) giving rise to phase-to-earth overvoltages. System studies have been made taking into account the system neutral grounding characteristics, and the earth fault factor has been found to be $k = 1,5$ (such a figure is just for the purpose of the example; in fact, a value of 1,5 is rather unusual at a voltage level of 230 kV where a value not greater than 1,3 is normally expected). The corresponding phase-to-earth representative overvoltage is $U_{rp} = 212$ kV.

Another source of temporary overvoltages is load rejection (refer to 4.3.2.3) which produces overvoltages affecting both phase-to-phase and phase-to-earth insulation. Analysis and system studies have shown that generator overspeed and regulation combine to produce overvoltages of 1,4 p.u. at station 1 (which is also rather high) which results in phase-to-earth and phase-to-phase representative overvoltages of $U_{rp} = 198$ kV and $U_{rp} = 343$ kV.

As mentioned in 4.3.2.6, an earth fault can combine with load rejection to give rise to other overvoltage amplitudes. In this example, such a combination does not occur because after load rejection, the system configuration has changed: circuit-breakers at station 1 have opened, external infeeds are gone, and the earth fault factor (k) at station 1 has been reduced below 1 (with the delta/grounded Y generator step-up transformer).

The representative temporary overvoltages are the highest obtained considering all possible sources:

- phase-to-earth: $U_{rp} = 212 \text{ kV}$;
- phase-to-phase: $U_{rp} = 343 \text{ kV}$.

G.2.2.1.3 Slow-front overvoltages

System studies have confirmed that slow-front overvoltages from remote lightning strokes (refer to 4.3.3.6) are not a problem in the system under consideration. On the other hand, slow-front overvoltages due to earth faults need to be considered only in systems with resonant neutral earthing (refer to 4.3.3.3), which is not the case in this example.

For the determination of the representative overvoltages, it may be necessary to distinguish between equipment at the line entrance which can be in the open-end condition during energization or re-energization at remote end (station 1), and equipment on the source side at the local end (station 2) which will be affected in a different way and by different stresses.

1) Particular surges affecting line entrance equipment (at station 1)

System studies using the phase-peak method (refer to Annex C) have shown that line re-energization from station 2 can result in 2 % overvoltages at the open-end line entrance at station 1 of $u_{e2} = 3,0 \text{ p.u.}$ and $u_{p2} = 4,5 \text{ p.u.}$ The representative overvoltages for external line entrance equipment, before applying surge arresters, are the truncation values of these overvoltage distributions. As shown in Annex C:

- $u_{et} = 1,25 u_{e2} - 0,25 \Rightarrow u_{et} = 700 \text{ kV}$;
- $u_{pt} = 1,25 U_{p2} - 0,43 \Rightarrow u_{pt} = 1\,039 \text{ kV}$.

2) Surge affecting all equipment (at station 1)

All the equipment located in station 1 is subjected to slow-front overvoltages due to local line energization and re-energization. However, these sending end surges are much lower than at the receiving end: for station 1, system studies result in $u_{e2} = 1,9 \text{ p.u.}$ and $u_{p2} = 2,9 \text{ p.u.}$ Corresponding values are $U_{et} = 425 \text{ kV}$ and $U_{pt} = 639 \text{ kV}$.

3) Surge arresters at the line entrance (at station 1)

To control the possible severe overvoltages originating from remote re-energization, metal-oxide surge arresters are installed at the line entrance (refer to 4.3.3.8), identical to those planned for transformer protection. The rating of these arresters is such that they can sustain the worst temporary overvoltage cycle (amplitude and duration). Their protection characteristics are:

- switching impulse ~~protective~~ protection level: $U_{ps} = 410 \text{ kV}$;
- lightning impulse ~~protective~~ protection level: $U_{pl} = 500 \text{ kV}$.

As explained in 4.3.3.8, with the use of surge arresters, the slow-front representative overvoltages can be directly given by U_{ps} (phase-to-earth) or $2 U_{ps}$ (phase-to-phase) if these protection values are lower than the corresponding maximum slow-front overvoltage stresses (U_{et} and U_{pt} values). This is the case for any stress except for line entrance equipment, phase-to-phase, so that the representative slow-front overvoltages are:

- phase-to-earth: $U_{rp} = 410 \text{ kV}$ for any equipment;
- phase-to-phase:
 - $U_{rp} = 639 \text{ kV}$ for any equipment except at line entrance;
 - $U_{rp} = 820 \text{ kV}$ for equipment at line entrance.

G.2.2.1.4 Fast-front overvoltages

In this example, only fast-front overvoltages from lightning have to be considered. A simplified statistical approach will be used which leads directly to the co-ordination withstand voltage (step 2 below), bypassing the need for a representative overvoltage.

G.2.2.2 Step 2: determination of the co-ordination withstand voltages – values of U_{cw}

G.2.2.2.1 General

According to Clause 5, different factors have to be applied to the previously determined values of representative overvoltages. These factors, which may vary with the shape of the considered overvoltage, take into account the adopted performance criteria (the economic or operational rate of failure which is acceptable) and the inaccuracies in the input data (e.g. arrester data).

G.2.2.2.2 Temporary overvoltages

For this class of overvoltages, the co-ordination withstand voltage is equal to the representative temporary overvoltage (refer to 5.3.2). In other words, the co-ordination factor K_c is equal to 1. Therefore:

- phase-to-earth: $U_{cw} = 212 \text{ kV}$;
- phase-to-phase: $U_{cw} = 343 \text{ kV}$.

G.2.2.2.3 Slow-front overvoltages

The deterministic approach ~~will be~~ is used. With such an approach, one ~~must~~ shall take into account that surge limitation by an arrester distorts the statistical distribution of these surges, creating a significant bulge in the probability distribution of surges at about the arrester ~~protective~~ protection level (refer to 5.3.3.1). Therefore, small uncertainties related to the arrester ~~protective~~ protection characteristic or to equipment strength could lead to an abnormally high increase in the failure rate. Figure 4 takes this into account by applying a deterministic co-ordination factor K_{cd} to the arrester protection level to obtain the U_{cw} values.

For line entrance equipment:

- phase-to-earth: $U_{ps}/U_{e2} = 410/600 = 0,68 \Rightarrow K_{cd} = 1,10$;
- phase-to-phase: $2 U_{ps}/U_{p2} = 820/900 = 0,91 \Rightarrow K_{cd} = 1,00$.

For all other equipment:

- phase-to-earth: $U_{ps}/U_{e2} = 410/380 = 1,08 \Rightarrow K_{cd} = 1,03$;
- phase-to-phase: $2 U_{ps}/U_{p2} = 820/580 = 1,41 \Rightarrow K_{cd} = 1,00$.

The resulting co-ordination withstand voltages are $K_{cd} \times U_{rp}$:

For line entrance equipment:

- phase-to-earth: $U_{cw} = 1,1 \times 410 \Rightarrow U_{cw} = 451 \text{ kV}$;
- phase-to-phase: $U_{cw} = 1,0 \times 820 \Rightarrow U_{cw} = 820 \text{ kV}$.

For all other equipment:

- phase-to-earth: $U_{cw} = 1,03 \times 410 \Rightarrow U_{cw} = 422 \text{ kV}$;
- phase-to-phase: $U_{cw} = 1,0 \times 639 \Rightarrow U_{cw} = 639 \text{ kV}$.

G.2.2.2.4 Fast-front overvoltages

A statistical approach is used (refer to 5.3.4.2), and more specifically, a simplified statistical approach (refer to Clause E.4). Here, the factor to be applied to U_{rp} is based on experience with particular line construction and on the calculated effect due to the separation between the arrester and the protected equipment.

One determines the length L_a of overhead line with an outage rate equal to the acceptable failure rate R_a . Then, taking account of the separation distance L , the number of lines n entering the station, and the span length L_{sp} , one calculates the effective ~~protective~~ protection level of the arrester, which is the desired value U_{cw} .

For this example, the following data are available: many arresters with a lightning ~~protective~~ protection level of 500 kV are located at different places (at line entrance and near the transformers). The maximum separation distance for internal insulation is 30 m; for external insulation, it is 60 m. Two steel tower lines characterized by $A = 4\,500$ (refer to Table E.2) and with a span length of 300 m are connected to the station. The lightning performance for such lines is one outage per 100 km per year. For the equipment to be installed in station 1, an acceptable failure rate is defined as 1 in 400 years.

Using Equation (E.18), the value of $L_a = 0,25$ km is found. Introducing the value of L_a and other parameters in Equation (E.19), the co-ordination withstand voltage is found:

- for internal insulation:

$$U_{cw} = 500 + [(4\,500 / 2) \times 30 / (300 + 250)] \Rightarrow U_{cw} = 622 \text{ kV};$$

- for external insulation:

$$U_{cw} = 500 + [(4\,500 / 2) \times 60 / (300 + 250)] \Rightarrow U_{cw} = 745 \text{ kV}.$$

Fast-front overvoltages affect the phase-to-phase and the phase-to-earth insulations in the same way.

G.2.2.3 Step 3: determination of the required withstand voltages – values of U_{rw}

G.2.2.3.1 General

The required withstand voltages are obtained by applying to the co-ordination withstand voltages two correction factors (refer to Clause 6): factor K_a which takes into account the altitude of the installation, and a safety factor K_s .

G.2.2.3.2 Safety factor

The recommended values for the safety factor K_s are defined in 6.3.5. The factor K_s is applicable to any type of overvoltage shape (temporary, slow-front, fast-front), phase-to-phase and phase-to-earth:

- for internal insulation: $K_s = 1,15$;
- for external insulation: $K_s = 1,05$.

G.2.2.3.3 Atmospheric correction factor

The altitude correction factor K_a is defined in 6.2.2 (Equation (11)). The factor K_a is applicable to external insulation only and its value depends on the overvoltage shape (via parameter m in Equation (11)).

For power-frequency withstand, short-duration tests on polluted insulators are required, and:

$$\Rightarrow m = 0,5.$$

For switching impulse withstand, the value of m is a function of the co-ordination withstand voltage according to Figure 9:

- phase-to-earth: $U_{cw} = 451 \text{ kV} \Rightarrow m = 0,94;$
- phase-to-phase: $U_{cw} = 820 \text{ kV} \Rightarrow m = 1,00.$

For lightning impulse withstand: $\Rightarrow m = 1,00.$

The installation is at an altitude $H = 1\,000 \text{ m}$. The corresponding values of K_a are:

- for power-frequency withstand: $K_a = 1,063$ (phase-to-phase and phase-to-earth);
- for switching impulse withstand: $K_a = 1,122$ (phase-to-earth),
 $K_a = 1,130$ (phase-to-phase);
- for lightning impulse withstand: $K_a = 1,130$ (phase-to-phase and phase-to-earth).

G.2.2.3.4 Required withstand voltages

The values for the required withstand voltages are obtained from: $U_{rw} = U_{cw} K_s K_a$, with U_{cw} values found in step 2 (G.2.2.2) and K_s and K_a values found in step 3 (G.2.2.3).

1) For temporary overvoltages

- external insulation:
 - phase-to-earth $\Rightarrow U_{rw} = 212 \times 1,05 \times 1,063 \Rightarrow U_{rw} = 237 \text{ kV},$
 - phase-to-phase $\Rightarrow U_{rw} = 343 \times 1,05 \times 1,063 \Rightarrow U_{rw} = 383 \text{ kV};$
- internal insulation:
 - phase-to-earth $\Rightarrow U_{rw} = 212 \times 1,15 \Rightarrow U_{rw} = 243 \text{ kV},$
 - phase-to-phase $\Rightarrow U_{rw} = 343 \times 1,15 \Rightarrow U_{rw} = 395 \text{ kV}.$

2) For slow-front overvoltages

For line entrance equipment:

- external insulation:
 - phase-to-earth $\Rightarrow U_{rw} = 451 \times 1,05 \times 1,122 \Rightarrow U_{rw} = 531 \text{ kV},$
 - phase-to-phase $\Rightarrow U_{rw} = 820 \times 1,05 \times 1,13 \Rightarrow U_{rw} = 973 \text{ kV}.$

For other equipment:

- external insulation:
 - phase-to-earth $\Rightarrow U_{rw} = 422 \times 1,05 \times 1,122 \Rightarrow U_{rw} = 497 \text{ kV},$
 - phase-to-phase $\Rightarrow U_{rw} = 639 \times 1,05 \times 1,13 \Rightarrow U_{rw} = 758 \text{ kV}.$
- internal insulation:
 - phase-to-earth $\Rightarrow U_{rw} = 422 \times 1,15 \Rightarrow U_{rw} = 485 \text{ kV},$
 - phase-to-phase $\Rightarrow U_{rw} = 639 \times 1,15 \Rightarrow U_{rw} = 735 \text{ kV}.$

3) For fast-front overvoltages:

- external insulation:
 - phase-to-earth $\Rightarrow U_{rw} = 745 \times 1,05 \times 1,13 \Rightarrow U_{rw} = 884 \text{ kV},$
 - phase-to-phase $\Rightarrow U_{rw} = 745 \times 1,05 \times 1,13 \Rightarrow U_{rw} = 884 \text{ kV}.$
- internal insulation:
 - phase-to-earth $\Rightarrow U_{rw} = 622 \times 1,15 \Rightarrow U_{rw} = 715 \text{ kV},$
 - phase-to-phase $\Rightarrow U_{rw} = 622 \times 1,15 \Rightarrow U_{rw} = 715 \text{ kV}.$

G.2.2.4 Step 4: conversion to withstand voltages normalized for range I

G.2.2.4.1 General

In range I, the insulation level is normally described by a set of two values as shown in Table 2 of IEC 60071-1:2006: a short-duration power-frequency withstand voltage and a lightning impulse withstand voltage. Table 1 gives the test conversion factor to be applied to the required withstand voltage for slow-front overvoltage to get such an equivalent set of values.

G.2.2.4.2 Conversion to short-duration power-frequency withstand voltage (SDWV)

For line entrance equipment:

- external insulation:
 - phase-to-earth $\Rightarrow$ $SDWV = 531 \times (0,6 + 531 / 8\,500) = 352 \text{ kV};$
 - phase-to-phase $\Rightarrow$ $SDWV = 973 \times (0,6 + 973 / 12\,700) = 658 \text{ kV}.$

For other equipment:

- external insulation:
 - phase-to-earth $\Rightarrow$ $SDWV = 497 \times (0,6 + 497 / 8\,500) = 327 \text{ kV};$
 - phase-to-phase $\Rightarrow$ $SDWV = 758 \times (0,6 + 758 / 12\,700) = 500 \text{ kV};$
- internal insulation:
 - phase-to-earth $\Rightarrow$ $SDWV = 485 \times 0,5 = 243 \text{ kV};$
 - phase-to-phase $\Rightarrow$ $SDWV = 735 \times 0,5 = 367 \text{ kV}.$

G.2.2.4.3 Conversion to lightning impulse withstand voltage (LIWV)

For line entrance equipment:

- external insulation:
 - phase-to-earth $\Rightarrow$ $LIWV = 531 \times 1,30 = 690 \text{ kV};$
 - phase-to-phase $\Rightarrow$ $LIWV = 973 \times (1,05 + 973 / 9\,000) = 1\,127 \text{ kV}.$

For other equipment:

- external insulation:
 - phase-to-earth $\Rightarrow$ $LIWV = 497 \times 1,30 = 646 \text{ kV};$
 - phase-to-phase $\Rightarrow$ $LIWV = 758 \times (1,05 + 758 / 9\,000) = 860 \text{ kV};$
- internal insulation:
 - phase-to-earth $\Rightarrow$ $LIWV = 485 \times 1,10 = 534 \text{ kV};$
 - phase-to-phase $\Rightarrow$ $LIWV = 735 \times 1,10 = 808 \text{ kV}.$

G.2.2.5 Step 5: selection of standard withstand voltage values

Table G.1 summarizes values $U_{rw(s)}$ of minimum required withstand voltages obtained from system studies (results in step 3) which become minimum test values to be applied to verify these withstands in terms of short-duration power-frequency, switching impulse and lightning impulse tests. In range I, the required switching impulse withstand voltage is normally covered by a standard short-duration power-frequency test or by a standard lightning impulse test. In Table G.1, values obtained after such conversions are indicated under $U_{rw(c)}$ (results from step 4). In this example, converted values for a lightning impulse test are retained so that converted values for a short-duration power-frequency test need no more consideration.

Table G.1 – Summary of minimum required withstand voltages obtained for the example shown in G.2.2

Values of U_{rw} — in kV r.m.s for short-duration power frequency — in kV peak for switching or lightning impulse kV		External insulation				Internal insulation	
		Line entrance equipment		Other equipment			
		$U_{rw(s)}$	$U_{rw(c)}$	$U_{rw(s)}$	$U_{rw(c)}$	$U_{rw(s)}$	$U_{rw(c)}$
Short-duration power-frequency (RMS)	phase-earth	237	352	237	327	243	243
	phase-phase	383	658	383	500	395	367
Switching impulse (peak)	phase-earth	531		497	—	485	—
	phase-phase	973	—	758	—	735	—
Lightning impulse (peak)	phase-earth	884	690	884	646	715	534
	phase-phase	884	1127	884	860	715	808
NOTE The figures are obtained from part 1 (G.2.2), without capacitor switching at remote station (station 2).							

Standard voltages to be defined for the purpose of the short-duration power-frequency and lightning impulse tests have to be selected taking into account results shown in bold characters in Table G.1 (highest value of minimum withstand required $U_{rw(s)}$ or converted value $U_{rw(c)}$) and standard values proposed in IEC 60071-1:2006 and IEC 60071-1:2006/AMD1:2010, 5.6 and 5.7. Normally, specified voltages are chosen in such a way as to correspond to a standard insulation level as defined in 3.36 of IEC 60071-1:2006 and shown in Table 2 of IEC 60071-1:2006.

Standardized values of 395 kV (for short-duration power-frequency) and 950 kV (for lightning impulse) correspond to such a standard insulation level for a system with $U_m = 245$ kV; these values will cover any insulation, phase-to-earth and phase-to-phase, except the phase-to-phase external insulation at line entrance for which a 1 127 kV minimum withstand value is required. However, in this example, three-phase equipment is not installed at line entrance so that a minimum phase-to-phase clearance can be specified instead of testing. According to table A.1 IEC 60071-1, a clearance of 2,35 m between phases would be required for line entrance equipment, corresponding to a standard lightning impulse withstand voltage of 1 175 kV. A minimum phase-to-earth and phase-to-phase clearance of 1,9 m is required for any other external insulation not located at line entrance. These clearances are solely based on insulation co-ordination requirements.

It will be noted that, for external phase-to-earth insulation, the high value specified for the short-duration power-frequency test (395 kV) is well above minimum requirement related to temporary overvoltages (237 kV). However, a 395 kV value corresponds to the standard insulation level having the required lightning withstand level of 950 kV. Refinements in studies could lead to lower requirements by one step for the phase-to-earth external insulation (360 kV/850 kV).

For the internal insulation, the selection of the same standard insulation level as for external insulation could be considered as leading to too much margin with respect to required lightning withstand voltages (715 kV phase-to-earth and 808 kV phase-to-phase). Other choices, considering the economic issue, are possible (refer to 5.10 of IEC 60071-1:2006 and IEC 60071-1:2006/AMD1:2010): specification of a lightning impulse withstand voltage of 850 kV, phase-to-phase and phase-to-earth; or 750 kV phase-to-earth with a special phase-to-phase test at 850 kV. However, the short-duration power-frequency test at a minimum value of 395 kV ~~must~~ shall be kept. Even if acceptable, the final issue related to these other choices would lead to a rated insulation level not corresponding to a standard insulation level as defined in IEC 60071-1.

G.2.3 Part 2: influence of capacitor switching at station 2

This second part of the example exposed in Clause G.2 deals with an additional slow-front overvoltage possibility originating from capacitor bank switching done at station 2 (remote station). All the other stresses considered in part 1 are present at their same values, with the same arrester implementation at station 1.

Results from system studies show that all equipment at station 1 (including line entrance equipment in normal operating closed condition) is subjected to severe voltage surges due to capacitor bank energization at station 2. These surges propagate and, due to amplification phenomenon (resonance at given frequencies), show the following maximum amplitudes at station 1:

- phase-to-earth:
 - $U_{e2} = 500$ kV;
 - $U_{et} = 575$ kV;
- phase-to-phase:
 - $U_{p2} = 750$ kV;
 - $U_{pt} = 852$ kV.

For the open-end line entrance equipment, the highest slow-front surges are those related to line re-energization described in part 1. But for all other equipment, the slow-front surges governing the insulation co-ordination procedure are now related to capacitor bank switching in station 2, which are higher than surges originating from local energization and re-energization (described in part 1). Hereafter, only this type of stress (new slow-front surges) is dealt with, conclusions for the other types of stress (temporary and fast-front overvoltages) remaining the same as discussed in part 1.

Values of representative slow-front overvoltages U_{rp} are now controlled by the surge arrester protection characteristic because $U_{ps} < U_{et}$ and $2 U_{ps} < U_{pt}$, so that:

- phase-to-earth: $U_{rp} = 410$ kV;
- phase-to-phase: $U_{rp} = 820$ kV.

To obtain the slow-front co-ordination withstand voltages U_{cw} , a deterministic co-ordination factor K_{cd} is applied to U_{rp} values by following the same procedure described in part 1:

- phase-to-earth: $U_{ps} / U_{e2} = 410 / 500 = 0,82 \Rightarrow K_{cd} = 1,10 \Rightarrow U_{cw} = 451$ kV;
- phase-to-phase: $2 U_{ps} / U_{p2} = 820 / 750 = 1,09 \Rightarrow K_{cd} = 1,00 \Rightarrow U_{cw} = 820$ kV.

The values for the safety factor K_s and for the atmospheric correction factor K_a keep approximately the same values as in part 1 so that the resulting required withstand voltages U_{rw} are:

- external insulation:
 - phase-to-earth $\Rightarrow U_{rw} = 451 \times 1,05 \times 1,122 \Rightarrow U_{rw} = 531$ kV;
 - phase-to-phase $\Rightarrow U_{rw} = 820 \times 1,05 \times 1,13 \Rightarrow U_{rw} = 973$ kV;
- internal insulation:
 - phase-to-earth $\Rightarrow U_{rw} = 451 \times 1,15 \Rightarrow U_{rw} = 518$ kV;
 - phase-to-phase $\Rightarrow U_{rw} = 820 \times 1,15 \Rightarrow U_{rw} = 943$ kV.

The required withstand voltages for slow-front surges are converted into short-duration power-frequency and lightning impulse withstand voltages (refer to part 1 for detailed information).

Conversion to short-duration power-frequency withstand voltage (SDWV):

- external insulation:
 - phase-to-earth $\Rightarrow$ $SDWV = 531 \times (0,6 + 531 / 8\,500) = 352 \text{ kV};$
 - phase-to-phase $\Rightarrow$ $SDWV = 973 \times (0,6 + 973 / 12\,700) = 658 \text{ kV};$
- internal insulation:
 - phase-to-earth $\Rightarrow$ $SDWV = 518 \times 0,5 = 259 \text{ kV};$
 - phase-to-phase $\Rightarrow$ $SDWV = 943 \times 0,5 = 472 \text{ kV}.$

Conversion to lightning impulse withstand voltage (LIWV):

- external insulation:
 - phase-to-earth $\Rightarrow$ $LIWV = 531 \times 1,30 = 690 \text{ kV};$
 - phase-to-phase $\Rightarrow$ $LIWV = 973 \times (1,05 + 973 / 9\,000) = 1\,127 \text{ kV};$
- internal insulation:
 - phase-to-earth $\Rightarrow$ $LIWV = 518 \times 1,10 = 570 \text{ kV};$
 - phase-to-phase $\Rightarrow$ $LIWV = 943 \times 1,10 = 1\,037 \text{ kV}.$

Table G.2 reflects the minimum withstand (or test) values required to take into account the different overvoltage stresses related to part 2 of the example exposed in Clause G.2. Minimum values required for the short-duration power-frequency and lightning impulse withstand tests are shown in bold characters.

Table G.2 – Summary of required withstand voltages obtained for the example shown in G.2.3

Values of U_{rw} — in kV rms for short-duration power frequency — in kV peak for switching or lightning impulse kV		External insulation				Internal insulation	
		Line entrance equipment		Other equipment			
		$U_{rw(s)}$	$U_{rw(c)}$	$U_{rw(s)}$	$U_{rw(c)}$	$U_{rw(s)}$	$U_{rw(c)}$
Short-duration power-frequency (RMS)	phase-earth	237	352	237	352	243	259
	phase-phase	383	658	383	658	395	472
Switching impulse (peak)	phase-earth	531	—	531	—	518	—
	phase-phase	973	—	973	—	943	—
Lightning impulse (peak)	phase-earth	884	690	884	690	715	570
	phase-phase	884	1127	884	1127	715	1037
NOTE The figures are obtained from part 2, with capacitor switching at remote station (station 2).							

A comparison between Table G.2 and Table G.1 shows the impact of slow-front overvoltages due to capacitor switching at station 2, mainly on phase-to-phase switching impulse requirements and on the resulting equivalent minimum testing values.

For external insulation, including longitudinal insulation, the same standard insulation level defined in part 1 (395 kV/950 kV) is also applicable here, no phase-to-phase test being required if a 2,35 m phase-to-phase clearance (corresponding to a standard lightning impulse withstand voltage of 1 175 kV) is adopted for all external equipment (not only at line entrance as for part 1).

For internal insulation, a standard insulation level applicable phase-to-phase and phase-to-earth of 460 kV/1 050 kV, corresponding to $U_m = 245 \text{ kV}$, can be chosen (refer to Table 2 of

IEC 60071-1:2006). This corresponds to one standard insulation level higher than in part 1 of this example, and is due to the switching of a capacitor at the remote station. Lower, phase-to-earth insulation levels, as discussed in part 1, could be retained but in any case a special phase-to-phase test at 1 050 kV would be required.

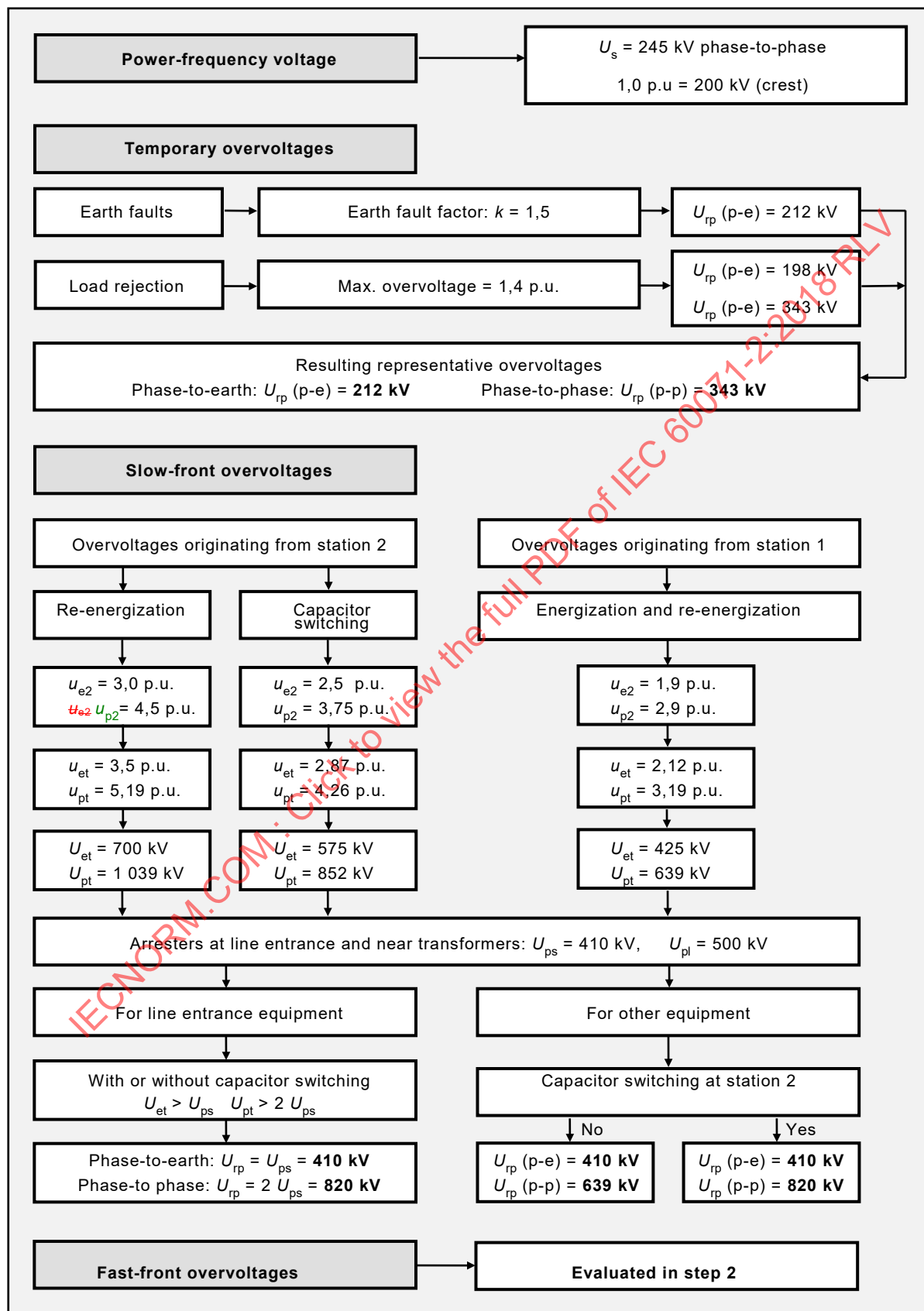
G.2.4 Part 3: flow charts related to the example of Clause G.2

The following flow charts summarize the insulation co-ordination procedure and the results obtained along the different steps. The flow charts include results obtained without (part 1) or with (part 2) capacitor switching at station 2.

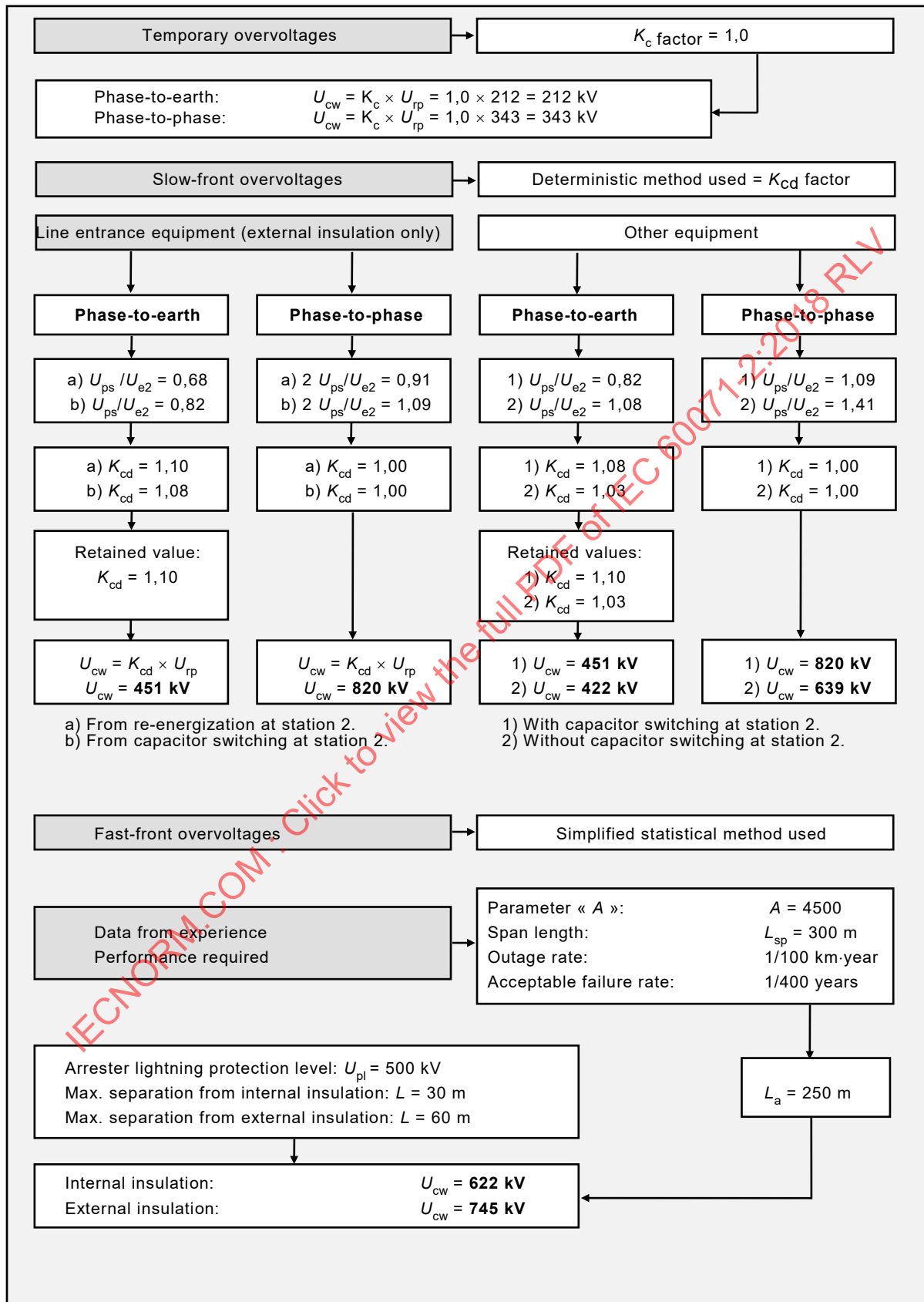
It should be noted that this example does not consider any means of mitigation to reduce the severe slow-front overvoltage surges from capacitor switching. As mentioned in 4.3.3.7, such measures could be considered, such as the use of closing resistors at the remote station to obtain a substantial reduction of slow-front stresses with a consequent reduction of withstand levels to be selected. This implies the necessity for additional system studies taking into account the presence of the means of mitigation and, on the basis of the new representative stresses found, to restart the insulation co-ordination procedure. For the particular example discussed here, this would lead to a reduction of some of the requirements obtained (inscribed under the flow chart of step 5 below), such as the phase-to-phase lightning impulse withstand voltage for internal insulation and the phase-to-phase clearance for external insulation.

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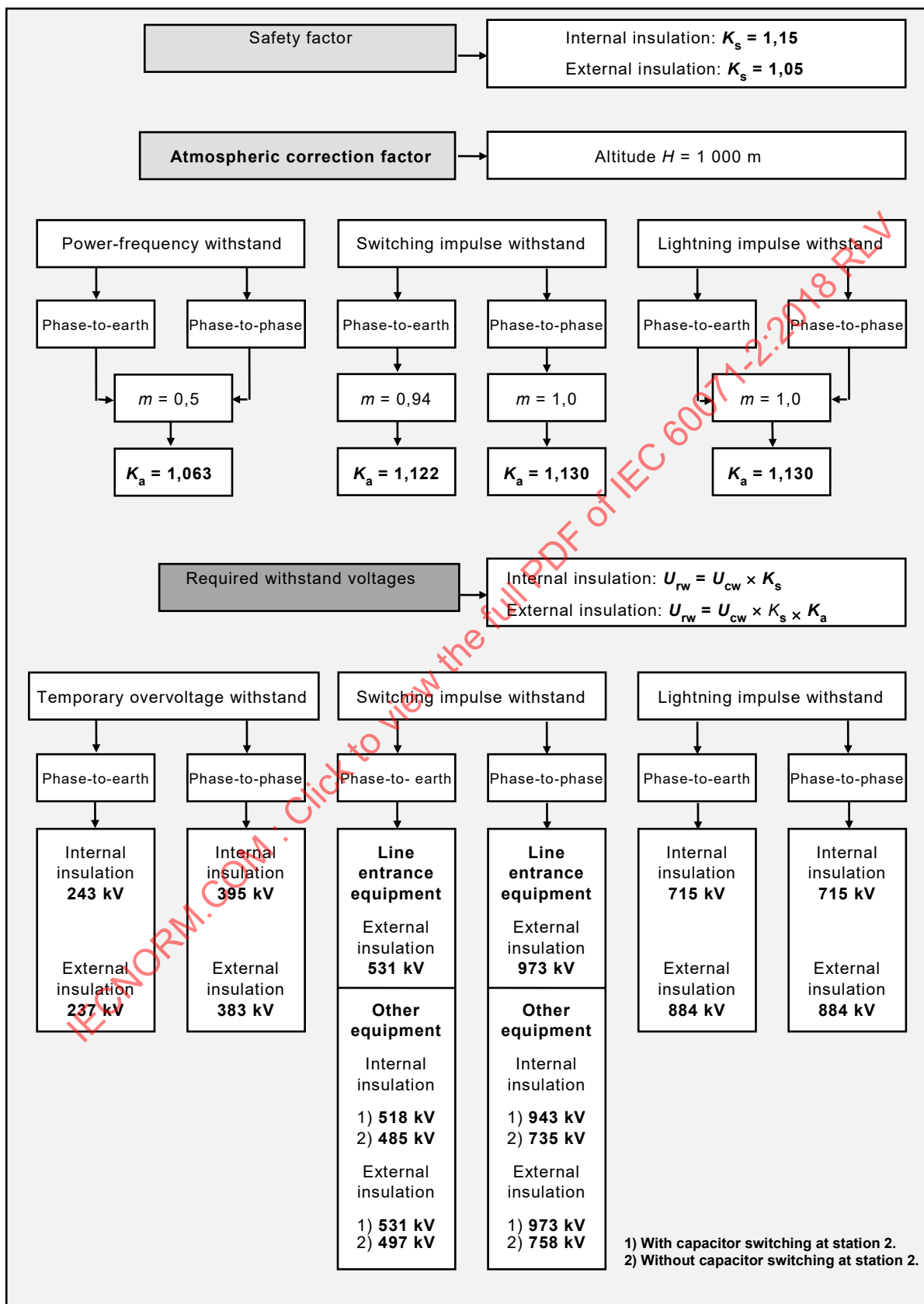
Step 1: Determination of the representative overvoltages (U_{rp})



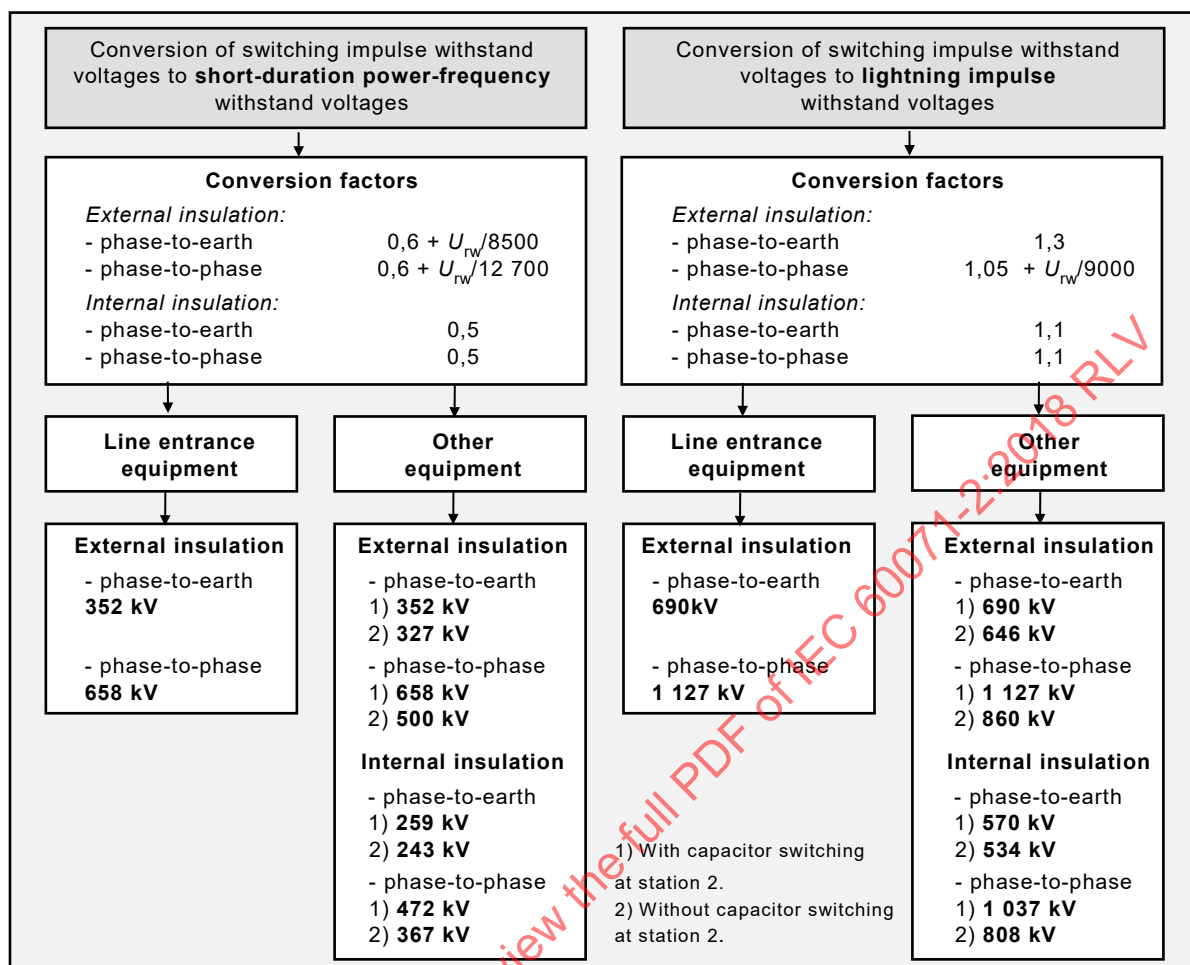
Step 2: Determination of the co-ordination withstand voltages (U_{cw})



Step 3: Determination of the required withstand voltages (U_{rw})



Step 4: Conversion to withstand voltages normalized for range I



Step 5: Selection of standard withstand voltage values

	Without capacitor switching at remote station. Refer to explanations related with Table G.1	With capacitor switching at remote station. Refer to explanations related with Table G.2
<u>Standard insulation level:</u>	395 kV/950 kV Applicable to any insulation	395 kV/950 kV External insulation 460 kV/1 050 kV Internal insulation
<u>External insulation</u> No phase-to-phase test required if clearances are:		
- for line entrance equipment:	2,35 m	2,35 m
- for other equipment:	1,90 m	2,35 m
<u>Internal insulation</u> Minimum standard lightning impulse level:		
- phase-to-earth:	750 kV	750 kV
- phase-to-phase:	850 kV	1 050 kV

G.3 Numerical example for a system in range II (with nominal voltage of 735 kV)

G.3.1 General

For the purpose of this example, one will assume the following basic data:

- the highest system voltage is: $U_s = 765$ kV;
- the pollution level is low to medium (refer to 5.3.2.2);
- the altitude is: $H = 1\,000$ m.

The altitude level is here assumed so as to cover all possible locations. The pollution level is assumed sufficiently mild that the standard insulation levels (and clearances) can be determined by the voltage stresses (usually the slow-front overvoltages for systems in range II).

Considerations of tower design such as conductor size and phase-to-phase spacing do not fall into the category of insulation co-ordination procedure. Only the phase-to-earth clearance results from the insulation co-ordination procedure since it depends on the slow-front overvoltages (in range II). Lightning considerations may dictate the type of overhead ground wires and counterpoise wires but this is generally the result of a separate study based on keraunic levels. Thus the transmission line design is not usually specified in terms of standard insulation levels but rather in terms of tower dimensions.

G.3.2 Step 1: determination of the representative overvoltages – values of U_{rp}

G.3.2.1 General

The representative temporary and slow-front overvoltages are usually determined from system studies (transient network analyser or digital simulation or a combination of both). For this example, results from such studies confirmed the following values:

- temporary overvoltages: $U_{rp} = 660$ kV (RMS, phase-to-earth);
- slow-front overvoltages: $U_{e2} = 1\,200$ kV (peak, phase-to-earth; phase-peak method).

G.3.2.2 Power-frequency and temporary overvoltages

The high level of temporary overvoltage (1,5 p.u.) is associated with situations involving long lines radially fed after a major load rejection. For systems in range II, the two standard withstand voltages normally specified are the lightning and the switching impulse levels. The conversion of the required short-duration power-frequency withstand voltage into an equivalent required switching impulse withstand voltage is discussed under step 4 (G.3.5) of this example.

G.3.2.3 Slow-front overvoltages

The slow-front overvoltage is related to line reclosing and is limited to about 2,0 p.u. by the use of closing resistors implemented on line circuit breakers.

The surge arrester rating is also determined from these same system studies (normally from the temporary overvoltage characteristics: amplitude and duration) and, for the particular case of this example, the following protection levels were determined:

- switching impulse ~~protective~~ protection level: $U_{ps} = 1\,300$ kV (peak value);
- lightning impulse ~~protective~~ protection level: $U_{pl} = 1\,500$ kV (peak value).

G.3.2.4 Fast-front overvoltages

The simplified statistical method for fast-front overvoltages will be used, leading directly to the co-ordination withstand voltage.

In this step and those that follow, only the phase-to-earth insulation is considered. Phase-to-phase insulation co-ordination will be treated at the end of the example as a separate item (see G.3.7).

G.3.3 Step 2: determination of the co-ordination withstand voltages – values of U_{cw}

G.3.3.1 General

The co-ordination withstand voltage is obtained by applying a co-ordination factor (K_c) to the representative overvoltages, this factor being either K_{cd} for the deterministic method or K_{cs} for the statistical method. Thus the determination of the co-ordination withstand voltages ~~must~~ **shall** be carried out for internal insulation (such as transformers) and external insulation separately.

G.3.3.2 U_{cw} for internal insulation

G.3.3.2.1 General

In this step, the determination of U_{cw} for internal insulation is carried out for power-frequency, slow-front and fast-front overvoltages.

G.3.3.2.2 U_{cw} for temporary overvoltages

For this class of overvoltages, the co-ordination withstand voltage is equal to the representative temporary overvoltage (refer to 5.3.2). In other words, the co-ordination factor $K_c = 1$. Therefore:

- phase-to-earth: $U_{cw} = 660$ kV.

G.3.3.2.3 U_{cw} for slow-front overvoltages

For equipment protected by surge arresters, the maximum slow-front overvoltage (and thus the slow-front representative overvoltage) is equal to the switching-impulse ~~protective~~ **protection** level of the surge arrester, namely 1 300 kV.

This value of 1 300 kV ~~must~~ **shall** be adjusted by the co-ordination factor K_{cd} to account for the skewing of the statistical distribution of the slow-front overvoltages as discussed in 5.3.3.1. It can be seen from Figure 4 that for a ratio of $U_{ps} / U_{e2} = 1,08$ (1 300 / 1 200) the value of K_{cd} is 1,03. Hence, the co-ordination withstand voltage for slow-front surges is 1 340 kV:

- representative slow-front overvoltage: $U_{rp} = 1\,300$ kV;
- deterministic co-ordination factor: $K_{cd} = 1,03$ kV;
- co-ordination withstand voltage: $U_{cw} = 1\,340$ kV.

G.3.3.2.4 U_{cw} for fast-front overvoltages

For equipment protected by surge arresters, the maximum fast-front overvoltage (and thus the fast-front representative overvoltage) is equal to the lightning-impulse ~~protective~~ **protection** level of the surge arrester, namely 1 500 kV.

However, to this value of 1 500 kV, one ~~must~~ **shall** add a voltage equal to $AL/(n(L_{sp} + L_a))$ according to Equation (E.19) to take into account the separation distance L between the surge arrester and the protected equipment, as explained in 4.3.4.5.

The parameters are obtained as follows:

- A : from Table E.2 (for an assumed four conductor bundle) is 11 000;
- n : the minimum number of connected overhead lines is assumed equal to two for this example;

- L : is equal to $a_1 + a_2 + a_3 + a_4$ according to Figure 3; is assumed equal to 40 m for this example;
- L_{sp} : length of the first line span is assumed equal to 400 m for this example;
- L_a : length of overhead line section with flashover rate equal to the acceptable failure rate. If the acceptable failure rate is assumed to be $1/(500 \text{ year})$ or $0,002/\text{year}$ and the line lightning flashover rate is $0,15/(100 \text{ km}\cdot\text{year})$, then L_a is 1,3 km.

Then, the separation term $AL/(n(L_{sp} + L_a))$ is 130 kV.

- Representative fast-front overvoltage: $U_{rp} = 1\,500 \text{ kV}$.
- Correction value for separation: 130 kV.
- Co-ordination withstand voltage: $U_{cw} = 1\,630 \text{ kV}$.

G.3.3.3 U_{cw} for external insulation

G.3.3.3.1 General

Determination of the co-ordination withstand voltage for external insulation is carried out for slow-front overvoltages using the statistical method because of the nature of the insulation. A statistical method could also be applied to fast-front overvoltages but this is generally not necessary for voltages in range II; refer to G.3.3.3.3 below.

G.3.3.3.2 U_{cw} for temporary overvoltages

These are the same as for the internal insulation (G.3.3.2.2).

G.3.3.3.3 U_{cw} for slow-front overvoltages

The value of the statistical co-ordination factor K_{cs} comes from choosing a risk of failure of the insulation that has been proven from experience to be acceptable. The relation between the risk of failure R and K_{cs} is shown in Figure 8 and, for a usually acceptable value of R in the range of 10^{-4} , the value of K_{cs} is 1,15. Hence the co-ordination withstand voltage is $U_{cw} = 1\,200 \text{ kV} \times 1,15 = 1\,380 \text{ kV}$:

- statistical overvoltage: $U_{e2} = 1\,200 \text{ kV}$;
- statistical co-ordination factor: $K_{cs} = 1,15$;
- co-ordination withstand voltage: $U_{cw} = 1\,380 \text{ kV}$.

G.3.3.3.4 U_{cw} for fast-front overvoltages

The determination of the co-ordination withstand voltage for fast-front overvoltage is not necessary since the lightning impulse withstand voltage of the minimum clearances that result from the switching impulse withstand voltage will be far in excess of those that should be determined solely by the lightning impulse withstand voltage required for the non-self-restoring insulation.

~~This is demonstrated at the end of this example when the question of air clearance to ground is discussed.~~

G.3.4 Step 3: determination of the required withstand voltages – values of U_{rw}

G.3.4.1 General

The required withstand voltage is obtained by applying a safety factor K_s to the co-ordination withstand voltage as explained in 6.3.5. The values of K_s are given as:

- for internal insulation: $K_s = 1,15$;
- for external insulation: $K_s = 1,05$.

For external insulation, an atmospheric correction factor K_a is also applied (refer to G.3.4.3 below).

G.3.4.2 U_{rw} for internal insulation

The values of U_{rw} for internal insulation are as follows:

- U_{cw} for temporary overvoltages: $U_{cw} = 660$ kV;
- safety factor: $K_s = 1,15$;
- U_{rw} for temporary overvoltages: $U_{rw} = 759$ kV;
- U_{cw} for slow-front overvoltages: $U_{cw} = 1\,340$ kV;
- safety factor: $K_s = 1,15$;
- U_{rw} for slow-front overvoltages: $U_{rw} = 1\,540$ kV;
- U_{cw} for fast-front overvoltages: $U_{cw} = 1\,630$ kV;
- safety factor: $K_s = 1,15$;
- U_{rw} for fast-front overvoltages: $U_{rw} = 1\,875$ kV.

G.3.4.3 U_{rw} for external insulation

For power-frequency, the atmospheric correction factor is determined assuming a short-duration power-frequency test on polluted insulators is required, for which $m = 0,5$ and assuming $H = 1\,000$ m, $K_a = 1,063$.

Hence, $U_{rw} = 660 \times 1,063 \times 1,05 = 737$ kV:

- U_{cw} for temporary overvoltages: $U_{cw} = 660$ kV;
- atmospheric correction factor: $K_a = 1,063$;
- safety factor: $K_s = 1,05$;
- U_{rw} for temporary overvoltage: $U_{rw} = 737$ kV.

The atmospheric correction factor K_a for slow-front overvoltages is based on the assumed altitude as explained in 6.2.2 and Equation (11). For $H = 1\,000$ m and $m = 0,6$ (from Figure 9), then $K_a = e^{0,07} = 1,07$. Hence $U_{rw} = 1\,380$ kV $\times 1,07 \times 1,05 = 1\,550$ kV:

- U_{cw} for slow-front overvoltages: $U_{cw} = 1\,380$ kV;
- atmospheric correction factor: $K_a = 1,07$;
- safety factor: $K_s = 1,05$;
- U_{rw} for slow-front overvoltages: $U_{rw} = 1\,550$ kV.

G.3.5 Step 4: conversion to switching impulse withstand voltages (SIWV)

Referring to 7.1, the required short-duration power-frequency withstand voltages are converted to an equivalent switching impulse withstand voltage (SIWV), according to Table 2.

- For internal insulation: $SIWV = 759 \times 2,3 = 1\,746$ kV.
- For external insulation: $SIWV = 737 \times 1,7 = 1\,253$ kV.

G.3.6 Step 5: selection of standard insulation levels

G.3.6.1 General

The standard withstand voltages U_w are obtained from the required withstand voltages by choosing the next highest value from the standard values listed in IEC 60071-1.

G.3.6.2 U_w for internal insulation

For the temporary overvoltage stresses, a switching withstand voltage of 1 750 kV would be required according to step 4. Considering this last requirement, many options are available. At first, a value of 1 750 kV is not standardized in IEC 60071-1, the highest one being 1 550 kV, so that a switching test at such a value would be considered as a special one. Another option is to realize an alternative test, as mentioned in 5.4 of IEC 60071-1:2006, to verify the withstand of internal insulation to power-frequency. For this example, an applied voltage test at a minimum value of 660 kV (1,5 p.u.) for a minimum duration of 1 min is required. It is recommended to refer to standards issued by the relevant apparatus committee (as for power transformers) which give more detailed information relative to such a test. For instance, to avoid saturation, such a test is performed with a source whose frequency is three or four times the nominal frequency. Also, fixed values are recommended for voltages and durations associated with the different cycles involved in such a test (such as 1,7 p.u. during 7 200 periods followed by 1,5 p.u. for 1 h).

- U_{rw} for slow-front overvoltages: $U_{rw} = 1\,540\text{ kV}$.
- Standard switching-impulse withstand voltage: $U_w = 1\,550\text{ kV}$.
- U_{rw} for fast-front overvoltages: $U_{rw} = 1\,875\text{ kV}$.
- Standard lightning impulse withstand voltage: $U_w = 1\,950\text{ kV}$.

G.3.6.3 U_w for external insulation

The lightning impulse withstand voltage of 1 950 kV would apply to the external insulation of equipment protected by arresters, such as transformers and shunt reactors.

In the case of equipment remotely located from the surge arresters such as current transformers, circuit-breakers, disconnectors and buswork busbar, the separation distance (see 4.3.4.5) has a greater impact and for this example it is decided to choose one step higher in the lightning impulse withstand voltage. Hence, for this equipment the standard lightning-impulse withstand voltage is $U_w = 2\,100\text{ kV}$.

- U_{rw} for slow-front overvoltages: $U_{rw} = 1\,550\text{ kV}$.
- Standard switching impulse withstand voltage: $U_w = 1\,550\text{ kV}$.
- Standard lightning impulse withstand voltage (protected equipment): $U_w = 1\,950\text{ kV}$.
- Standard lightning impulse withstand voltage (unprotected equipment): $U_w = 2\,100\text{ kV}$.

The standard switching impulse withstand voltage of 1 550 kV is more than sufficient to cover the required switching impulse withstand voltage of 1 253 kV converted from the power-frequency requirements (external insulation).

G.3.7 Considerations relative to phase-to-phase insulation co-ordination

The phase-to-phase dielectric strength of the external insulation of three-phase equipment is usually tested with equal impulses of positive and negative polarity. The actual test values are determined from a consideration of the positive and negative slow-front overvoltages (which are the most critical) as explained in Clause C.4. Based on G.3.7, the assumption is made that $B = 0,6$ from which $F_1 = 0,463$ and $F_2 = 0,074$. In this example, the value of B ($B = \tan \phi$) comes from Figure C.5 which gives an inclination angle $\phi \cong 30^\circ$ for the considered three-phase equipment (height above earth $\cong 16\text{ m}$ and phase-to-phase distance $\cong 8\text{ m}$). The required test voltages are obtained as follows:

- phase-to-earth slow-front overvoltage: $U_{e2} = 1\,200\text{ kV}$;
- phase-to-phase slow-front overvoltage: $U_{p2} = 2\,040\text{ kV}$.

The phase-to-earth slow-front overvoltage was determined in G.3.2. The phase-to-phase slow-front overvoltage is found from Figure 2: at $U_{e2} = 1,92\text{ p.u.}$, the ratio of U_{p2}/U_{e2} is 1,7 which gives $U_{p2} = 2\,040\text{ kV}$. Equation (C.14) gives the phase-to-phase representative overvoltage:

$$U_{p2-re} = 2 (F_1 U_{p2} + F_2 U_{e2}) = 2\,067 \text{ kV}.$$

The co-ordination phase-to-phase withstand voltage is obtained applying a co-ordination factor $K_{cs} = 1,15$:

$$U_{p-cw} = K_{cs} U_{p2-re} = 2\,377 \text{ kV}.$$

The required phase-to-phase withstand voltage is based on an altitude correction factor $K_a = 1,07$ and a safety factor $K_s = 1,05$ (the same procedure as for phase-to-earth insulation, see G.3.4):

$$U_{p-rw} = K_a K_s U_{p-cw} = 2\,670 \text{ kV}.$$

Test values are thus specified as $\pm 1\,335 \text{ kV}$ but, as these are not standard values, the test itself is not a standard test since there is very little three-phase equipment at the 735 kV level.

For the temporary overvoltage, we have a representative overvoltage of 660 kV phase-to-earth from step 1 yielding a phase-to-phase voltage of 1 143 kV. This results in the same value for the co-ordination withstand voltage since $K_c = 1,0$ as in step 2. Applying the safety factors and atmospheric correction factors, we obtain the required withstand voltages:

- internal insulation: $U_{rw} = 1\,143 \times 1,15 = 1\,314 \text{ kV}$;
- external insulation: $U_{rw} = 1\,143 \times 1,063 \times 1,05 = 1\,276 \text{ kV}$.

These are converted into phase-to-phase switching impulse withstand voltages (SIWV):

- internal insulation: $SIWV = 1\,314 \times 2,3 = 3\,022 \text{ kV}$;
- external insulation: $SIWV = 1\,276 \times 1,7 = 2\,169 \text{ kV}$.

The previously determined switching impulse test voltage of 2 670 kV is adequate to cover the external insulation power-frequency requirement but not the internal insulation. Special measures as described in G.3.6.2 would be required.

G.3.8 Phase-to-earth clearances

The required phase-to-earth clearance for switching impulses can be obtained from ~~table A.2 IEC 60071-1~~ and a standard switching impulse withstand voltage of 1 550 kV.

For the conductor-structure configuration (slow-front gap factor $K = 1,35$), the minimum clearance is 4 900 mm. For the rod-structure configuration (slow-front gap factor $K < 1,15$), the minimum clearance is 6 400 mm. The lightning impulse withstand voltage of such clearances can be estimated from the equations given in Annex F. Using Equation (F.7) to obtain the equivalent fast-front gap factors, we obtain:

- conductor-structure: $K_{ff}^+ = 0,74 + 0,26 \times 1,35 = 1,05$;
- rod-structure: $K_{ff}^+ = 0,74 + 0,26 \times 1,15 = 1,04$.

Using $K_{ff}^+ = 1,04$ to be conservative, we obtain from Equations (F.6) and (F.7):

- $U_{50RP} = K_{ff}^+ 530 d = 1,04 \times 530 \times 4,9 = 2\,700 \text{ kV}$; and
- $LIWV = U_{50RP} - 1,3 Z = U_{50RP} (1 - 1,3 z) = 2\,700 (1 - 1,3 \times 0,03) = 2\,595 \text{ kV}$,

which is well above the standard lightning impulse withstand voltage of 2 100 kV from G.3.6.3.

G.3.9 Phase-to-phase clearances

The required phase-to-phase clearance can be obtained from Equation (C.12) which states that $U_0^+ = U^+ + BU^-$ where U_0^+ is an equivalent phase-to-earth voltage that represents the effect of a positive voltage on one phase (U^+) and a negative voltage on the other phase (U^-). From the work carried out in G.3.7, with the values of $U^+ = U^- = 1\,335$ kV and with $B = 0,6$, one can find U_0^+ as:

$$U_0^+ = 1\,335 \times 1,6 = 2\,136 \text{ kV}$$

The corresponding value of U_{50} is given by $U_{50} = U_{10} / 0,922 = 2\,317$ kV; d is obtained from Equations (F.3) and (F.5), and for gap factors $K = 1,62$ (parallel conductor configuration) and $K = 1,45$ (rod-conductor configuration):

$$2\,317 = K\,1\,080 \ln(0,46\,d + 1)$$

from which phase-to-phase clearances are:

- conductor-conductor: $d = 6,0$ m;
- rod-conductor: $d = 7,4$ m.

From ~~table A.3~~ IEC 60071-1, a standard phase-to-earth switching impulse withstand voltage of 1 550 kV leads to standard phase-to-phase minimum clearances of 7,6 m (conductor-conductor) and 9,4 m (rod-conductor). Therefore, use of the above-calculated clearances would require a special test.

G.4 Numerical example for substations in distribution systems with U_m up to 36 kV in range I

G.4.1 General

For equipment in this voltage range, IEC 60071-1 specifies standard rated short-duration power-frequency and lightning impulse withstand voltages. The selection of these values is illustrated in Table G.3 for $U_m = 24$ kV, where the values are examples and not valid for general application.

For the purpose of this example, one will assume the following basic data:

- the highest system voltage is: $U_s = 24$ kV;
- the pollution level is: light;
- the altitude is: $H = 1\,000$ m.

The altitude level here is assumed to cover all possible locations.

G.4.2 Step 1: determination of the representative overvoltages – values of U_{rp}

G.4.2.1 Power-frequency and temporary overvoltages

Owing to the neutral earthing practice, the highest overvoltages phase-to-earth originate from earth faults. Values up to the highest system voltage are frequent. In this example, the representative temporary overvoltage is the assumed maximum value equal to the highest system voltage 24 kV.

Overvoltages phase-to-phase originate from load rejections. A full load rejection in the distribution system itself does not cause substantial high overvoltages. However, a load rejection in the transmission system, to which the distribution system is connected, may have to be considered. In this example it is assumed that the load rejection temporary overvoltage reaches 1,15 times the highest system voltage, which is $1,15 \times U_s = 27,6$ kV or approximately

28 kV. This value is assumed to be the highest possible voltage stress and thus is the representative temporary phase-to-phase overvoltage: $U_{rp} = 28$ kV.

G.4.2.2 Slow-front overvoltages

Slow-front overvoltages may originate from earth faults or line energization or re-energization. As distribution transformers usually remain connected during a re-energization of lines, and as the reclosing is not fast, the presence of trapped charges is improbable. The re-energization overvoltages, therefore, have the same probability distribution as those due to energization. The 2 % values in Table G.3 are selected according to Annex C for the phase-peak method taking into account the usual operation conditions, no closing resistors, complex feeding network and no parallel compensation. The 2 % values are assumed to be $u_{e2} = 2,6$ p.u. (phase-to-earth) and $u_{p2} = 3,86$ p.u. (phase-to-phase).

As the deterministic insulation co-ordination procedure is sufficient for distribution systems and as surge arresters do not usually limit slow-front overvoltages in this voltage range, the representative slow-front overvoltages U_{rp} are considered to correspond to the truncation values U_{et} and U_{pt} of the overvoltage probability distributions. With the equations of Annex C, the truncation values are obtained: $u_{et} = 3,0$ p.u. which leads to $U_{rp} = 59$ kV phase-to-earth and $u_{pt} = 4,4$ p.u. which leads to $U_{rp} = 86$ kV phase-to-phase.

G.4.2.3 Fast-front overvoltages

With the exception of motor switching by some type of circuit-breakers, fast-front overvoltages due to switching operations can be neglected.

Fast-front lightning overvoltages are transmitted on the lines connected to the substation. The simplified method described in Clause E.4 is applied to estimate the return periods of the representative lightning overvoltage amplitudes. No reference value is specified and, therefore, no value can be given in Table G.3.

G.4.3 Step 2: determination of the co-ordination withstand voltages – values of U_{cw}

G.4.3.1 Temporary overvoltages

As the previously defined representative temporary overvoltages correspond to the maximum assumed voltage stresses, the deterministic insulation co-ordination procedure is applicable (see Clause 5). The deterministic co-ordination factor is $K_c = 1$ and the resulting co-ordination power-frequency withstand voltages U_{cw} correspond to the representative overvoltage values U_{rp} ($U_{cw} = K_c \cdot U_{rp} = U_{rp}$).

G.4.3.2 Slow-front overvoltages

The co-ordination withstand voltages U_{cw} are obtained as: $U_{cw} = K_{cd} U_{rp}$. The deterministic co-ordination factor is $K_{cd} = 1$ because the insulation co-ordination procedure is applied to the truncation values of the overvoltage distributions (no skewing effect as discussed in 5.3.3.1). Therefore, in this example, values of the co-ordination withstand voltages are the same as those for representative slow-front overvoltages: $U_{cw} = 59$ kV phase-to-earth and $U_{cw} = 86$ kV phase-to-phase.

G.4.3.3 Fast-front overvoltages

For the determination of the co-ordination lightning impulse withstand voltages, the following values are assumed:

- the arrester lightning impulse protection level is $U_{pl} = 80$ kV;
- four wood-pole lines ($n = 4$) are connected to the station. Referring to Table E.2, the corresponding value for the factor A is 2 700;

- the observed overhead line outage rate is $R_{km} = 6/(100 \text{ km} \cdot \text{year})$ or, in the recommended units, $R_{km} = 6 \times 10^{-5}/(\text{m} \cdot \text{year})$;
- the span length is $L_{sp} = 100 \text{ m}$;
- the acceptable failure rate is $R_a = 1/400 \text{ year}$.

As it is common practice to install arresters close to the power transformers, the separation distance may be different for internal insulation (example: 3 m) and external insulation (example: 5 m). Therefore, the co-ordination withstand voltages values U_{cw} may be different for different equipment.

With these values, the overhead line section, in which the outage rate will be equal to the acceptable failure rate, will be in accordance with Equation (E.18):

$$L_a = 42 \text{ m}$$

This means that protection is required for lightning strokes to the first span of the overhead line.

The co-ordination lightning impulse withstand voltages are obtained according to Equation (E.19) as $U_{cw} = 94 \text{ kV}$ for internal insulation (power transformer, distance to the arrester = 3 m) and $U_{cw} = 104 \text{ kV}$ for the more distant external insulation.

G.4.4 Step 3: determination of required withstand voltages – values of U_{rw}

G.4.4.1 General

The required withstand voltages are obtained by applying the recommended safety factors (see 6.3.5) and the altitude correction (see 6.2.2). For the example given, it is assumed that substations of the same design shall be used up to altitudes of 1 000 m.

G.4.4.2 Safety factors

The recommended safety factors from 6.3.5 are:

- for internal insulation: $K_s = 1,15$;
- for external insulation: $K_s = 1,05$.

G.4.4.3 Altitude correction factor

The altitude correction factor is defined in 6.2.2. It is applicable to the external insulation only and its value depends on the overvoltage shape (parameter m in Equation (11)).

- For power-frequency (clean insulators), $m = 1,0$.
- For slow-front overvoltages, the value of m depends on the value of U_{cw} . For values of U_{cw} less than 300 kV phase-to-earth or 1 200 kV phase-to-phase, $m = 1,0$.
- For lightning impulse withstand, $m = 1,0$ and $K_a = 1,13$.

G.4.4.4 Temporary overvoltage

The temporary overvoltage values are as follows:

- Phase-to-earth:
 - internal insulation $\Rightarrow U_{rw} = U_{cw} \times 1,15 = 24 \times 1,15 = 28 \text{ kV}$;
 - external insulation $\Rightarrow U_{rw} = U_{cw} \times 1,05 \times 1,13 = 24 \times 1,05 \times 1,13 = 28 \text{ kV}$.
- Phase-to-phase:
 - internal insulation $\Rightarrow U_{rw} = U_{cw} \times 1,15 = 28 \times 1,15 = 32 \text{ kV}$;

- external insulation $\Rightarrow U_{rw} = U_{cw} \times 1,05 \times 1,13 = 28 \times 1,05 \times 1,13 = 33 \text{ kV}$.

G.4.4.5 Slow-front overvoltage

The slow-front overvoltage values are as follows:

- Phase-to-earth:
 - internal insulation $\Rightarrow U_{rw} = U_{cw} \times 1,15 = 59 \times 1,15 = 68 \text{ kV}$;
 - external insulation $\Rightarrow U_{rw} = U_{cw} \times 1,05 \times 1,13 = 59 \times 1,05 \times 1,13 = 70 \text{ kV}$.
- Phase-to-phase:
 - internal insulation $\Rightarrow U_{rw} = U_{cw} \times 1,15 = 86 \times 1,15 = 99 \text{ kV}$;
 - external insulation $\Rightarrow U_{rw} = U_{cw} \times 1,05 \times 1,13 = 86 \times 1,05 \times 1,13 = 102 \text{ kV}$.

G.4.4.6 Fast-front overvoltage

The fast-front overvoltage values are as follows:

- internal insulation: $\Rightarrow U_{rw} = U_{cw} \times 1,15 = 95 \times 1,15 = 109 \text{ kV}$;
- external insulation: $\Rightarrow U_{rw} = U_{cw} \times 1,05 \times 1,13 = 95 \times 1,05 \times 1,13 = 125 \text{ kV}$.

G.4.5 Step 4: conversion to standard short-duration power-frequency and lightning impulse withstand voltages

G.4.5.1 General

For the selection of the standard withstand voltages in Table 2 of IEC 60071-1:2006, the required switching impulse withstand voltages are converted into short-duration power-frequency withstand voltages and into lightning impulse withstand voltages by applying the test conversion factors of Table 2 (for internal insulation, factors corresponding to liquid-immersed insulation are selected).

G.4.5.2 Conversion to short-duration power-frequency withstand voltage (SDWV)

The conversion values to SDWV are as follows:

- Phase-to-earth:
 - internal insulation $\Rightarrow \text{SDWV} = U_{rw} \times 0,5 = 68 \times 0,5 = 34 \text{ kV}$;
 - external insulation $\Rightarrow \text{SDWV} = U_{rw} \times 0,6 = 70 \times 0,6 = 42 \text{ kV}$.
- Phase-to-phase:
 - internal insulation $\Rightarrow \text{SDWV} = U_{rw} \times 0,5 = 99 \times 0,5 = 50 \text{ kV}$;
 - external insulation $\Rightarrow \text{SDWV} = U_{rw} \times 0,6 = 102 \times 0,6 = 61 \text{ kV}$.

G.4.5.3 Conversion to lightning impulse withstand voltage (LIWV)

The conversion values to LIWV are as follows:

- Phase-to-earth:
 - internal insulation $\Rightarrow \text{LIWV} = U_{rw} \times 1,10 = 68 \times 1,1 = 75 \text{ kV}$;
 - external insulation $\Rightarrow \text{LIWV} = U_{rw} \times 1,06 = 70 \times 1,06 = 74 \text{ kV}$.
- Phase-to-phase:
 - internal insulation $\Rightarrow \text{LIWV} = U_{rw} \times 1,10 = 99 \times 1,1 = 109 \text{ kV}$;
 - external insulation $\Rightarrow \text{LIWV} = U_{rw} \times 1,06 = 102 \times 1,06 = 108 \text{ kV}$.

G.4.6 Step 5: selection of standard withstand voltages

Table 2 of IEC 60071-1:2006 gives, for $U_m = 24$ kV, a standard short-duration power-frequency withstand voltage of 50 kV. This is adequate to cover the requirements for temporary overvoltage and all slow-front overvoltages except the phase-to-phase requirement for external insulation which can be accommodated by adequate air clearances. Table 2 of IEC 60071-1:2006 provides three possible values for the standard lightning impulse withstand voltage for $U_m = 24$ kV. Selection of a value of 125 kV covers the lightning impulse requirement as well as the switching impulse withstand voltage for external phase-to-phase insulation.

G.4.7 Summary of insulation co-ordination procedure for the example of Clause G.4

Table G.3 summarizes values obtained while completing the insulation co-ordination procedure for this example, for a considered maximum operating voltage $U_s = 24$ kV.

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Table G.3 – Values related to the insulation co-ordination procedure for the example in G.4

Type of overvoltage		Temporary				Slow-front				Fast-front	
		Phase-to-earth		Phase-to-phase		Phase-to-earth		Phase-to-phase		Phase-to-earth and phase-to-phase	
		Internal	External	Internal	External	Internal	External	Internal	External	Internal	External
Step 1 Representative voltage stresses in service	Insulation										
		24 kV	24 kV	28 kV	28 kV	59 kV	59 kV	86 kV	86 kV	—	—
Step 2 Co-ordination withstand voltages	Values of U_{rp} Values of K_c or K_{cd} Values of U_{cw}	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	—	—
		24 kV	24 kV	28 kV	28 kV	59 kV	59 kV	86 kV	86 kV	95 kV	105 kV
Step 3 Required withstand voltages	Safety factor K_s Altitude correction K_a Values of U_{rw}	1,15	1,05	1,15	1,05	1,15	1,05	1,15	1,05	1,15	1,05
		—	1,13	1,13	1,13	—	1,13	—	1,13	—	1,13
Step 4 Standard withstand voltages	1) Test conversion factors 2) Resulting required withstand voltages	28 kV	28 kV	32 kV	33 kV	68 kV	70 kV	99 kV	102 kV	109 kV	125 kV
		To short-duration power-frequency To lightning impulse				0,5	0,6	0,5	0,6		
Step 5 Selection of standard withstand voltages	Short duration power-frequency Lightning impulse					34 kV	42 kV	50 kV	61 kV		
		Short-duration power-frequency 50 kV				75 kV	74 kV	109 kV	108 kV	Lightning impulse 125 kV	

Annex H (informative)

Atmospheric correction – Altitude correction

H.1 General principles

H.1.1 Atmospheric correction in standard tests

IEC 60060-1 specifies the atmospheric correction factors for testing of air clearances and insulators with the standardized

- short-duration power-frequency voltage,
- switching impulse voltage,
- lightning impulse withstand voltage, and
- direct voltage.

Direct test voltages are disregarded here, because such tests are not required for systems within the scope of IEC 60071-1.

The standard insulation levels of external insulation refer to the standard reference atmosphere as given in IEC 60071-1:2006, 5.9.2, and IEC 60060-1:2010, 4.3.1.

The standard reference atmosphere is:

- ambient air temperature ϑ_0 : 20 °C
- absolute air pressure p_0 : 1 013 hPa (1 013 mbar)
- absolute air humidity h_0 : 11 g/m³

NOTE Deviating from the standards mentioned above, the letter symbol ϑ is used here for ambient air temperature to be in line with the common usage in scientific literature.

Any deviation of air temperature, pressure or humidity from these reference values will affect the dielectric strength of the external insulation. These deviations have to be corrected in the test to verify a certain standard insulation as required in IEC 60060-1:2010, 4.3. In accordance with this document, the atmospheric correction factor is defined as

$$K_t(t) = k_1 \times k_2 \quad (\text{H.1})$$

where

k_1 is the air density correction factor;

k_2 is the humidity correction factor.

$K_t(t)$ is time dependent according to the varying conditions in the considered time period (seasons or years) and corresponds with the correction factor K_t of IEC 60060-1 for the moment of test.

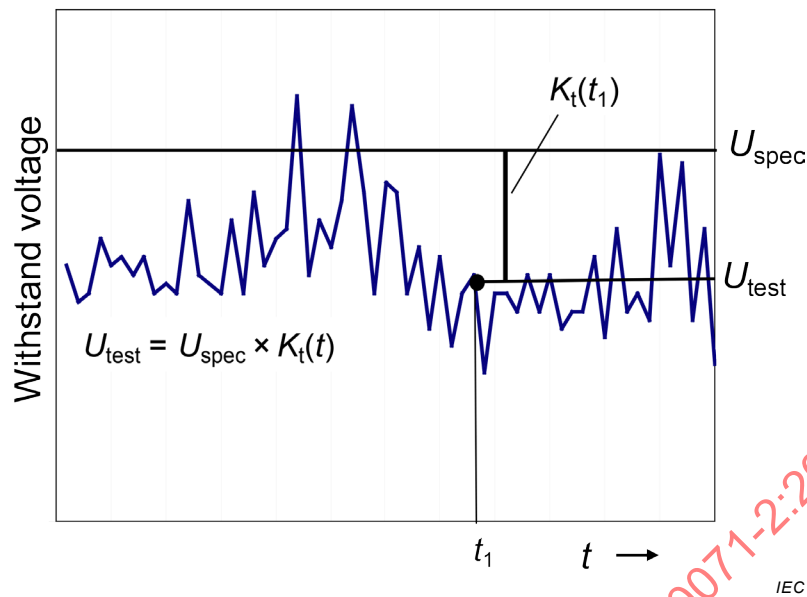


Figure H.1 – Principle of the atmospheric correction during test of a specified insulation level according to the procedure of IEC 60060-1

The principles of the atmospheric correction during tests are outlined in Figure H.1. The atmospheric conditions at the test location vary throughout for example the year. Therefore, the atmospheric correction factor $K_t(t)$ at the time of testing and the voltage U_{test} to be applied to the test object vary accordingly to prove the specified voltage U_{spec} , which is related to the standard reference atmosphere and normally in line with the standard withstand voltages according to IEC 60071-1 and applicable product standards.

$$U_{\text{spec}} = \frac{U_{\text{test}}}{K_t(t)} \quad (\text{H.2})$$

During testing, by considering the atmospheric condition, the altitude of the test location is covered by the atmospheric correction of IEC 60060-1. The altitude correction of standard insulation levels has no relation to testing in a certain location at a certain time.

H.1.2 Task of atmospheric correction in insulation co-ordination

The actual withstand voltage of external insulation of equipment in service $U_{10}(t)$ varies over the year in the same way as during testing according to IEC 60060-1. The atmospheric correction factor and the safety correction factor used in insulation co-ordination have to cover these variations in order to achieve the specified insulation when stressing external insulation with these atmospheric conditions.

The task of insulation co-ordination is to determine one required withstand voltage value that results in an acceptable risk-of-flashover taking into account the varying withstand voltage over the life time of the equipment.

Based on the co-ordination withstand voltage, the correction has to be chosen in the way that the required withstand voltage covers sufficiently the actual withstand voltages in service:

$$U_{\text{rw}} = \frac{K_s \times U_{\text{cw}}}{K_t} \quad (\text{H.3})$$

where

U_{rw} is the required withstand voltage;

U_{cw} is the co-ordination withstand voltage;

K_s is the safety factor;

K_t is the atmospheric correction factor (selected value out of $K_t(t)$).

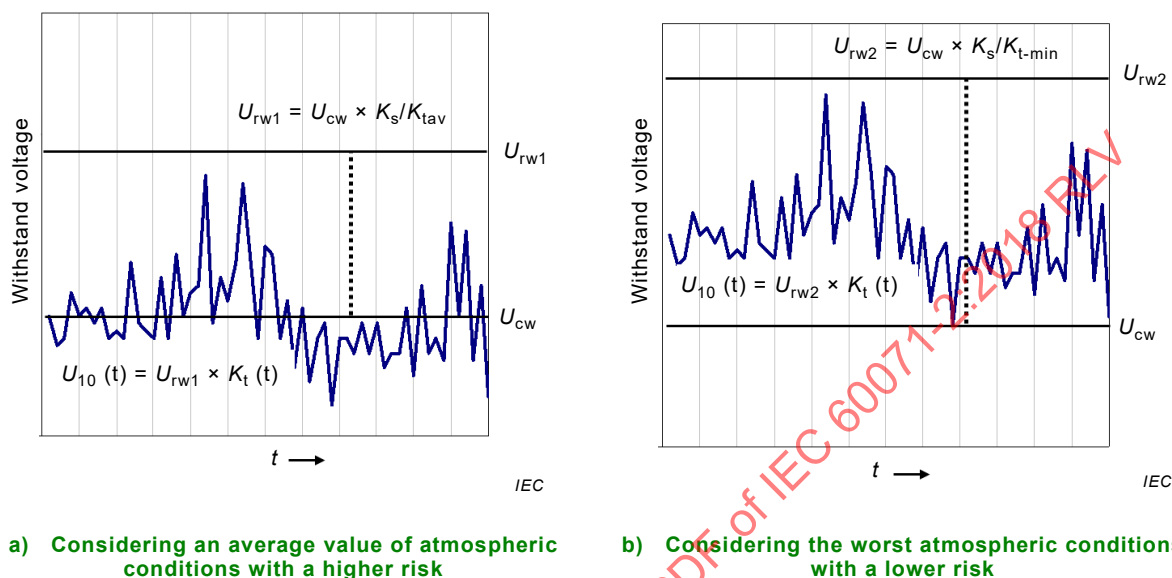


Figure H.2 – Principal task of the atmospheric correction in insulation co-ordination according to IEC 60071-1

Figure H.2 shows this procedure in principle. In Figure H.2 a), the correction is based on an average value of atmospheric correction K_{tav} resulting in a required withstand voltage U_{rw1} , which covers the actual time dependent withstand voltage of equipment $U_{10}(t)$. Considering the worst atmospheric condition with K_{t-min} will lead to a higher required withstand voltage U_{rw2} as shown in Figure H.2 b). This includes a lower risk of failure in comparison to Figure H.2 a).

The safety factor K_s is increasing the required withstand voltage by a constant factor and has to be considered in the process of insulation co-ordination. For convenient reading, it is neglected in the following.

From the required withstand voltage U_{rw} results a standard rated withstand voltage U_w according to IEC 60071-1, which normally is the voltage U_{spec} applied during a withstand test after atmospheric correction with $K_t(t)$ according to IEC 60060-1.

The atmospheric correction according to IEC 60060-1 can only be performed when all necessary data for the atmospheric conditions, the required insulation level of the equipment and the dimensions of the equipment are known. For the specification of the required withstand voltages in the insulation co-ordination process of IEC 60071-1, these data are frequently not fully available, and simplifications have to be adopted to determine the required withstand voltages. The application of atmospheric correction can be simplified in most cases by using an altitude correction factor only. The validation of this simplification and the limits of its application are shown in the following Clauses H.2 to H.4.

H.2 Atmospheric correction in insulation co-ordination

H.2.1 Factors for atmospheric correction

For air clearances and dry insulators, the atmospheric correction factor K_t is given in IEC 60060-1 as

$$K_t = k_1 \times k_2 = \delta^m \times k_h^w \quad (\text{H.4})$$

where

δ is the relative air density;

k_h is the parameter for humidity depending on air density and test voltage;

m, w are the exponents depending on parameter g (each parameter is defined in IEC 60060-1).

For configurations with inhomogeneous electric field distributions under impulse voltages, as they are usually present in the higher voltage ranges, the parameter g is always below 1,2. In this range of g the exponents are equal:

$$m = w \quad (\text{H.5})$$

With this simplification, for $g \leq 1,2$, the atmospheric correction factor to be applied to the voltages stressing the air clearances of equipment is given by

$$K_t = (\delta \times k_h)^m \quad (\text{H.6})$$

With δ and k_h as defined in IEC 60060-1, a detailed equation for the atmospheric correction K_t with the three atmospheric parameters pressure, temperature and humidity and exponent m is given.

H.2.2 General characteristics for moderate climates

To find an overall valid atmospheric correction for the location of installation, the variations of the weather conditions over the year have to be investigated.

Generally, the relative air density δ is high in winter time due to the low temperature and low in summer due to the high temperature. The humidity, described by correction factor k_h , shows the opposite trend. For the overall correction $\delta \times k_h$ the values of relative air density and humidity compensate each other. The variation of the overall correction $\delta \times k_h$ over the year is much smaller than the variation of the air density alone owing to the compensating influence of the humidity.

This situation is valid also for high altitudes. Although the relative air density δ is low due to the high altitude, and humidity correction factor k_h is low due to low temperature, both are following the same trend as at the stations on sea level.

Owing to the strong correlation between temperature and absolute humidity, it is appropriate to separate the atmospheric correction into two parts (Equation (H.7)), which seem to be independent one from each other: One factor being the air pressure related to the reference pressure (p/p_0), the second factor being the inverted relative temperature multiplied by the humidity correction factor ($T_0/T \times k_h$).

$$K_t = [\delta \times k_h]^m = \left[\frac{p}{p_0} \times \frac{T_0}{T} \times k_h \right]^m \quad (\text{H.7})$$

Due to the compensation effect, the term $(T_0/T \times k_h)$ is nearly equal to 1 for all altitudes. The given relation is valid for regions with moderate climate which provide sufficient air humidity at increasing temperature.

The term (p/p_0) fits very well to the average overall atmospheric correction $\delta \times k_h$. Therefore the best estimation for the average atmospheric correction $\delta \times k_h$ is the related average pressure p/p_0 .

With these considerations of the compensating effect and with Equation (H.7) follows that, for insulation co-ordination purpose, the atmospheric correction factor K_t can be simply used by taking only the air pressure p into account:

$$K_t = \left[\frac{p}{p_0} \right]^m \quad (\text{H.8})$$

H.2.3 Special atmospheric conditions

For regions with special atmospheric conditions, different considerations may apply. Figure H.3 shows the summary of data from various weather stations around the world, comparing the overall atmospheric correction $\delta \times k_h$ with the pressure related correction p/p_0 . For most locations, the difference is within the standard deviation of the values justifying the considerations for moderate climates above.

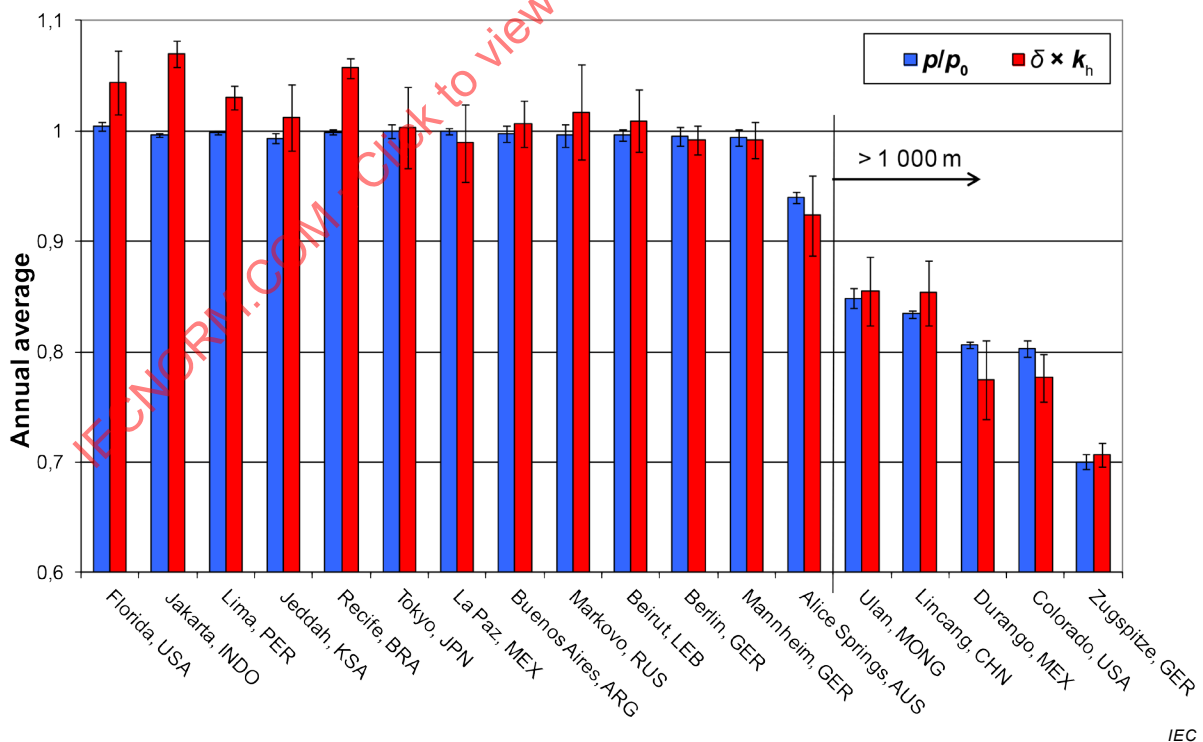


Figure H.3 – Comparison of atmospheric correction $\delta \times k_h$ with relative air pressure p/p_0 for various weather stations around the world

Higher differences show special atmospheric conditions which may need special consideration. There is no compensation and the application of the complete atmospheric correction may become necessary instead of the simplification by taking in account the pressure only. For example, for tropical climate with high temperature and very high humidity (like Jakarta, Indonesia and Recife, Brazil), factor $(T_0/T \times k_h)$ dominates the correction $\delta \times k_h$.

For such special atmospheric conditions at sea level it should be noted that this difference is covered by the insulation co-ordination procedure for normal environmental conditions which includes the altitude of 1 000 m. This leads to a pressure related correction with p/p_0 (correction factor 1,13) covering the overall correction $\delta \times k_h$, and no further consideration is needed.

For areas at high altitude with a large difference it is recommended to consider the complete atmospheric correction $\delta \times k_h$ to cover the effects of pressure, temperature and humidity.

H.2.4 Altitude dependency of air pressure

As shown above, the atmospheric correction can be reduced in most cases to a correction considering the air pressure only. The dependency of air pressure and altitude will be described in the following.

According to ISO 2533:1975, the simultaneous solution of the equations of static atmosphere and the perfect gas law gives a dependency of air pressure p on altitude H (ISO 2533:1975, Equation (12)). A linear reduction of temperature with altitude is included by a temperature gradient. By using a constant average temperature the dependency of p versus H can be simplified to the exponential function:

$$p = p_0 e^{-\frac{H}{8150}} \quad (\text{H.9})$$

The deviation of this simplified way of pressure calculation to the pressure calculation including the temperature gradient of ISO 2533 is shown in Figure H.4. The maximum deviation up to nearly 4 000 m altitude is less than 0,5 %. The difference is small and the simplified equation can be applied with sufficient accuracy.

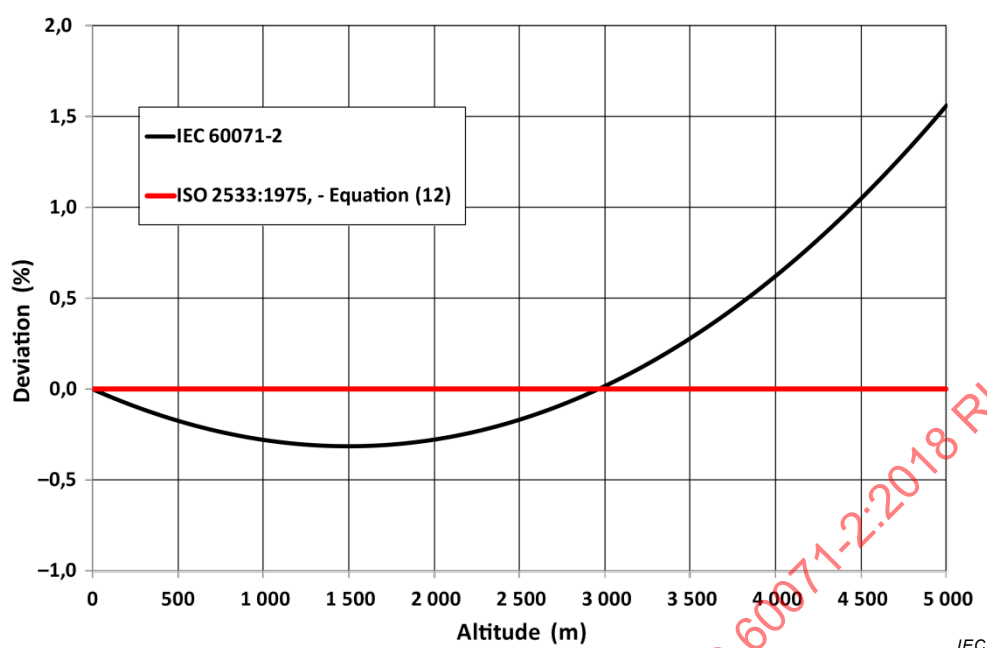


Figure H.4 – Deviation of simplified pressure calculation by exponential function in this document from the temperature dependent pressure calculation of ISO 2533

H.3 Altitude correction

H.3.1 Definition of the altitude correction factor

With the basic idea of atmospheric correction for insulation co-ordination to simplify it to a pure pressure dependent correction the correction factor K_t can be written in exponential form by combining Equations (H.8) and (H.9).

$$K_t = \left(\frac{p}{p_0} \right)^m = e^{-m \frac{H}{8150}} \quad (\text{H.10})$$

It describes the reduction of the withstand voltage at elevated altitude.

The altitude correction factor has to compensate the reduction. It is defined as a factor, by which the rated withstand voltage has to be increased to a higher value at standard reference atmosphere in order to assure a withstand voltage equal to the required value at certain altitude.

The altitude correction factor is given by

$$K_a = \frac{1}{K_t} = e^{m \frac{H}{8150}} \quad (\text{H.11})$$

The altitude correction is a simplification of the atmospheric correction. It implies that the differences in the atmospheric conditions at an elevated altitude can be described by one single parameter, namely the installation altitude H of the equipment.

H.3.2 Principle of altitude correction

In insulation co-ordination, the co-ordination withstand voltage U_{cw} has to be applied with the safety factor K_s and the altitude correction factor K_a to achieve the required withstand voltage U_{rw} .

$$U_{rw} = K_s \times K_a \times U_{cw} \quad (\text{H.12})$$

Figure H.5 shows the principle of altitude correction for an example of $U_m = 420$ kV and a rated lightning impulse withstand voltage of 1 425 kV. The actual withstand voltage of the equipment decreases from the rated value at sea level with the installation altitude according to the decreasing air pressure.

The value 1 425 kV has been derived from the co-ordination withstand voltage $U_{cw} = 1\,200$ kV multiplied by the safety factor $K_s = 1,05$ recommended in this document for external insulation. As this example relates to a standardized equipment, an altitude correction factor $K_a = 1,13$ (according to the pressure at 1 000 m) has been applied. The design meets the requirements for the withstand voltage to be equal to 1 260 kV ($1,05 U_{cw}$) exactly up to 1 000 m.

In order to meet the design requirement for the external insulation at altitudes above 1 000 m (e.g. 3 000 m in Figure H.5), the withstand voltage of the external insulation at standard reference atmosphere has to be increased by altitude correction according to the altitude of installation. An altitude correction according Equation (H.11) has to be applied to cover the requirements at installation altitude. With $K_a = 1,45$, a withstand voltage of 1 822 kV at sea level is necessary to meet the requirements at 3 000 m.

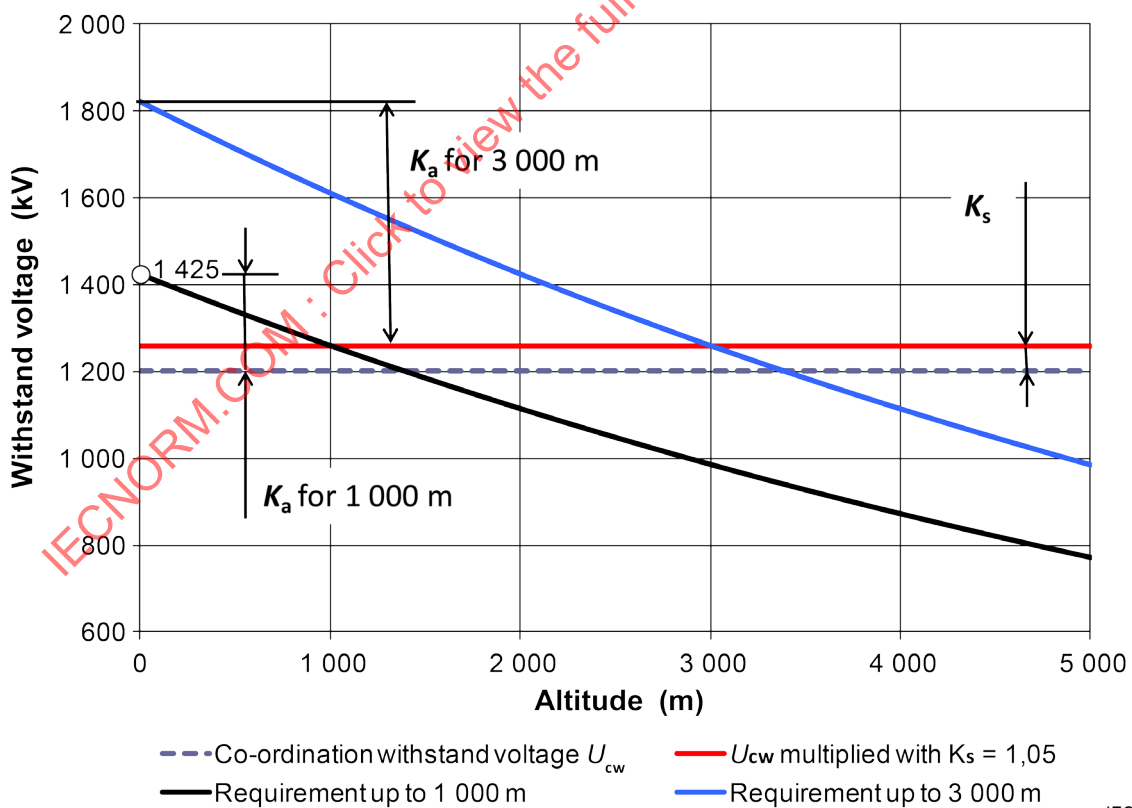


**Figure H.5 – Principle of altitude correction:
decreasing withstand voltage U_{10} of equipment with increasing altitude**

H.3.3 Standard equipment operating at altitudes up to 1 000 m

When equipment designed according to an existing IEC standard is used, the equipment shall fulfill all requirements of the relevant standard concerning the environmental conditions. For the external insulation, it means that equipment shall be able to operate in the range of atmospheric conditions specified in the standards. Normal environmental conditions in IEC 60071-1 and in equipment standards (e.g. IEC 62271-1) specify among others an altitude of operation up to 1 000 m.

It is evident that the insulation design shall take into account the variations of the atmospheric conditions within this specified range. Considering the compensating effect of humidity and temperature, the altitude up to 1 000 m can be covered by the pressure related altitude correction factor to meet the requirements of normal environmental conditions. For example, for lightning impulse (with exponent $m = 1,0$), an altitude correction factor of $K_a = 1,13$ according to Equation (H.11) has to be applied to cover the required installation altitude up to 1 000 m.

IEC 60071-1 has standardized a list of rated withstand voltages, which are based on the experience with equipment located in systems that are operated under normal environmental conditions. These conditions include altitudes up to 1 000 m and, consequently, the range of rated withstand voltages is assumed to cover the requirements for all external insulations to be located at altitudes up to 1 000 m.

As a conclusion, the following has to be stated.

- The rated withstand voltage values standardized in IEC 60071-1 are valid for the standard reference atmospheric conditions and only for these conditions. The standard reference atmospheric conditions include the average pressure at sea level altitude.
- For each U_m value, the associated range of rated withstand voltages proposed in the present standard cover the requirements for all equipment operating under normal environmental conditions including those to be installed at altitudes up to 1 000 m.

Following the general practice of insulation co-ordination procedure for standardized equipment an altitude correction factor according to Equation (H.11) has to be applied to cover the required installation altitude up to 1 000 m.

H.3.4 Equipment operating at altitudes above 1 000 m

Besides the normal environmental conditions, further requirements may arise from special environmental conditions among which an altitude exceeding 1 000 m is of special interest for the external insulation. Generally, it has to be considered by altitude correction according Equation (H.11).

Only equipment which is standardized and approved for altitudes up to 1 000 m needs to be corrected by Equation (H.13) for installations above 1 000 m. The standardized voltage levels have to be increased by:

$$K_{a1000} = e^{m \times \frac{H-1000}{8150}} \quad (\text{H.13})$$

This equation takes into account that rated withstand voltages of standardized equipment already covers the necessary correction up to altitudes of 1 000 m.

H.4 Selection of the exponent m

H.4.1 General

The exponent m in atmospheric and altitude correction takes into account the discharge behavior of the considered air gap.

For the following voltage and overvoltage classes, the exponent m may be applied.

1) Co-ordination long-duration power-frequency withstand voltages

As long as specific values of exponent m to determine the pollution withstand voltage are not specified by IEC TC 36, the following value may be applied:

$m = 0,5$ for overhead line insulators;

$m = 0,8$ for station insulators, bushings and housings.

2) Co-ordination short-duration power-frequency withstand voltages

A conservative estimate may be used:

$m = 1$.

3) Co-ordination lightning impulse withstand voltages

For lightning impulses, the exponent m is equal to 1, which has to be expected for a streamer discharge where the flashover voltage is linearly dependent on the gap clearance:

$m = 1$.

This is valid also for the combined lightning impulse/power-frequency voltage of longitudinal insulations. Reason is that lightning impulses are so short in time duration that the flashover will be a streamer discharge. The flashover voltage, therefore, increases linearly with distance.

4) Co-ordination switching impulse withstand voltages

For switching impulses, the exponent m is obtained for each co-ordination withstand voltage U_{cw} . An according dependency is given in Figure 9.

The derivation of exponent m for standard switching impulse voltage shapes is shown in H.4.2. It shows in detail that the exponent m is, beside U_{cw} , depending on altitude H and gap factor K . Figure H.6 or Figure H.7 should be used for selection of exponent m to determine the altitude correction factor K_a when dealing with standard impulse shapes.

The derivation of exponent m for critical switching impulse voltage shapes is shown in H.4.3 in the same way with the results in Figure H.8 and Figure H.9.

H.4.2 Derivation of exponent m for switching impulse voltage

The exponent m can be derived from a set of well-known and approved relations:

- 1) flashover characteristic based on rod-plane gaps (Equation (F.4)) for standard switching impulse voltage;
- 2) parameter g providing the exponent m (IEC 60060-1);
- 3) atmospheric correction;
- 4) normalized conventional standard deviation $z = 0,06$ for switching impulse;
- 5) pressure related exponential function of altitude correction.

With this set of relations a dependency of exponent m on the co-ordination withstand voltage U_{cw} with the parameters K and H can be derived as described in the following.

Basically, exponent m is derived from the equation of parameter g and the equation of the flashover characteristic of phase-to-earth configuration. In both equations, the air gap clearance L is used and will be set equal.

For both equations, the 50 % flashover voltages are needed. Taking Equation (7) and considering that

U_{cw} is the 10% flashover voltage U_{10} , and

U_{c50} is the 50% flashover voltage U_{50} ,

U_{c50} can be calculated as follows:

$$U_{c50} = \frac{U_{cw}}{1 - 1,3 \times z} \quad (\text{H.14})$$

The normalized value of conventional standard deviation is 6 % for switching impulse voltage referred to U_{50} .

Air gap clearance d from parameter g

The minimum air clearance d of equipment is not known and has to be determined.

Based on the equation for the parameter g of IEC 60060-1 the applicable minimum clearance d at the location of installation is given by

$$d = \frac{U_{c50}}{500 \times g \times \delta \times k_h} \quad (\text{H.15})$$

Air gap clearance d from flashover characteristic based on rod-plane gaps

To determine the air clearances necessary for a required 50 % flashover voltage, a voltage based on the characteristic of a rod-plane configuration has been used (Equation (F.4)).

$$U_{r50} = K \times 500 \times d^{0,6} \quad (\text{H.16})$$

The required 50 % flashover voltage U_{r50} valid for reference conditions can be converted to the co-ordination flashover voltage U_{c50} by atmospheric correction (disregarding the safety factor K_s in this respect):

$$U_{r50} = \frac{U_{c50}}{K_t} = \frac{U_{c50}}{(\delta \times k_h)^m} \quad (\text{H.17})$$

The air gap clearance is given now by:

$$d = \left[\frac{U_{c50}}{500 \times K \times (\delta \times k_h)^m} \right]^{1/0,6} \quad (\text{H.18})$$

Setting equal Equations (H.15) and (H.18) leads to:

$$\frac{U_{c50}}{500 \times g \times \delta \times k_h} = \left[\frac{U_{c50}}{500 \times K \times (\delta \times k_h)^m} \right]^{1/0,6} \quad (H.19)$$

Replace g by (from IEC 60060-1):

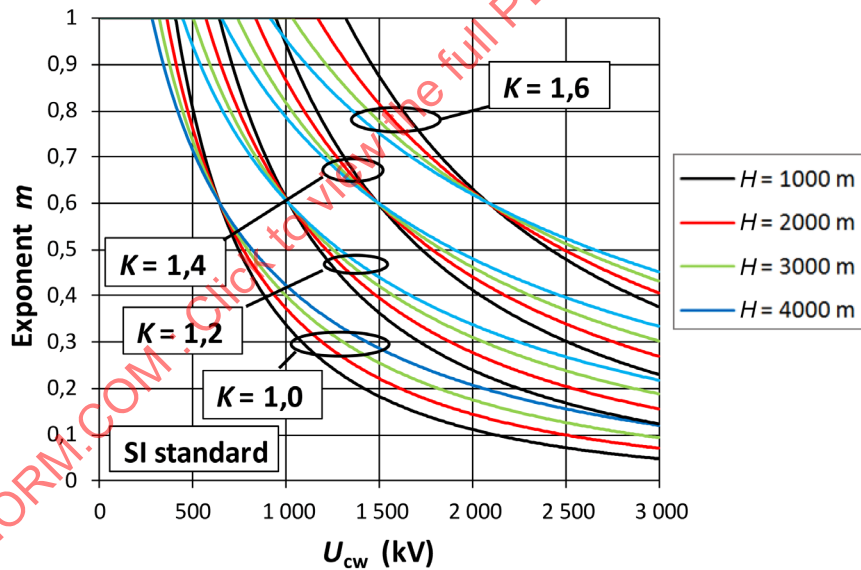
$$g = 0,1 + \sqrt{0,8 \times m + 0,01} \quad (H.20)$$

The term of the atmospheric correction $\delta \times k_h$ is known from the designated installation and can be replaced by

$$\delta \times k_h = \frac{-H}{e^{8/150}} \quad (H.21)$$

Including Equations (H.14), (H.20) and (H.21) into (H.19) leads to the dependency of exponent m on U_{cw} with the parameters H and K . Equation (H.19) can only be solved iteratively.

The dependency of exponent m on the co-ordination withstand voltage U_{cw} is plotted in Figure H.6 for selected gap factors K and selected altitudes H up to 4 000 m. Typical values of the gap factor K are indicated in Table G.1 and Table G.2.



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Figure H.6 – Sets of m -curves for standard switching impulse voltage including the variations in altitude for each gap factor

The exponent m varies in a wide range considering the two parameters altitude and gap factor. By examining the effect of exponent m on altitude correction factor K_a it can be stated that the sensitivity of K_a on variations in m is low. Due to the fact that the sensitivity is decreasing with altitude the m curves for the highest altitude can be used in a first approach for the lower altitudes by accepting a maximum failure within engineering tolerance of $\pm 3\%$ (Figure H.7).

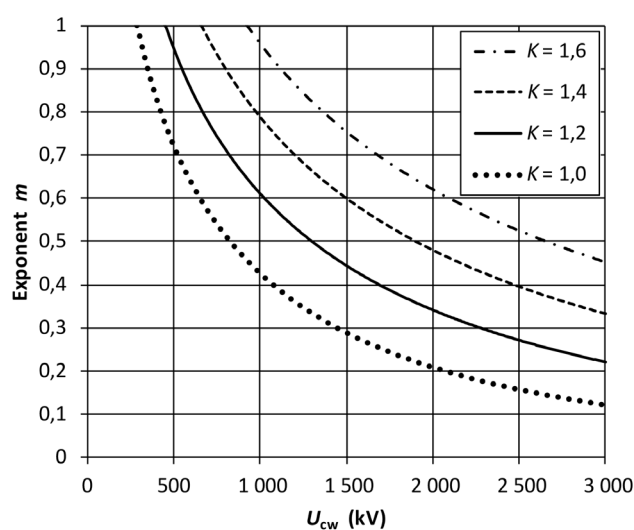


Figure H.7 – Exponent m for standard switching impulse voltage for selected gap factors covering altitudes up to 4 000 m

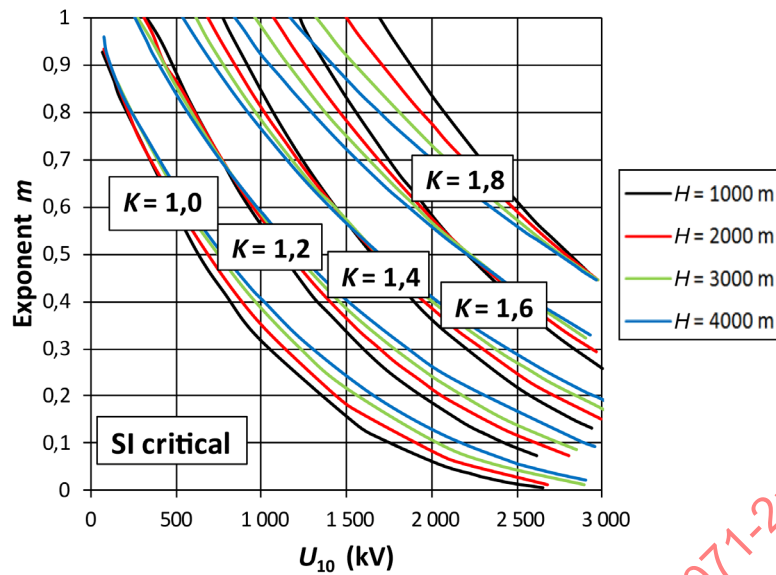
H.4.3 Derivation of exponent m for critical switching impulse voltage

If the critical switching impulse voltage is used for determination of exponent m the derivation can be done in the same way as for standard switching impulse (described in H.4.2) by just replacing the equation for the flashover characteristics. The characteristic based on rod-plane gaps (based on Equation (F.3)) for switching impulse voltage with critical front time strength has to be used.

$$U_{r50} = K \times 1\,080 \times \ln(0,46 \times d + 1) \quad (\text{H.22})$$

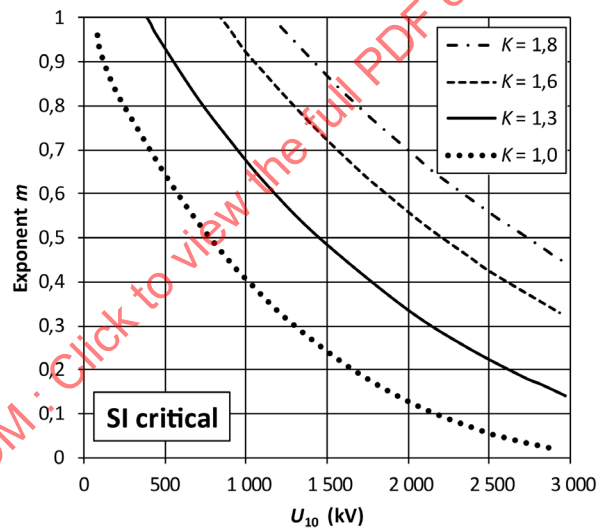
All other relations remain unchanged.

The outcome is also a set of curves for each gap factor covering the selected altitudes 1 000 m up to 4 000 m (Figure H.8) and the reduced diagram for all altitudes up to 4 000 m (Figure H.9).



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Figure H.8 – Sets of m -curves for critical switching impulse voltage including the variations in altitude for each gap factor



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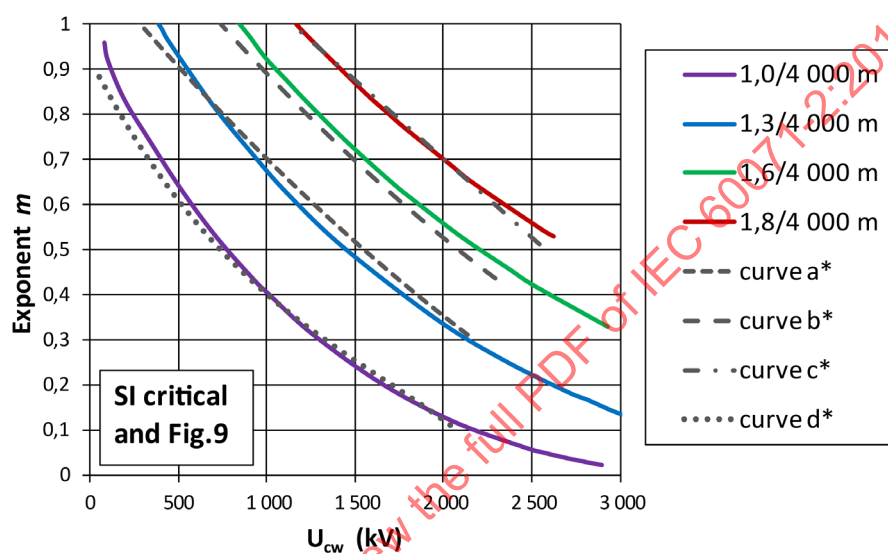
Figure H.9 – Exponent m for critical switching impulse voltage for selected gap factors covering altitudes up to 4 000 m

The curves are more flat than the curves determined by the equation for the standard switching impulse. They have a similar gradient in comparison with the m -curves of Figure 9.

After selection of appropriate parameters for gap factor K and altitude H , it can be shown that some curves are in good accordance with the curves of Figure 9. The conformity is visualized in Figure H.10, and a comparison of the functional expressions of Figure 9 to the selected parameters is listed in Table H.1.

Table H.1 – Comparison of functional expressions of Figure 9 with the selected parameters from the derivation of m -curves with critical switching impulse

Insulation according Figure 9		Determination by critical SI Equation (F.3) Parameter: gap factor/altitude
Phase-to-earth	curve a*	1,3/4 000
Longitudinal	curve b*	1,6/4 000
Phase-to-phase	curve c*	1,8/4 000
Rod-plane gap	curve d*	1,0/4 000
NOTE The asterisks defining the curves refer to Figure H.10.		



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Figure H.10 – Accordance of m -curves from Figure 9 with determination of exponent m by means of critical switching impulse voltage for selected gap factors and altitudes

Figure 9 has been used for several years. To avoid changes in actual practical designs by replacing the curves of Figure 9 with the determined curves described above they can be used further on. It is recommended to investigate the validity of the new curves according Figure H.6 and Figure H.7 as well when dealing with standard impulse shapes only.

Annex I (informative)

Evaluation method of non-standard lightning overvoltage shape for representative voltages and overvoltages

I.1 General remarks

In the insulation co-ordination stage of "representative overvoltage", overvoltage shapes are supposed to be the standard voltage shapes, which is especially significant for a lightning impulse. Recent researches have analysed field surges, clarified insulating characteristics for field real surges in comparison with those for the standard voltage shape in the lightning surge time region, and proposed the shape evaluation method for GIS (Gas insulated switchgear) [14] and transformer [15]. These techniques have been discussed in CIGRE working groups, and adopted in the technical brochures [11], [16], [17]. According to the aforementioned documents, the decay of the field overvoltage is generally large, making the insulation requirements not as severe as those of the standard overvoltage shape. Consequently, it could be possible in some cases to use lower withstand voltages.

I.2 Lightning overvoltage shape

From the results of the analyses of lightning overvoltage, disconnector switching overvoltage, and measurements at UHV and 550 kV substations, representative overvoltage shapes were extracted as the following five types, "Shape A" to "Shape E". The rise time of the shape crest varies, as a whole, in the range of 0,1 μ s to 1,0 μ s for GIS and 0,5 μ s to 1,5 μ s for transformer.

- Shape A: pulse-shape.
- Shape B: the shape front has a steep pulse-shaped part, and the shape tail is flat (ratio between peak and flat part: 0,7/0,9 both for GIS and transformer).
- Shape C: a damped oscillatory shape whose first peak is maximum (frequency: 0,5 MHz to 5,0 MHz for GIS, 0,4 MHz to 1,0 MHz for transformer).
- Shape D: a damped oscillatory shape whose second peak has the crest value (frequency: 0,5 MHz to 5,0 MHz for GIS, 0,4 MHz to 1,0 MHz for transformer).
- Shape E: double-frequency oscillatory shape (lower frequency: approx. 1,0 MHz, upper frequency: approx. 5,0 MHz for GIS).

Shape B appears depending upon the positional relationships with protected points when the lightning arrester operates. Shapes C and D occur as a result of a negative and/or positive reflection inside and/or outside the substation. Shape A corresponds to the one when the decay of the DC component and/or oscillatory components of shapes B, C and D are large. Also, shape E occurs during a re-striking inside a substation as a disconnector surge, when there exist two oscillation routes within a substation. Thus, in general, it can be said that these shapes are representative shapes in view of the mechanism under which they occur. Figure I.1 a) to e) show examples of shapes A, B, C, D, and E.

I.3 Evaluation method for GIS

I.3.1 Experiments

The SF₆ gas gap and partly the insulating spacer surface were used as the insulating elements of GIS. The electrodes used in the tests generated quasi-equal electric fields whose utilization factors (η) were 0,60 and 0,45. The gas pressure was basically an absolute pressure of 0,50 MPa. With changing shape parameters, such as the frequency and the decay time, more than 200 cases were examined. Moreover, effects of other factors were

investigated, like the scale, the gas pressure, the voltage polarity, superposition with DC, electrode material, and roughness.

As an example of the results, Figure I.2 shows the characteristics with respect to the shape E. The minimum value of the insulation breakdown V-t characteristics is 259 kV, which is 1,19 times that of the case of a standard lightning impulse. In other words, this means that it is possible to evaluate the overvoltage into the standard voltage with dividing the crest value by 1,19. This interpretation applies to the other experimental results as well.

The insulation characteristics are arranged according to the duration time of the 80 % level of the peak value. Figure I.3 presents how to calculate the duration time t_d : the sum of $t_{d1} + t_{d2}$. All of the characteristics for shape A, the pulse parts of shape B, and shapes C and D, and the double-frequency oscillatory shape E, lie roughly along one characteristic line. This characteristic corresponds to equations in the "Calculation of evaluation factor K_{ev} " box in Figure I.4 later discussed.

I.3.2 Evaluation of overvoltage shape

The overvoltage shape is resolved into elements including each oscillatory shape, the flat part, and so on. It is then evaluated based on the characteristics as described above, and finally the crest value that is evaluated into an equivalent standard voltage shape. Figure I.4 exhibits the whole evaluation flow for GIS together with for transformer referred to in I.4.2.

Figure I.5 shows an example of the lightning overvoltage applied to GIS in a UHV substation. This overvoltage is classified to the shape B whose tail level is approximately 60% of the peak, after the steep oscillatory surge has decayed. Table I.1 shows the results of analyzing and evaluating this overvoltage shape using the flow of Figure I.4. In this case, the shape crest is severer than the shape tail, and the representative overvoltage is equivalent to a 2 094 kV (25 % lower).

I.4 Evaluation method for transformer

I.4.1 Experiments

The oil gap, section-to-section insulation and turn-to-turn insulation were used as the insulating elements of a transformer. About 100 cases were examined with changing shape parameters, such as the frequency and the decay time.

As an example of the results, Figure I.6 exhibits the characteristics with respect to shape C of the turn-to-turn insulation. The average value of the insulation breakdown V-t characteristics is 185 kV, which is 1,26 times that of the case of a standard lightning impulse. In a similar manner to GIS, this means that it is possible to evaluate the overvoltage into the standard voltage with dividing the crest value by 1,26. This interpretation applies to the other experimental results as well.

Concerning the oil gap and section-to-section insulation, when the insulation characteristics are arranged according to the duration time of the 80 % level of the peak value, all of the characteristics for shape A, the pulse parts of shape B, and shapes C and D, lie roughly along one characteristic line. Meanwhile, regarding the turn-to-turn insulation, when the insulation characteristics are arranged according to the duration time of the 90 % level of the peak value, all of the characteristics for shape A, the pulse parts of shape B, and shapes C and D, lie roughly along one characteristic line. However, in contrast to the other models, the duration time for 90 % and higher in the case of an oscillatory shape is not a total value, but is calculated separately for each shape as shape A.

I.4.2 Evaluation of overvoltage shape

The shape is resolved into elements V_{pij} including each oscillatory shape, the flat part, and so on. It is then evaluated based on the characteristics as described above, and finally the crest

value is evaluated as the equivalent standard voltage V_{sj} . The whole overvoltage shape evaluation flow for an oil-filled transformer is presented in Figure I.4 together with for GIS.

Figure I.7 is an example of a lightning overvoltage applied to a transformer in a 550 kV substation. In this case, the shape tail maintains a level of about 70 % with respect to the peak after the steep oscillatory surge has decayed. Table I.2 summarizes the results of analyzing and evaluating this shape using the flow of Figure I.4. The severest part of the overvoltage is the pulse-shaped one "No. 2" with respect to the turn-to-turn insulation. The crest value of equivalent standard voltage is 934 kV (24 % lower).

To think of the principle of construction, these methods both for GIS and transformer can be generally applicable to lower voltage systems as well as 550 kV and above.

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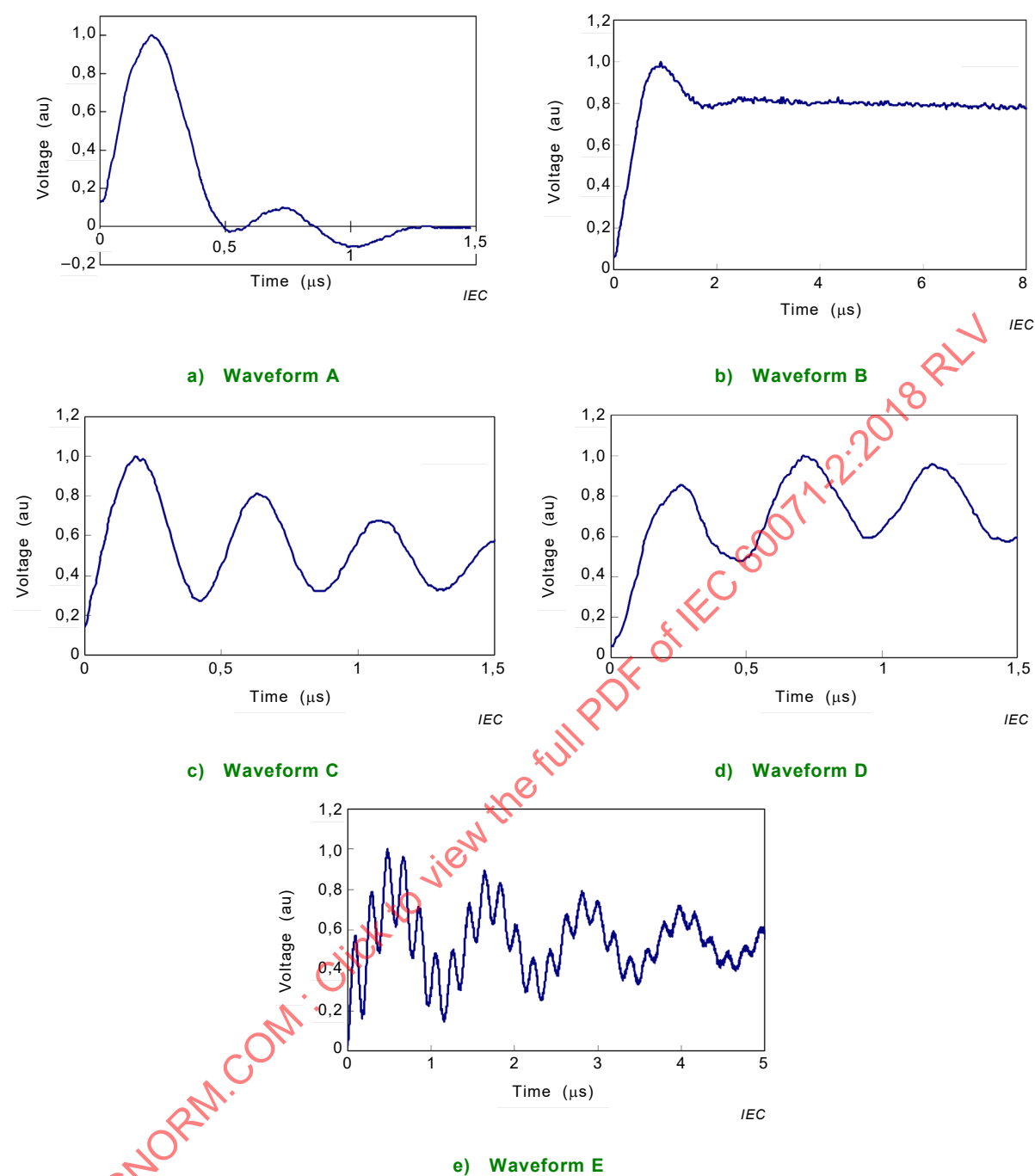


Figure I.1 – Examples of lightning overvoltage shapes

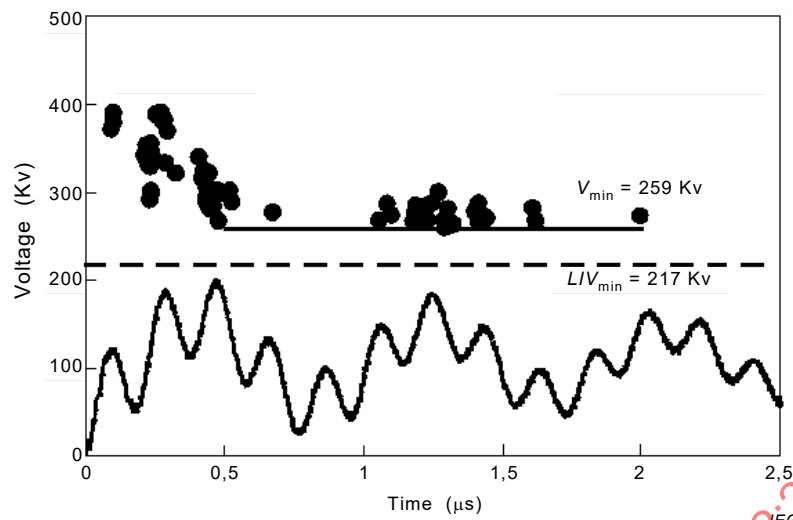


Figure I.2 – Example of insulation characteristics with respect to lightning overvoltages of the SF₆ gas gap (Shape E)

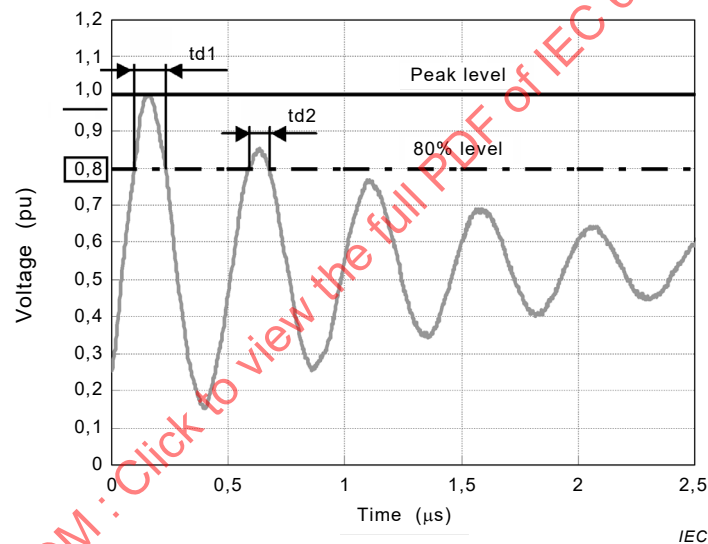


Figure I.3 – Calculation of duration time T_d

Table I.1 – Evaluation of the lightning overvoltage in the GIS of UHV system

Shape element	80 % duration time	Peak voltage	Evaluation ratio	Equivalent standard LI Vol.
B (shape crest)	0,16 μs	2 617 kV	1,25 (1,30)	2 094 kV [$\eta = 0,60$] (2 016 kV [$\eta = 0,45$])
B (shape tail)	-	1 517 kV	0,90	1 686 kV

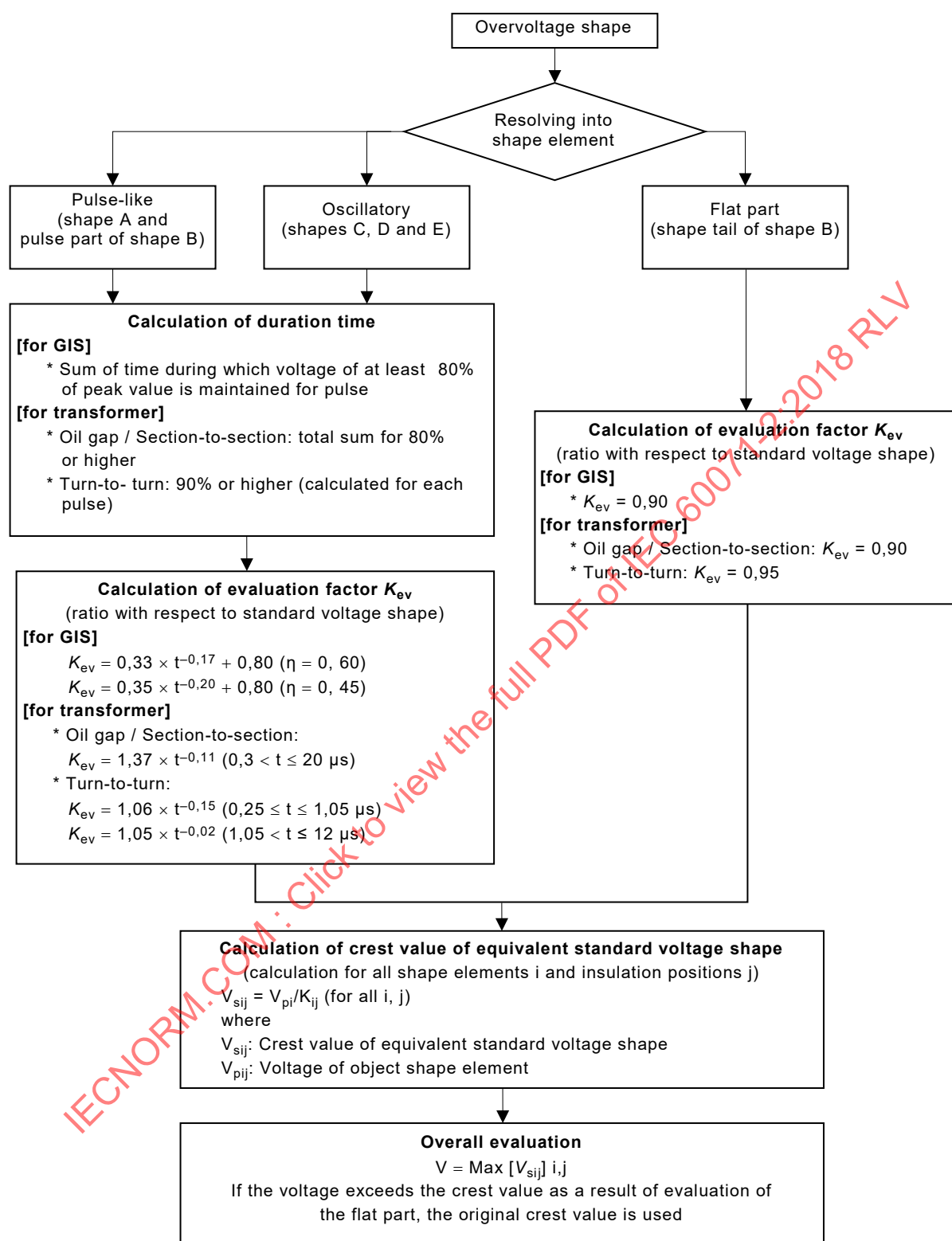


Figure I.4 – Shape evaluation flow for GIS and transformer

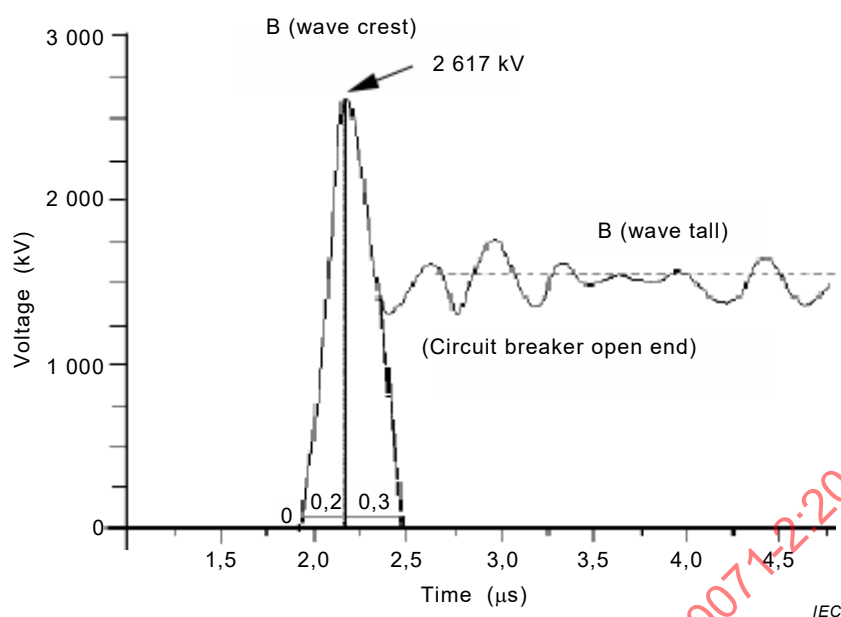


Figure I.5 – Application to GIS lightning overvoltage

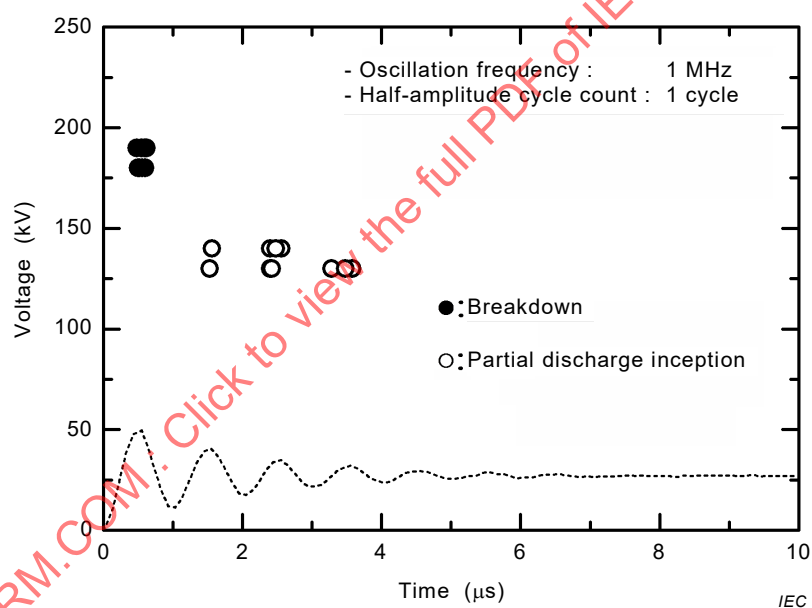


Figure I.6 – Example of insulation characteristics with respect to lightning overvoltage of the turn-to-turn insulation (Shape C)

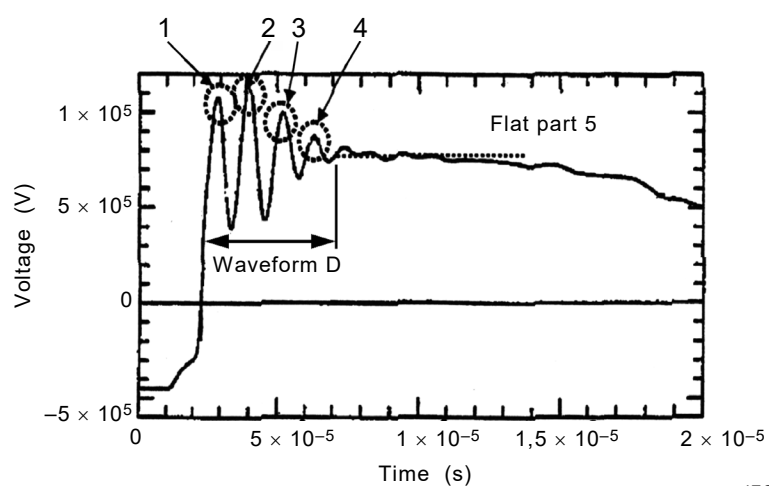


Figure I.7 – Application to transformer lightning overvoltage

Table I.2 – Evaluation of lightning overvoltage in the transformer of 500 kV system

Insulation element	Shape element	Duration time	Peak voltage	Evaluation ratio	Equivalent standard LI Vol.
Oil gap / Section-to-section	Oscillatory parts (1~4): C or D	0,84 μ s	1 158 kV	1,40	827kV
	Flat part (5)	-	784 kV	0,90	871kV
Turn-to-turn	Max pulse (2)	0,35 μ s	1 158 kV	1,24	934kV
	Other pulses (1)	0,35 μ s	1 084 kV	1,24	874kV
	Flat part (5)	-	784 kV	0,95	825kV

Annex J **(informative)**

Insulation co-ordination for very-fast-front overvoltages in UHV substations

J.1 General

VFFO in GIS have been studied by various CIGRÉ working groups and a common CIGRÉ technical brochure TB 519 [13] was published.

VFFO were considered to be more important for insulation co-ordination in UHV AC substations, than in HV substations. VFFO in GIS are of greater concern at UHV, because the ratio of the lightning impulse withstand voltage to the rated voltage is comparably low. VFFO can become the limiting dielectric stress.

Especially in the UHV range, the knowledge of the VFFO level is necessary as basis for the insulation co-ordination and the evaluation of potential risks and countermeasures. Because the VFFO are determined by superposition of traveling waves, they depend strongly on the specific configuration and it is not possible to give generally valid voltage values. It is necessary to perform a system analysis by accurate simulation for each substation to assess the VFFO.

As an indication, the required withstand voltage depends on the dielectric behavior of the equipment and the trapped charge behavior of the disconnector. As a result, the withstand voltages could vary for different equipment (transformer, SF₆ insulation, air insulation) and different disconnector design.

A three step procedure is recommended for VFFO insulation co-ordination. This procedure is outlined in Figure J.1, and its steps are described in Clause J.3.

A more detailed description of the procedure can be found in TB 519 [13]. The general approach is based on the insulation co-ordination procedure for the determination of rated or standard insulation level according to IEC 60071-1.

J.2 Influence of disconnector design

The value of the VFFO depends on the voltage drop at the disconnector just before striking. The voltage drop is dependent on the charge remaining on the load side of the disconnector from the preceding striking. The "trapped charge" is the charge remaining after the last striking of an opening operation, and the trapped charge voltage (TCV) is the voltage resulting from this charge.

This TCV is specific for each disconnector design and depends mainly on the contact speed and the field homogeneity of the contact system.

For slow acting disconnectors (contact speed < 1 m/s) the maximum trapped charge voltage lies well below 1 p.u. The resulting VFFO is in the range of 1,7 p.u. and reaches 2,0 p.u. for very specific cases.

Fast acting disconnectors (contact speed > 1 m/s) exhibit trapped charge levels up to 1 p.u. Consequently generally higher VFFO are produced compared to the slow acting disconnector. The integration of a damping resistor into the disconnector is a proven mitigation measure, VFFO amplitudes in the range around 1,3 p.u. can be reached.

J.3 Insulation co-ordination for VFFO

1) Step 1: Calculation of peak value and rise time of VFFO

- System analysis (using a travelling wave computer simulation program).
- Calculation of the maximum peak value $U_{\max-VFFO}$ and rise time for the GIS and the connected equipment.
- If known, the real trapped charge behavior of the disconnector should be used, i.e.
 - the 99 % probability value determined by simulation, or
 - maximum values measured during testing.
- Otherwise, the worst case assumption of a trapped charge voltage of –1 p.u. should be used for the simulation.
- The accuracy of the simulation model shall be verified.

In the context of insulation co-ordination process, travelling wave simulation is a well-established instrument. However, the accuracy of a VFFO simulation depends on the quality of the model of each individual GIS component. In order to achieve reasonable results, even for time periods of some micro-seconds or for very complex GIS structures, accurate models for all components, internal and external, connected to the GIS, are necessary. This allows for calculating VFFO which differ less than 5 % from measured voltage curves. The accuracy of a simulation is usually verified by VFFO measurement on a GIS test pole or the actual gas-insulated substation arrangement and the comparison of simulated and measured VFFO.

2) Step 2: Calculation of required VFFO withstand voltage ($U_{rw-VFFO}$) and comparison to LIWV

The required VFFO withstand voltage $U_{rw-VFFO}$ shall be calculated for the different equipment by multiplication of $U_{\max-VFFO}$ with K-factors:

- Co-ordination factor K_C : K_C covers the statistical distribution and frequency of occurrence of VFFO and the inaccuracy of simulation. In case of a proved simulation tool a co-ordination factor K_C of 1,05 is recommended. $U_{\max-VFFO}$ multiplied with K_C gives the VFFO co-ordination voltage $U_{cw-VFFO}$.
- Safety factor K_S and atmospheric correction factor K_t : K_S covers the aging behavior in service, quality of installation and other unknown influences. For external insulation a safety factor K_S of 1,05, for internal insulation (applicable for any equipment) a safety factor K_S of 1,15 is recommended. In case of external insulation the atmospheric correction factor K_t shall be applied. $U_{cw-VFFO}$ multiplied with K_S and K_t gives the required VFFO withstand voltage $U_{rw-VFFO}$.

3) Step 3: Definition of measures according to the insulation co-ordination

The required VFFO withstand voltage $U_{rw-VFFO}$ is compared to the LIWV in order to determine a risk of insulation failure. For this purpose, the required VFFO withstand voltage $U_{rw-VFFO}$ has to be multiplied with a test conversion factor K_{tc} :

- K_{tc} describes the different withstand behavior under VFFO and standard LI voltage stress. For SF₆ insulated systems the recommended K_{tc} is 0,95. The recommended test conversion factor K_{tc} for oil or oil/solid insulated systems is 1,0.

Based on the result of the comparison

- if $K_{tc} \times U_{rw-VFFO} < \text{LIWV}$, no measures are required;
- otherwise, measures to mitigate the risk of failure should be considered.

Mitigation may be achieved for instance by applying a disconnector with low(er) TCV or a disconnector with integrated damping resistor. Other measures may also be appropriate, for instance increasing of the LIWV.

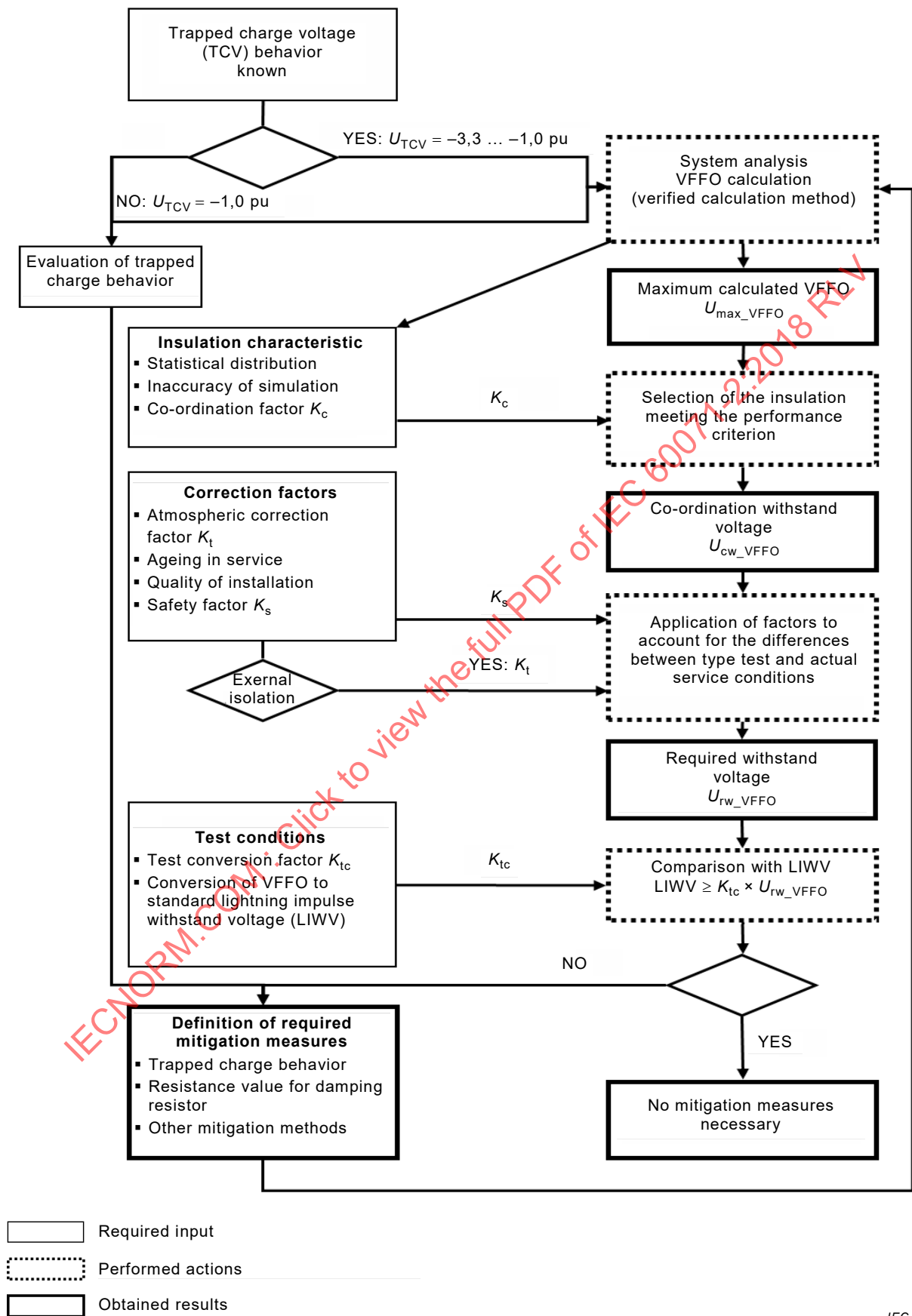


Figure J.1 – Insulation co-ordination for very-fast-front overvoltages

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**Insulation co-ordination –
Part 2: Application guidelines**

**Coordination de l'isolement –
Partie 2: Lignes directrices en matière d'application**

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

INSULATION CO-ORDINATION –**Part 2: Application guidelines****FOREWORD**

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International Standard IEC 60071-2 has been prepared by IEC technical committee 28: Insulation co-ordination.

This fourth edition cancels and replaces the third edition published in 1996. This edition constitutes a technical revision.

This edition includes the following significant technical changes with respect to the previous edition:

- a) the annex on clearance in air to assure a specified impulse withstand voltage installation is deleted because the annex in IEC 60071-1 is overlapped;
- b) 4.2 and 4.3 on surge arresters are updated;
- c) 4.3.5 on very-fast-front overvoltages is revised. Annex J on insulation co-ordination for very-fast-front overvoltages in UHV substations is added;
- d) Annex H on atmospheric correction – altitude correction is added.

e) Annex I on evaluation method of non-standard lightning overvoltage shape is added.

The text of this International Standard is based on the following documents:

FDIS	Report on voting
28/255/FDIS	28/256/RVD

Full information on the voting for the approval of this International Standard can be found in the report on voting indicated in the above table.

This document has been drafted in accordance with the ISO/IEC Directives, Part 2.

It has the status of a horizontal standard in accordance with IEC Guide 108.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under "<http://webstore.iec.ch>" in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

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INSULATION CO-ORDINATION –

Part 2: Application guidelines

1 Scope

This part of IEC 60071 constitutes application guidelines and deals with the selection of insulation levels of equipment or installations for three-phase electrical systems. Its aim is to give guidance for the determination of the rated withstand voltages for ranges I and II of IEC 60071-1 and to justify the association of these rated values with the standardized highest voltages for equipment.

This association is for insulation co-ordination purposes only. The requirements for human safety are not covered by this document.

This document covers three-phase systems with nominal voltages above 1 kV. The values derived or proposed herein are generally applicable only to such systems. However, the concepts presented are also valid for two-phase or single-phase systems.

This document covers phase-to-earth, phase-to-phase and longitudinal insulation.

This document is not intended to deal with routine tests. These are to be specified by the relevant product committees.

The content of this document strictly follows the flow chart of the insulation co-ordination process presented in Figure 1 of IEC 60071-1:2006. Clauses 4 to 7 correspond to the squares in this flow chart and give detailed information on the concepts governing the insulation co-ordination process which leads to the establishment of the required withstand levels.

This document emphasizes the necessity of considering, at the very beginning, all origins, all classes and all types of voltage stresses in service irrespective of the range of highest voltage for equipment. Only at the end of the process, when the selection of the standard withstand voltages takes place, does the principle of covering a particular service voltage stress by a standard withstand voltage apply. Also, at this final step, this document refers to the correlation made in IEC 60071-1 between the standard insulation levels and the highest voltage for equipment.

The annexes contain examples and detailed information which explain or support the concepts described in the main text, and the basic analytical techniques used.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60060-1:2010, *High-voltage test techniques – Part 1: General definitions and test requirements*

IEC 60071-1:2006, *Insulation co-ordination – Part 1: Definitions, principles and rules*
IEC 60071-1:2006/AMD1:2010

IEC 60505:2011, *Evaluation and qualification of electrical insulation systems*

IEC TS 60815-1, *Selection and dimensioning of high-voltage insulators intended for use in polluted conditions – Part 1: Definitions, information and general principles*

ISO 2533:1975, *Standard Atmosphere*

3 Terms, definitions, abbreviated terms and symbols

3.1 Terms and definitions

No terms and definitions are listed in this document.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at <http://www.electropedia.org/>
- ISO Online browsing platform: available at <http://www.iso.org/obp>

3.2 Abbreviated terms

MOSA	metal-oxide surge arrester
SFO	slow-front overvoltage
FFO	fast-front overvoltage
VFFO	very-fast-front overvoltage
LSA	line surge arrester
EGLA	externally gapped line arrester
NGLA	non-gapped line arrester
LIWV	lightning impulse withstand voltage
SIWV	switching impulse withstand voltage
SDWV	short-duration power-frequency withstand voltage
LIPL	lightning impulse protection level
SIPL	switching impulse protection level
GIS	gas-insulated switchgear
UHV	ultra high voltage
TOV	temporary power-frequency overvoltages
SVU	series varistor unit
ESDD	equivalent salt deposit density
TCV	trapped charge voltage

3.3 Symbols

For the purpose of this document, the following symbols and definitions apply. The symbol is followed by the unit to be normally considered, dimensionless quantities being indicated by (-).

Some quantities are expressed in p.u. A per unit quantity is the ratio of the actual value of an electrical parameter (voltage, current, frequency, power, impedance, etc.) to a given reference value of the same parameter.

A	(kV)	parameter characterizing the influence of the lightning severity for the equipment depending on the type of overhead line connected to it

a_1	(m)	length of the lead connecting the surge arrester to the line
a_2	(m)	length of the lead connecting the surge arrester to earth
a_3	(m)	length of the phase conductor between the surge arrester and the protected equipment
a_4	(m)	length of the active part of the surge arrester
B	(-)	factor used when describing the phase-to-phase discharge characteristic
C_e	(nF)	capacitance to earth of transformer primary windings
C_s	(nF)	series capacitance of transformer primary windings
C_2	(nF)	phase-to-earth capacitance of the transformer secondary winding
C_{12}	(nF)	capacitance between primary and secondary windings of transformers
C_{1in}	(nF)	equivalent input capacitance of the terminal 1 of three-phase transformers
C_{2in}	(nF)	equivalent input capacitance of the terminal 2 of three-phase transformers
C_{3in}	(nF)	equivalent input capacitance of the terminal 3 of three-phase transformers
c	(m/μs)	velocity of light
c_f	(p.u.)	coupling factor of voltages between earth wire and phase conductor of overhead lines
E_0	(kV/m)	soil ionization gradient
F		function describing the cumulative distribution of overvoltage amplitudes, where $F(U) = 1 - P(U)$; see Clause B.3
f		function describing the probability density of overvoltage amplitudes
d_r	(-)	dividing ratio of capacitively transferred surges
H	(m)	altitude above sea-level
h	(-)	power-frequency voltage factor for transferred surges in transformers
H_t	(m)	height above ground
I	(kA)	lightning current amplitude
I_g	(kA)	limit lightning current in tower footing resistance calculation
I_n	(kA)	nominal discharge current of an arrester
J	(-)	winding factor for inductively transferred surges in transformers
K	(-)	gap factor taking into account the influence of the gap configuration on the strength
K_a	(-)	altitude correction factor
K_c	(-)	co-ordination factor
K_s	(-)	safety factor
K_{cd}	(-)	deterministic co-ordination factor
K_{co}	(μs/(kVm))	corona damping constant
K_{cs}	(-)	statistical co-ordination factor
K_{f+}	(-)	gap factor for fast-front impulses of positive polarity
K_{f-}	(-)	gap factor for fast-front impulses of negative polarity
K_{ev}	(-)	evaluation factor of ratio for lightning overvoltage with respect to standard voltage shape

k	(-)	earth fault factor
k_h	(-)	parameter for humidity correction
d	(m)	separation distance between surge arrester and protected equipment
L_a	(m)	overhead line length yielding to an outage rate equal to the acceptable one (related to R_a)
L_t	(m)	overhead line length for which the lightning outage rate is equal to the adopted return rate (related to R_t)
L_{sp}	(m)	span length
M	(-)	number of insulations in parallel considered to be simultaneously stressed by an overvoltage
m	(-)	exponent in the atmospheric correction factor formula for external insulation withstand
N	(-)	number of conventional deviations between U_{50} and U_{spec} of a self-restoring insulation
n	(-)	number of overhead lines considered connected to a station in the evaluation of the impinging surge amplitude
P	(%)	probability of discharge of a self-restoring insulation
P_w	(%)	probability of withstand of self-restoring insulation
q	(-)	response factor of transformer windings for inductively transferred surges
Q_{rs}	(C)	repetitive charge transfer rating of an arrester
Q_{th}	(C)	thermal charge transfer rating of an arrester
R	(-)	risk of failure (failures per event)
R_a	(1/a)	acceptable failure rate for apparatus; for transmission lines, this parameter is normally expressed in terms of (1/a)/100 km
R_{hc}	(Ω)	high current value of the tower footing resistance
R_{km}	(1/(m.a))	overhead line outage rate per year for a design corresponding to the first kilometre in front of the station
R_{lc}	(Ω)	low current value of the tower footing resistance
R_p	(1/a)	shielding penetration rate of overhead lines
R_{sf}	(1/a)	shielding failure flashover rate of overhead lines
R_t	(1/a)	adopted overvoltage return rate (reference value)
R_u	(kV)	radius of a circle in the U^+/U^- plane describing the phase-phase-earth slow-front overvoltages
R_0	(Ω)	zero sequence resistance
R_1	(Ω)	positive sequence resistance
R_2	(Ω)	negative sequence resistance
S	(kV/ μ s)	steepness of a lightning surge impinging on a substation
S_e	(kV)	conventional deviation of phase-to-earth overvoltage distribution
S_p	(kV)	conventional deviation of phase-to-phase overvoltage distribution
S_{rp}	(kV/ μ s)	representative steepness of a lightning impinging surge
s_e	(-)	normalized value of the conventional deviation S_e (S_e referred to U_{e50})
s_p	(-)	normalized value of the conventional deviation S_p (S_p referred to U_{p50})
t_s	(μ s)	travel time of a lightning surge

U	(kV)	amplitude of an overvoltage (or of a voltage)
U^+	(kV)	positive switching impulse component in a phase-to-phase insulation test
U^-	(kV)	negative switching impulse component in a phase-to-phase insulation test
U_{spec}	(kV)	truncation value of the discharge probability function $P(U)$ of a self-restoring insulation: $P(U \leq U_{\text{spec}}) = 0$
U_0^+	(kV)	equivalent positive phase-to-earth component used to represent the most critical phase-to-phase overvoltage
U_{1e}	(kV)	temporary overvoltage to earth at the neutral of the primary winding of a transformer
U_{2e}	(kV)	temporary overvoltage to earth at the neutral of the secondary winding of a transformer
U_{2N}	(kV)	rated voltage of the secondary winding of a transformer
U_{10}	(kV)	value of the 10 % discharge voltage of self-restoring insulation; this value is the statistical withstand voltage of the insulation defined in 3.23 b) of IEC 60071-1:2006
U_{16}	(kV)	value of the 16 % discharge voltage of self-restoring insulation
U_{50}	(kV)	value of the 50 % discharge voltage of self-restoring insulation
U_{50M}	(kV)	value of the 50 % discharge voltage of M parallel self-restoring insulations
U_{50RP}	(kV)	value of the 50 % discharge voltage of a rod-plane gap
U_c	(kV)	continuous operating voltage of an arrester
U_c^+	(kV)	positive component defining the centre of a circle which describes the phase-phase-earth slow-front overvoltages
U_c^-	(kV)	negative component defining the centre of a circle which describes the phase-phase-earth slow-front overvoltages
U_{cw}	(kV)	co-ordination withstand voltage of equipment.
U_e	(kV)	amplitude of a phase-to-earth overvoltage
U_{et}	(kV)	truncation value of the cumulative distribution $F(U_e)$ of the phase-to-earth overvoltages: $F(U_e \geq U_{et}) = 0$ (see Clause B.3)
U_{e2}	(kV)	value of the phase-to-earth overvoltage having a 2 % probability of being exceeded: $F(U_e \geq U_{e2}) = 0,02$ (see Clause B.3)
U_{e50}	(kV)	50 % value of the cumulative distribution $F(U_e)$ of the phase-to-earth overvoltages (see Clause B.3)
U_l	(kV)	amplitude of the impinging lightning overvoltage surge
U_m	(kV)	highest voltage for equipment
U_p	(kV)	amplitude of a phase-to-phase overvoltage
U_{p2}	(kV)	value of the phase-to-phase overvoltage having a 2 % probability of being exceeded: $F(U_p \geq U_{p2}) = 0,02$ (see Clause B.3)
U_{p50}	(kV)	50 % value of the cumulative distribution $F(U_p)$ of the phase-to-phase overvoltages (see Clause B.3)
U_r	(kV)	rated voltage of an arrester based on temporary overvoltages
U_s	(kV)	highest voltage of a system
U_w	(kV)	standard withstand voltage
U_{pl}	(kV)	lightning impulse protection level of an arrester
U_{ps}	(kV)	switching impulse protection level of an arrester

U_{pt}	(kV)	truncation value of the cumulative distribution $F(U_p)$ of the phase-to-phase overvoltages: $F(U_p \geq U_{pt}) = 0$ (see Clause B.3)
U_{rp}	(kV)	amplitude of the representative overvoltage
U_{rw}	(kV)	required withstand voltage
U_{T1}	(kV)	overvoltage applied at the primary winding of a transformer which produces (by transference) an overvoltage on the secondary winding.
U_{T2}	(kV)	overvoltage at the secondary winding of a transformer produced (by transference) by an overvoltage applied on the primary winding.
UHV	(-)	ultra high voltage: the highest voltage of the transmission system exceeding 800 kV.
u	(p.u.)	per unit value of the amplitude of an overvoltage (or of a voltage) referred to $U_s \sqrt{2}/\sqrt{3}$.
w_{21}	(-)	ratio of transformer secondary to primary phase-to-phase voltage.
W	(kJ)	required energy absorption of an arrester.
W_{th}	(kJ/kV)	thermal energy rating of an arrester.
X	(m)	distance between struck point of lightning and substation.
X_p	(km)	limit overhead line distance within which lightning events have to be considered.
X_T	(km)	overhead line length to be used in simplified lightning overvoltage calculations.
X_0	(Ω)	zero sequence reactance of a system.
X_1	(Ω)	positive sequence reactance of a system.
X_2	(Ω)	negative sequence reactance of a system.
x	(-)	normalized variable in a discharge probability function $P(U)$ of a self-restoring insulation.
x_M	(-)	normalized variable in a discharge probability function $P(U)$ of M parallel self-restoring insulations.
Z	(kV)	conventional deviation of the discharge probability function $P(U)$ of a self-restoring insulation.
Z_0	(Ω)	zero sequence impedance.
Z_1	(Ω)	positive sequence impedance.
Z_2	(Ω)	negative sequence impedance.
Z_e	(Ω)	surge impedance of the overhead line earth wire.
Z_L	(Ω)	surge impedance of the overhead line.
Z_M	(kV)	conventional deviation of the discharge probability function $P(U)$ of M parallel self-restoring insulations.
Z_s	(Ω)	surge impedance of the substation phase conductor.
z	(-)	normalized value of the conventional deviation Z referred to U_{50} .
α	(-)	ratio of the negative switching impulse component to the sum of both components (negative + positive) of a phase-to-phase overvoltage.
β	(kV)	scale parameter of a Weibull cumulative function.
U_0	(kV)	truncation value of a Weibull cumulative function.
η	(-)	electric field utilization factor.
ϕ		Gaussian integral function.

ϕ	(-)	inclination angle of a phase-to-phase insulation characteristic.
γ	(-)	shape parameter of a Weibull-3 cumulative function.
σ	(p.u.)	per unit value of the conventional deviation (S_e or S_p) of an overvoltage distribution.
ρ	(Ωm)	soil resistivity.
τ	(μs)	tail time constant of a lightning overvoltage due to back-flashovers on overhead lines.

4 Representative voltage stresses in service

4.1 Origin and classification of voltage stresses

In IEC 60071-1, the voltage stresses are classified by suitable parameters such as the duration of the power-frequency voltage or the shape of an overvoltage according to their effect on the insulation or on the protection device. The voltage stresses within these classes have several origins:

- continuous (power-frequency) voltages: they originate from the system operation under normal operating conditions;
- temporary overvoltages: they can originate from faults, switching operations such as load rejection, resonance conditions, non-linearities (ferroresonances) or by a combination of these;
- slow-front overvoltages: they can originate from faults, switching operations or direct lightning strokes to the conductors of overhead lines;
- fast-front overvoltages: they can originate from switching operations, lightning strokes or faults;
- very-fast-front overvoltages: they can originate from faults or switching operations in gas-insulated substations (GIS);
- combined overvoltages: they may have any origin mentioned above. They occur between the phases of a system (phase-to-phase), or on the same phase between separated parts of a system (longitudinal).

All the preceding overvoltage stresses, except combined overvoltages, are discussed as separate items under 4.3. Combined overvoltages are discussed where appropriate within one or more of these items.

In all classifications of voltage stresses, transference through transformers should be taken into account (see Annex D).

In general, all classes of overvoltages may exist in both voltage ranges I and II (see IEC 60071-1). However, experience has shown that certain voltage classifications are of more critical importance in a particular voltage range; this will be dealt with in this document. In any case, it should be noted that the best knowledge of the stresses (peak values and shapes) is obtained with detailed studies employing adequate models for the system and for the characteristics of the overvoltage limiting devices.

In the analysis of power system, digital simulation tools, such as electromagnetic transients simulation tool, have been used in many countries. In some countries, the comparison of analysis results and measured values is also performed in each country. Its validity has been confirmed up to UHV systems. For example, in the case of UHV lines in Japan and China, the maximum error between measurements and simulation for switching overvoltages is about

5 %, which is agreeable in the design of transmission lines. From more detailed information, reference can be made to the CIGRE activity [1]¹.

4.2 Characteristics of overvoltage protection devices

4.2.1 General remarks

To ensure a safe, reliable and economic design and operation of high voltage networks, substations and equipment, the use of overvoltage protection devices is necessary.

The overvoltage protection devices shall be designed and installed to limit the magnitudes of overvoltages at the terminals of the equipment to be protected. Generally, an effective overvoltage protection is provided against slow-front overvoltages (SFO) and fast-front overvoltages (FFO).

It has to be regarded that, especially under FFO conditions, the overvoltage at the terminals of the overvoltage protection device and of the equipment to be protected are in general not the same. Inductive voltage drops across connecting leads and, much more, travelling wave processes are responsible for that.

Metal-oxide surge arresters (MOSA) without gaps are the "standard" arresters that are to be installed in all substations or directly at the pole mounted transformers and cable terminations in distribution lines. As surge arresters have a limited protection distance in the range of only a few, up to several tens of meters, depending on the system voltage level, they shall be installed as close as possible to the equipment to be protected. It may be necessary to install additional arresters at the line entrances of substations.

In some countries, MOSA with internal series gaps are used, which are applied to power systems of U_s up to 52 kV and which are covered by their own test standard (IEC 60099-6).

Besides this general application of MOSA as protection devices, line surge arresters (LSA) are often used for overhead transmission and distribution lines. They prevent insulator flashovers due to direct lightning strikes to the conductor of an unshielded line, by a shielding failure of a shielded line or due to back flashovers. For this purpose, externally gapped (EGLA) and non-gapped (NGLA) line arresters are used.

In addition, spark gaps are still sometimes taken into account as an alternative overvoltage limiting device, although standards are not available within IEC. In general, however, surge arresters should be preferred, as spark gaps produce steep voltage rises directly at the equipment to be protected, and their sparkover characteristic under FFO is sometimes critical. As no standard exists, their sparkover voltage versus time characteristics should be requested from the manufacturer or established by the user on the basis of his own specifications.

4.2.2 Metal-oxide surge arresters without gaps (MOSA)

4.2.2.1 General

The protection characteristics and application of MOSA are specified by IEC 60099-4 and IEC 60099-5.

The general procedure for selection of surge arresters is recommended in IEC 60099-5:

- determination of continuous operating voltage U_c ;
- determination of rated voltage U_r based on temporary overvoltages;

¹ Numbers in square brackets refer to the Bibliography.

- determination of required energy absorption W and selection of nominal discharge current I_n ;
- determination of lightning impulse protection level U_{pl} and switching impulse protection level U_{ps} .

The protection levels can be used for representative slow-front and fast-front overvoltages. The co-ordination lightning impulse withstand voltage is determined under consideration of the lightning performance of the overhead lines, the acceptable failure rate of the equipment and the protection zone of the arrester.

The procedure is iterative. If, after the selection procedure, the protection levels of MOSA are too high, a lower continuous voltage, a higher nominal discharge current, a higher energy absorption capability or a reduced distance between the arrester and the protected equipment should be investigated. These measures will result either in lower MOSA residual voltages at a given impressed impulse current amplitude or in reduced overvoltage levels at the protected equipment for a given MOSA residual voltage.

The evaluation of protection levels gives a value representing a generally acceptable approximation. IEC 60099-5 gives detailed information about the protection performance of surge arresters.

4.2.2.2 Protection characteristics related to fast-front overvoltages

The following voltages characterize the fast-front protection level of a MOSA:

- lightning impulse protection level U_{pl} (also designated as LIPL);
- maximum residual voltage at steep current impulse.

The lightning impulse protection level is the maximum residual voltage at the nominal discharge current with an 8 μ s to 20 μ s (IEC 60099-4). For the insulation co-ordination of UHV systems, surge arresters with low protection levels are of particular importance. The nominal discharge current for UHV arresters is typically 20 kA.

The resulting steep current impulse (with a front time of 1 μ s) protection voltage has to be considered in case of inductive voltage drops across the connection leads and the arrester length. The background is described in IEC 60099-5.

4.2.2.3 Protection characteristics related to slow-front overvoltages

The slow-front protection level of a MOSA is characterized by the switching impulse protection level U_{ps} (also designated as SIPL), which is the maximum residual voltage at the specified switching impulse discharge current as specified in IEC 60099-4 or at other current magnitudes on agreement between arrester manufacturer and user. Inductive voltage drops and travelling wave phenomena (protection distances) does not have to be considered.

For distribution arresters, switching impulse protection levels are not specified, as this is usually not a concern in distribution systems.

Especially for UHV arresters, other switching impulse currents may be used due to the possible suppression of slow-front overvoltages in UHV systems by adopting the following measures:

- controlled switching;
- circuit breakers with closing or closing/opening resistors;
- any combination of the above measures.

4.2.2.4 Energy handling capability

Energy handling capability of a MOSA is defined by two characteristics.

- a) For distribution ("D") arresters, which are further sub-classified as DH, DM, DL arresters (the letters "H", "M" and "L" in the designation standing for "high", "medium" and "low" duty, respectively):
- repetitive charge transfer rating, Q_{rs} ;
 - thermal charge transfer rating, Q_{th} .
- b) For station ("S") arresters, which are further sub-classified as SH, SM, SL arresters:
- repetitive charge transfer rating, Q_{rs} ;
 - thermal energy rating, W_{th} .

NOTE The former line discharge class system for station arresters does not exist anymore since IEC 60099-4:2014.

4.2.3 Line surge arresters (LSA) for overhead transmission and distribution lines

Purpose and characteristics of line surge arresters are described in IEC 60099-5. Non gapped line arresters (NGLA) are basically standard MOSA, tested according to IEC 60099-4, while externally gapped line arresters (EGLA) are tested according to IEC 60099-8.

Energy handling capability of NGLAs is defined, in addition to the characteristics of MOSA, by their rated lightning impulse discharge capability.

EGLAs protect insulator assemblies only from lightning-caused flashovers. Therefore, it is important to determine the lightning impulse protection characteristics of the arrester comprising the sparkover voltage for fast-front and standard lightning impulse, and the residual voltages for the nominal discharge current. Additionally, the insulation withstand of the EGLA with respect to maximum slow-front overvoltages on the system has to be determined.

The correct co-ordination between flashover characteristics of the insulator assembly and the sparkover voltage of the EGLA shall be demonstrated with standard lightning impulse voltage and the residual voltages. Any sparkover operation under lightning impulse voltage shall occur in the external series gap of the EGLA without causing any flashover of the insulator assembly to be protected.

EGLAs have no operating duties for slow-front surges and temporary power-frequency overvoltages (TOV).

EGLAs shall not operate, in sound as well as in failed (overloaded) condition of the series varistor unit (SVU), at the specified switching impulse withstand voltage and maximum TOV level of the system.

The rated voltage of an EGLA is the maximum permissible RMS value of power frequency voltage between its terminals, at which it is designed to operate correctly. It shall, therefore, be equal to or higher than the maximum power-frequency temporary overvoltage expected in the intended installation. The rated voltage is also used as a reference parameter for the specification of operating and current interrupting characteristics.

EGLAs are classified by their nominal discharge currents and their high current impulse withstand capabilities. Two alternative classification systems are available ("Series X" and "Series Y"; for details see IEC 60099-8).

4.3 Representative voltages and overvoltages

4.3.1 Continuous (power-frequency) voltage

Under normal operating conditions, the power-frequency voltage can be expected to vary somewhat in magnitude and to differ from one point of the system to another. For purposes of insulation design and co-ordination, the representative continuous power-frequency voltage

shall, however, be considered as constant and equal to the highest system voltage. In practice, up to 72,5 kV, the highest system voltage U_s may be substantially lower than the highest voltage for equipment U_m , while, with the increase of the voltage, both values tend to become equal.

4.3.2 Temporary overvoltages

4.3.2.1 General

Temporary overvoltages are characterized by their amplitudes, their voltage shape and their duration. All parameters depend on the origin of the overvoltages, and amplitudes and shapes may even vary during the overvoltage duration.

For insulation co-ordination purposes, the representative temporary overvoltage is considered to have the shape of the standard short duration (1 min) power-frequency voltage. Its amplitude may be defined by one value (the assumed maximum), a set of peak values, or a complete statistical distribution of peak values. The selected amplitude of the representative temporary overvoltage shall take into account

- the amplitude and duration of the actual overvoltage in service, and
- the amplitude/duration power frequency withstand characteristic of the insulation considered.

If the latter characteristic is not known, as a simplification the amplitude may be taken as equal to the actual maximum overvoltage having an actual duration of less than 1 min in service, and the duration may be taken as 1 min.

In particular cases, a statistical co-ordination procedure may be adopted describing the representative overvoltage by an amplitude/duration distribution frequency of the temporary overvoltages expected in service (see 5.3.2).

4.3.2.2 Earth faults

A phase-to-earth fault may result in phase-to-earth overvoltages affecting the two other phases. Temporary overvoltages between phases or across longitudinal insulation normally do not arise. The overvoltage shape is a power-frequency voltage.

The overvoltage amplitudes depend on the system neutral earthing and the fault location. Guidance for their determination is given in Annex A. In normal system configurations, the representative overvoltage amplitude should be assumed equal to its maximum value. Abnormal system configurations, for example system parts with unearthed neutrals in a normally earthed neutral system, should be dealt with separately, taking into account their probability of occurrence simultaneously with earth faults.

The duration of the overvoltage corresponds to the duration of the fault (until fault clearing). In earthed neutral systems, it is generally less than 1 s. In resonant earthed neutral systems with fault clearing it is generally less than 10 s. In systems without earth-fault clearing, the duration may be several hours. In such cases, it may be necessary to define the continuous power-frequency voltage as the value of temporary overvoltage during earth fault.

NOTE Attention is drawn to the fact that the highest voltage at power-frequency which can appear on a sound phase during the occurrence of an earth fault depends not only on the earth fault factor but also on the value of the operating voltage at the time of the fault which can be generally taken as the highest system voltage U_s .

4.3.2.3 Load rejection

Phase-to-earth and longitudinal temporary overvoltages due to load rejection depend on the rejected load, on the system layout after disconnection and on the characteristics of the sources (short-circuit power at the station, speed and voltage regulation of the generators, etc.).

The three phase-to-earth voltage rises are identical and, therefore, the same relative overvoltages occur phase-to-earth and phase-to-phase. These rises may be especially important in the case of load rejection at the remote end of a long line (Ferranti effect) and they mainly affect the apparatus at the station connected on the source side of the remote open circuit-breaker.

The longitudinal temporary overvoltages depend on the degree of phase angle difference after network separation, the worst possible situation being a phase opposition.

From the point of view of overvoltages, a distinction should be made between various types of system layouts. As examples, the following extreme cases can be considered:

- systems with relatively short lines and high values of the short-circuit power at the terminal stations, where low overvoltages occur;
- systems with long lines and low values of the short-circuit power at the generating site, which are usually in the extra-high voltage range at their initial stage, and on which very high overvoltages can arise if a large load is suddenly disconnected.

In analysing temporary overvoltages, it is recommended that consideration be given to the following (where the 1,0 p.u. reference voltage equals $U_s \sqrt{2}/\sqrt{3}$)

- In moderately extended systems, a full load rejection can give rise to phase-to-earth overvoltages with amplitude usually below 1,2 p.u. The overvoltage duration depends on the operation of voltage-control equipment and may be up to several minutes;
- In extended systems, after a full load rejection, the phase-to-earth overvoltages may reach 1,5 p.u., or even more when Ferranti or resonance effects occur. Their duration may be in the order of some seconds;
- If only static loads are on the rejected side, the longitudinal temporary overvoltage is normally equal to the phase-to-earth overvoltage. In systems with motors or generators on the rejected side, a network separation can give rise to a longitudinal temporary overvoltage composed of two phase-to-earth overvoltage components in phase opposition, whose maximum amplitude is normally below 2,5 p.u. (greater values can be observed for exceptional cases such as very extended high-voltage systems).

4.3.2.4 Resonance and ferroresonance

Temporary overvoltages due to resonance and ferroresonance generally arise when circuits with large capacitive elements (lines, cables, series compensated lines) and inductive elements (transformers, shunt reactors) having non-linear magnetizing characteristics are energized, or as a result of load rejections.

Temporary overvoltages due to resonance phenomena can reach extremely high values. They shall be prevented or limited by measures recommended in 4.3.2.7. They shall therefore not normally be considered as the basis for the selection of the surge arrester rated voltage or for the insulation design unless these remedial measures are not sufficient (see 4.3.2.8).

4.3.2.5 Longitudinal overvoltages during synchronization

The representative longitudinal temporary overvoltages are derived from the expected overvoltage in service which has an amplitude equal to twice the phase-to-earth operating voltage and a duration of several seconds to some minutes.

Furthermore, when synchronization is frequent, the probability of occurrence of an earth fault and consequent overvoltage shall be considered. In such cases, the representative overvoltage amplitudes are the sum of the assumed maximum earth-fault overvoltage on one terminal and the continuous operating voltage in phase opposition on the other.

4.3.2.6 Combinations of temporary overvoltage origins

4.3.2.6.1 General

Temporary overvoltages of different origins shall be treated as combined only after careful examination of their probability of simultaneous occurrence. Such combinations may lead to higher arrester ratings with the consequence of higher protection and insulation levels; this is technically and economically justified only if this probability of simultaneous occurrence is sufficiently high.

4.3.2.6.2 Earth fault with load rejection

The combination earth fault with load rejection can exist when, during a fault on the line, the load side breaker opens first and the disconnected load causes a load rejection overvoltage in the still faulted part of the system until the supply side circuit-breaker opens.

The combination earth fault with load rejection can also exist when a large load is switched off and the temporary overvoltage due to this causes a subsequent earth fault on the remaining system. The probability of such an event, however, is small when the overvoltages due to the change of load are themselves small, and a subsequent fault is only likely to occur in extreme conditions such as in massive pollution conditions.

The combination can further occur as a result of a line fault followed by failure of a circuit-breaker to open. The probability of such a combination, although small, is not negligible since these events are not statistically independent. Such an occurrence, which results in a generator connected through a transformer to a faulted long line, can result in significant overvoltage on the healthy phases. The overvoltage consists of a slow-front transient and a prolonged variable temporary overvoltage which is a function of generator characteristics and governor-voltage regulator actions.

If such combinations are considered probable, system studies are recommended. Without such studies, one may be led to believe that it is necessary to combine these overvoltages, but this is considered too pessimistic for the following reasons:

- the earth fault factor changes when it is related to the load rejection overvoltage;
- the system configuration has changed after the load change – for example, the earth fault factor at generator transformers with earthed neutral is less than 1 after being disconnected from the system;
- for system transformers, the loss of full rated load is not usual.

4.3.2.6.3 Other combinations

As resonance phenomena should be avoided, their combination with other origins should only be considered as an additional result of these resonances. In some systems, however, it is not readily possible to avoid resonance phenomena, and, for such systems, it is important to carry out detailed studies.

4.3.2.7 Limitation of temporary overvoltages

4.3.2.7.1 Earth-fault overvoltages

Earth-fault overvoltages depend on the system parameters and can only be controlled by selecting these parameters during the system design. The overvoltage amplitudes are normally less severe in earthed neutral systems. However, an exception exists in earthed neutral systems, a part of which in unusual situations can become separated with unearthed transformer neutrals. In such a situation, the duration of the high overvoltages due to earth faults in the separated part can be controlled by fast earthing at these neutrals, by switches or by specially selected neutral surge arresters, which short-circuit the neutral after failing.

4.3.2.7.2 Sudden changes of load

These overvoltages can be controlled by shunt reactors, series capacitors or static compensators.

4.3.2.7.3 Resonance and ferroresonance

These overvoltages should be limited by de-tuning the system from the resonance frequency, by changing the system configuration, or by damping resistors.

4.3.2.8 Surge arrester protection against temporary overvoltages

Usually, the selection of the rated voltage of the surge arrester is based upon the envelope of the temporary overvoltage expected, taking into account the energy dissipation capability of the surge arrester. In general, matching the surge arrester rating with the temporary overvoltage stress is more critical in range II, where the margins are lower, than in range I. Usually, the energy capability of the surge arrester under temporary overvoltage stress is expressed as an amplitude/duration characteristic furnished by the manufacturer.

For practical purposes, surge arresters do not limit temporary overvoltages. An exception is given for temporary overvoltages due to resonance effects, for which surge arresters may be applied to limit or even to prevent such overvoltages. For such an application, careful studies on the thermal stresses imposed on the surge arresters should be performed to avoid their overloading.

4.3.3 Slow-front overvoltages

4.3.3.1 General

Slow-front overvoltages have front durations of some tens to some thousands of microseconds and tail durations in the same order of magnitude, and are oscillatory by nature. They generally arise from:

- line energization and re-energization;
- faults and fault clearing;
- load rejections;
- switching of capacitive or inductive currents;
- distant lightning strokes to the conductor of overhead lines.

The representative voltage stress is characterized by

- a representative voltage shape, and
- a representative amplitude which can be either an assumed maximum overvoltage or a probability distribution of the overvoltage amplitudes.

The representative voltage shape is the standard switching impulse (time to peak 250 μ s, and time to half-value on the tail 2 500 μ s). The representative amplitude is the amplitude of the overvoltage considered independently from its actual time to peak. However, in some systems in range II, overvoltages with very long fronts may occur and the representative amplitude may be derived by taking into account the influence of the front duration upon the dielectric strength of the insulation.

The probability distribution of the overvoltages without surge arrester operation is characterized by its 2 % value, its deviation and its truncation value. Although not perfectly valid, the probability distribution can be approximated by a Gaussian distribution between the 50 % value and the truncation value, above which no values are assumed to exist. Alternatively, a modified Weibull distribution may be used (see Annex B).

The assumed maximum value of the representative overvoltage is equal to the truncation value of the overvoltages (see 4.3.3.2 to 4.3.3.7) or equal to the switching impulse protection level of the surge arrester (see 4.3.3.8), whichever is the lower value.

4.3.3.2 Overvoltages due to line energization and re-energization

4.3.3.2.1 General

A three-phase line energization or re-energization produces switching overvoltages on all three phases of the line. Therefore, each switching operation produces three phase-to-earth and, correspondingly, three phase-to-phase overvoltages [1].

In the evaluation of the overvoltages for practical application, several simplifications have been introduced. Concerning the number of overvoltages per switching operation, two methods are in use.

- Phase-peak method: from each switching operation, the highest peak value of the overvoltage on each phase-to-earth or between each combination of phases is included in the overvoltage probability distribution, i.e. each operation contributes three peak values to the representative overvoltage probability distribution. This distribution then has to be assumed to be equal for each of the three insulations involved in each part of insulation, phase-to-earth, phase-to-phase or longitudinal.
- Case-peak method: from each switching operation, the highest peak value of the overvoltages of all three phases to earth or between all three phases is included in the overvoltage probability distribution, i.e. each operation contributes one value to the representative overvoltage distribution. This distribution is then applicable to one insulation within each type.

The overvoltage amplitudes due to line energization depend on several factors including type of circuit-breaker (closing resistor or not), nature and short-circuit power of the busbar from which the line is energized, the nature of the compensation used and the length of the energized line, type of the line termination (open, transformer, surge arrester), etc.

Three-phase re-energizations may generate high slow-front overvoltages due to trapped charges on the re-energized line. At the time of the re-energization, the amplitude of the overvoltage remaining on the line (due to the trapped charge) may be as high as the temporary overvoltage peak. The discharge of this trapped charge depends on the equipment remaining connected to the line, insulator surface conductivity, conductor corona conditions, and re-closing time.

In normal systems single-phase re-energization (re-closing) does not generate overvoltages higher than those from energization. However, for lines in which resonance or Ferranti effects may be significant, single-phase re-closing may result in higher overvoltages than three-phase energization.

The correct probability distribution of the overvoltage amplitudes can be obtained only from careful simulation of switching operations by digital computation, transient analysers, etc., and typical values such as shown in Figure 1 should be considered only as a rough guide. All considerations relate to the overvoltages at the open end of the line (receiving end). The overvoltages at the sending end may be substantially smaller than those at the open end. For reasons given in Annex C, Figure 1 may be used for both the phase-peak and case-peak methods.

4.3.3.2.2 Phase-to-earth overvoltages

A procedure for the estimation of the probability distribution of the representative overvoltages is given in Annex C.

As a rough guide, Figure 1 shows the range of the 2 % overvoltage values (in p.u. of $U_s \sqrt{2}/\sqrt{3}$) which may be expected between phase and earth without limitation by surge arresters [5]. The data in Figure 1 are based on a number of field results and studies and include the effects of most of the factors determining the overvoltages.

Figure 1 should be used as an indication of whether or not the overvoltages for a given situation can be high enough to cause a problem. If so, the range of values indicates to what extent the overvoltages can be limited. For this purpose, detailed studies would be required.

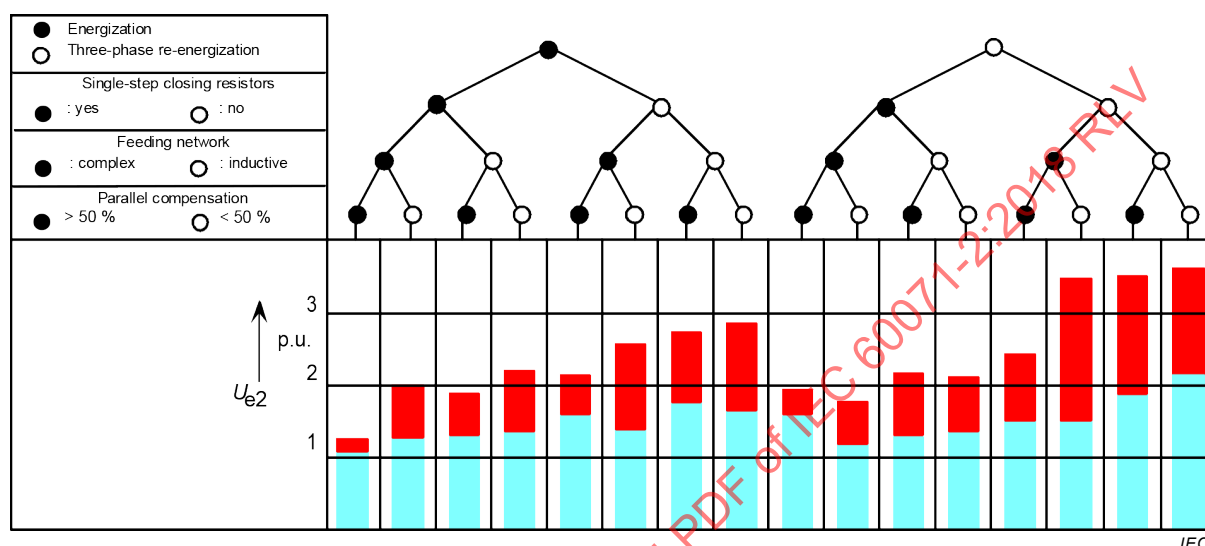


Figure 1 – Range of 2 % slow-front overvoltages at the receiving end due to line energization and re-energization

4.3.3.2.3 Phase-to-phase overvoltages

In the evaluation of the phase-to-phase overvoltages, an additional parameter needs to be added. As the insulation is sensitive to the subdivision of a given phase-to-phase overvoltage value into two phase-to-earth components, the selection of a specific instant shall take into account the insulation characteristics. Two instants have been selected [1]:

- instant of phase-to-phase overvoltage peak: this instant gives the highest phase-to-phase overvoltage value. It represents the highest stress for all insulation configurations, for which the dielectric strength between phases is not sensitive to the subdivision into components. Typical examples are the insulation between windings or short air clearances,
- phase-to-phase overvoltage at the instant of the phase-to-earth overvoltage peak: although this instant gives lower overvoltage values than the instant of the phase-to-phase overvoltage peak, it may be more severe for insulation configurations for which the dielectric strength between phases is influenced by the subdivision into components. Typical examples are large air clearances, for which the instant of the positive phase-to-earth peak is most severe, or gas-insulated substations (three-phase enclosed), for which the negative peak is most severe.

The statistical characteristics of the phase-to-phase overvoltages and the relations between the values belonging to the two instants are described in Annex C. It is concluded that for all insulation types, except for air clearances in range II, the representative overvoltage between phases is equal to the phase-to-phase overvoltage peak. For air clearances in range II, and more particularly for system voltages equal to or greater than 500 kV, the representative phase-to-phase overvoltage should be determined from the overvoltage peaks phase-to-earth and phase-to-phase as described in Annex C.

The 2 % phase-to-phase overvoltage value can approximately be determined from the phase-to-earth overvoltage. Figure 2 shows the range of possible ratios between the 2 % values phase-to-phase and phase-to-earth. The upper limit of this range applies to fast three-phase re-energization overvoltages, the lower limit to three-phase energization overvoltages.

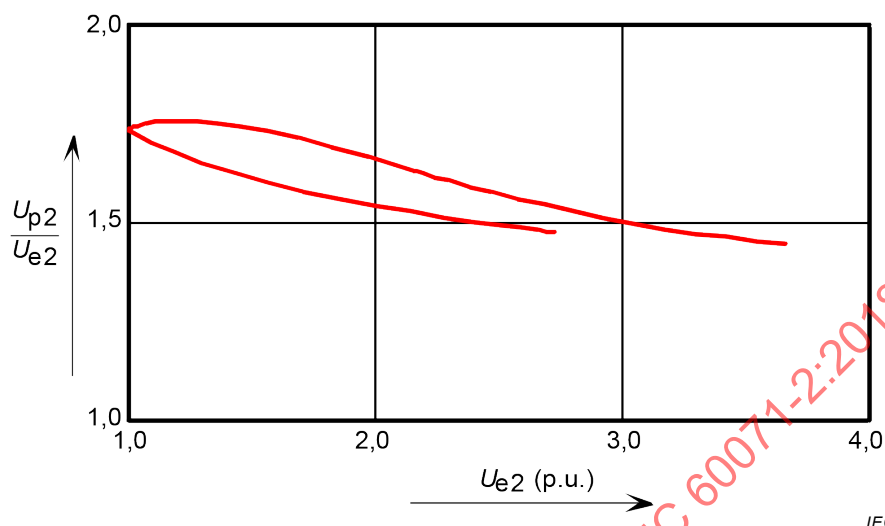


Figure 2 – Ratio between the 2 % values of slow-front overvoltages phase-to-phase and phase-to-earth

4.3.3.2.4 Longitudinal overvoltages

Longitudinal overvoltages between the terminals during energization or re-energization are composed of the continuous operating voltage at one terminal and the switching overvoltage at the other. In synchronized systems, the highest switching overvoltage peak and the operating voltage have the same polarity, and the longitudinal insulation has a lower overvoltage than the phase-to-earth insulation.

The longitudinal insulation between non-synchronous systems, however, can be subjected to energization overvoltages at one terminal and the normal operating voltage peak of opposite polarity at the other.

For the slow-front overvoltage component, the same principles as for the phase-to-earth insulations apply.

4.3.3.2.5 Assumed maximum overvoltages

If no protection by surge arresters is applied, the assumed maximum energization or re-energization overvoltage is:

- for the phase-to-earth overvoltage: the truncation value U_{et} ;
- for the phase-to-phase overvoltage: the truncation value U_{pt} or, for the external insulation in range II, the value determined according to Annex C, both subdivided into two equal components with opposite polarities;
- for the longitudinal overvoltage: the truncation value U_{et} of the phase-to-earth overvoltage due to energization at one terminal, and the opposite polarity peak of the normal operating voltage at the other terminal.

This definition of the maximum longitudinal overvoltage assumes that power frequencies are synchronized (via a parallel path) at both terminals so that the longitudinal overvoltages due to re-energization need not be considered separately (because the effect of any trapped charge is taken into account by this assumption).

4.3.3.3 Fault and fault-clearing overvoltages

Slow-front overvoltages are generated at fault-initiation and fault-clearing by the change in voltage from operating voltage to temporary overvoltage on the healthy phases and the return from a value close to zero back to the operating voltage on the faulted phase. Both origins cause only overvoltages between phase and earth. The overvoltages between phases can be neglected. Conservative estimates for the assumed maximum value of the representative overvoltage U_{et} are as follows:

- fault initiation $U_{et} = (2k - 1) U_s \sqrt{2}/\sqrt{3}$ (kV crest)

where k is the earth fault factor.

- fault clearing $U_{et} = 2,0 U_s \sqrt{2}/\sqrt{3}$ (kV crest)

In range I, overvoltages caused by earth faults shall be considered for systems with isolated or resonant earthed transformer neutrals in which the earth fault factor is approximately equal to $\sqrt{3}$. For these systems, the insulation co-ordination can be based on the assumed maximum overvoltage and the probability of their amplitudes needs no consideration.

In range II, when the overvoltages due to line energization or re-energization are controlled to values below 2 p.u., fault and fault clearing overvoltages require careful examination if they are not controlled to the same degree.

4.3.3.4 Overvoltages due to load rejection

Slow-front overvoltages due to load rejection are only of importance in systems of range II in which the energization and re-energization overvoltages are controlled to values below 2 p.u. In these cases, they need examination, especially when generator transformers or long transmission lines are involved.

4.3.3.5 Overvoltages due to switching of inductive and capacitive currents

The switching of inductive or capacitive currents can give rise to overvoltages, which may require attention. In particular, the following switching operations should be taken into consideration:

- interruption of the starting currents of motors;
- interruption of inductive currents, for example when interrupting the magnetizing current of a transformer or when switching off a shunt reactor [6];
- switching and operation of arc furnaces and their transformers, which may lead to current chopping;
- switching of unloaded cables and of capacitor banks;
- interruption of currents by high-voltage fuses.

Restrikes of circuit-breakers occurring while interrupting capacitive currents (switching off unloaded lines, cables or capacitor banks) may generate particularly dangerous overvoltages and the use of restrike-free breakers is necessary. Furthermore, when energizing capacitor banks, in particular ungrounded banks, care should be taken to assess the phase-to-phase overvoltages (see also 4.3.4.3).

4.3.3.6 Slow-front lightning overvoltages

In systems with long lines (longer than 100 km), slow-front lightning overvoltages originate from distant lightning strokes to the phase conductor, when the lightning current is sufficiently small so as not to cause a flashover of the line insulation and when the strike occurs at a sufficient distance from the considered location to produce a slow-front.

As lightning currents have times to half-value rarely exceeding 200 μ s, overvoltages with high amplitudes and times-to-crest critical for the insulation do not occur. Slow-front lightning overvoltages, therefore, are of minor importance for insulation co-ordination and are usually neglected.

4.3.3.7 Limitation of slow-front overvoltages

The most commonly used method of limiting line switching overvoltages is by the use of closing resistors on line breakers. Other means, like point-on-wave control and varistors across interrupting chambers, can also be used to limit overvoltages due to line energization and inductive or capacitive switching.

Inductive voltage transformers connected to the line terminals effectively reduce the charges trapped on the phases of the line after opening. The slow front overvoltages due to a subsequent three-phase re-energization are thus limited to the level of simple line energization.

The saturation effect of the switching impulse strength has a large impact to the air clearances. Closing or opening resistors, surge arresters and/or controlled switching can reduce switching overvoltages.

4.3.3.8 Surge arrester protection against slow-front overvoltages

Metal-oxide arresters without gaps and specially designed gapped arresters are suitable to protect against slow-front overvoltages in systems with moderate temporary overvoltages, whereas non-linear resistor type arresters operate for slow-front overvoltages only in extreme cases due to the sparkover characteristics of the series gap.

NOTE When the arresters are installed at the ends of long transmission lines for the purpose of limiting slow-front overvoltages, the overvoltages in the middle of the line can be substantially higher than at the line ends.

As a general rule, it can be assumed that metal-oxide arresters limit the phase-to-earth overvoltage amplitudes (kV peak) to approximately twice the arrester rated voltage (kV RMS). This means that metal-oxide surge arresters are suitable for limiting slow-front overvoltages due to line energization and re-energization and switching of inductive and capacitive currents, but not, in general, overvoltages caused by earth faults and fault clearing, as the expected amplitudes of the latter are too low (exception may be made in the case of faults occurring on series-compensated lines).

Overvoltages originating from line energization and re-energization give currents normally less than about 0,5 kA to 2 kA through the arresters (see IEC 60099-4). In this current range, the knowledge of the exact current amplitude is not so important owing to the extreme non-linearity of the metal-oxide material. The slight dependence on current front times which the metal-oxide surge arresters exhibit is also negligible for slow-front overvoltages and can be neglected. Furthermore, it is not necessary to take separation effects into account within substations. Distant overhead line insulation, however, may be stressed by overvoltages substantially higher than the protection level.

Surge arresters are usually installed phase-to-earth and it should be observed that, if metal-oxide arresters are used to limit slow-front overvoltages to a level lower than 70 % of the 2 % value of the uncontrolled overvoltage phase-to-earth, the phase-to-phase overvoltages may reach about twice the phase-to-earth protection level of the arrester. The phase-to-phase overvoltage will then consist of two phase-to-earth components with the most frequent subdivision 1:1 [7]. See also 5.3.4.1.

The assumed maximum value of the representative phase-to-earth overvoltage is equal to the protection level of the surge arrester: $U_{rp} = U_{ps}$.

For the phase-to-phase overvoltages, it is twice the protection level or the truncation value of the phase-to-phase overvoltages determined in Annex C, whichever is the smaller value. If

lower phase-to-phase overvoltages are required, additional arresters between phases should be installed.

In all cases, the application of surge arresters to control slow-front overvoltages shall take into account the required duty cycle and energy dissipation requirements in choosing the appropriate surge arrester classification.

4.3.4 Fast-front overvoltages

4.3.4.1 Lightning overvoltages affecting overhead lines

Lightning overvoltages are caused by direct strokes to the phase conductors or by back-flashovers, or are induced by lightning strokes to earth close to the line. Induced lightning surges generally cause overvoltages below 400 kV on the overhead line and are, therefore, of importance only for systems in the lower system voltage range. Owing to the high insulation withstand, back-flashovers are less probable in range II than in range I and are rare on systems at 500 kV and above.

The representative shape of the lightning overvoltage is the standard lightning impulse (1,2/50 μ s). The representative amplitude is either given as an assumed maximum or by a probability distribution of peak values usually given as the peak value dependent on the overvoltage return rate.

4.3.4.2 Lightning overvoltages affecting substations

4.3.4.2.1 General

The lightning overvoltages in substations and their rates of occurrence depend on

- the lightning performance of the overhead lines connected to it,
- the substation layout, size and in particular the number of lines connected to it, and
- the instantaneous value of the operating voltage (at the moment of the stroke).

The severity of lightning overvoltages for the substation equipment is determined from the combination of these three factors, and several steps are necessary to assure adequate protection. The amplitudes of the overvoltages (without limitation by surge arrester) are usually too high to base insulation co-ordination on these values. In some cases, however, in particular with cable connected substations, the self-protection provided by the low surge impedance of the cables may reduce the amplitudes of the lightning overvoltages to suitably low values (see Annex E).

For the phase-to-phase and the longitudinal insulation, the instantaneous power frequency voltage value on the opposite terminals shall be considered. For the phase-to-phase insulation, it can be assumed that the effects of power-frequency voltage and coupling between the overhead line conductors cancel each other and the opposite terminal can be considered as earthed. For the longitudinal insulation, however, such cancelling effects do not exist and the power-frequency voltage shall be taken into account.

4.3.4.2.2 Direct strokes

Shielding penetrations occur at a random point on the power-frequency wave. The effect of the power-frequency at the opposite terminal of a longitudinal insulation has to be taken into account by

- calculating the lightning overvoltage return rates for different instantaneous values of the operating voltage,
- evaluating the insulation failure probability for the various subdivisions into components – usually the sum of the two components is the decisive parameter,

- determining the insulation failure rate dependent on the sum of the lightning overvoltage and of the instantaneous value of power-frequency, and
- applying the performance criterion to this expected failure rate to obtain the necessary sum of the two components.

If this sum is subdivided into a lightning impulse component equal to the representative lightning overvoltage phase-to-earth and a power-frequency component, the power-frequency voltage component will be smaller than the operating voltage phase-to-earth peak. It has been found that a factor of 0,7 may be considered suitable. This means that, for shielding penetration, the longitudinal representative overvoltage should be composed of the representative lightning overvoltage to earth at one terminal and 0,7 times the operating voltage phase-to-earth peak with opposite polarity at the other.

4.3.4.2.3 Back flashovers

Back flashovers are most likely to occur on the phase which has the highest instantaneous power-frequency voltage value of opposite polarity. This means that, for substations, the representative longitudinal lightning overvoltage shall be equal to the sum of the representative lightning overvoltage to earth at one terminal and of the operating voltage peak at the other (opposite polarity).

4.3.4.3 Overvoltages due to switching operations and faults

Fast-front switching overvoltages occur when equipment is connected to or disconnected from the system via short connections mainly within substations. Fast-front overvoltages can also occur when external insulation flashes over. Such events can cause particularly severe stresses on nearby internal insulation (such as windings).

Although in general oscillatory, for insulation co-ordination purposes the representative overvoltage shape can be considered to correspond to the standard lightning impulse (1,2/50 μ s). However, special attention should be paid to equipment with windings because of high inter-turn stresses.

The maximum peak overvoltages depend on type and behaviour of the switching equipment. As the overvoltage peak values are usually smaller than those caused by lightning, their importance is restricted to special cases. It is, therefore, technically justified to characterize the amplitude of the representative overvoltage by the maximum following values (in p.u. of $U_s \sqrt{2}/\sqrt{3}$):

- circuit-breaker switching without restrike: 2 p.u.;
- circuit-breaker switching with restrike: 3 p.u.;

NOTE When switching reactive loads, some types of medium voltage circuit breakers tend to produce multiple transient current interruptions resulting in overvoltages up to 6 p.u. unless appropriate protection measures are taken.

- disconnecter switching: 3 p.u.

As simultaneous occurrence of fast-front switching overvoltages on more than one phase is highly improbable, one can assume that phase-to-phase overvoltages higher than phase-to-earth overvoltages do not exist. For the latter, the previously defined assumed maximum values can be used to check the importance of such overvoltages. If they determine the insulation lightning impulse withstand voltage, more careful investigations are recommended.

4.3.4.4 Limitation of fast-front overvoltage occurrences

Lightning overvoltage occurrences can be limited by appropriate design for the overhead lines. Possible design measures for the limitation of lightning overvoltage occurrences are the following:

- for direct lightning strokes to conductors: appropriate earth-wire shielding design;

- for back flashovers: reduction of the tower footing earthing impedance or addition of insulation;
- usage of line surge arresters.

In some cases, earthed crossarms or spark gaps have been used close to substations in an attempt to limit the amplitude of incoming lightning overvoltages. However, such measures tend to increase the likelihood of flashovers near the station with the consequent generation of fast-front surges. Furthermore, special attention should be given to shielding and tower earthing near the station to lower the probability of back flashovers at this location.

Since transmission towers in range II are taller and inter-phase distances are longer than those in range I, direct lightning strokes to phase conductors should be a matter of some concern in range II even though a ground wire is equipped, especially over 550 kV systems.

The severity of fast-front overvoltages generated by switching operations can be limited by the selection of adequate switching equipment (restrike-free interrupters or breakers, low current chopping characteristic, use of opening or closing resistors, point-on-wave control, etc.).

4.3.4.5 Surge arrester protection against fast-front overvoltages

The protection afforded by surge arresters against fast-front overvoltages depends on

- the amplitude and shape of the overvoltage,
- the protection characteristic of the surge arrester,
- the amplitude and shape of the current through the surge arrester,
- the surge impedance and/or capacitance of the protected equipment,
- the distance between arrester and protected equipment including earthing connections (see Figure 3), and
- the number and surge impedance of the connected lines.

For protection against lightning overvoltages, surge arresters with the following nominal discharge currents are generally applied:

- for systems with U_m in range I: 5 kA or 10 kA;
- for systems with U_m in range II: 10 kA or 20 kA.

When currents through the arrester are expected to be higher than its nominal discharge current, it shall be verified that the corresponding residual voltages still provide a suitable overvoltage limitation.

For the determination of the energy absorption (due to lightning) of surge arresters installed in a substation, it is usually sufficient to assume that the representative amplitude of the prospective lightning overvoltage reaching the substation is equal to the negative 50 % lightning impulse withstand voltage of the overhead line. However, for the total energy absorption, one should consider the possibility that a lightning flash may consist of multiple strokes.

The protection characteristics of a surge arrester are only valid at its location. The corresponding overvoltage limitation at the equipment location, therefore, should account for the separation between the two locations. The greater the separation distance of the surge arrester from the protected equipment, the less is its protection efficient for this equipment, and, in fact, the overvoltage applied to the equipment increases above the protection level of the arrester with increasing separation distance. Furthermore, if the effect due to the length of the arrester is neglected in the determination of its protection characteristics, this length shall be added to the length of the connecting leads in the evaluation of the effective overvoltage limitation. For metal-oxide arresters without gaps, the reaction time of the material itself may be neglected and the arrester length can be added to the connection leads.

For simplified estimation of the representative overvoltage at the protected object, Equation (1) can be used. However, for transformer protection, Equation (1) should be used with caution since a capacitance of more than a few hundred picofarads may result in higher overvoltages.

$$U_{rp} = U_{pl} + 2St_s \quad \text{for } U_{pl} \geq 2St_s \quad (1)$$

$$U_{rp} = 2 U_{pl} \quad \text{for } U_{pl} < 2St_s \quad (2)$$

where

U_{pl} is the lightning impulse protective level of the arrester (kV);

S is the steepness of the impinging surge (kV/μs);

t_s is the travel time of the lightning surge determined as following:

$$t_s = L / c \quad (3)$$

where

c is the velocity of light (300 m/μs);

L is the sum of a_1 , a_2 , a_3 , and a_4 (distances from Figure 3 [m]).

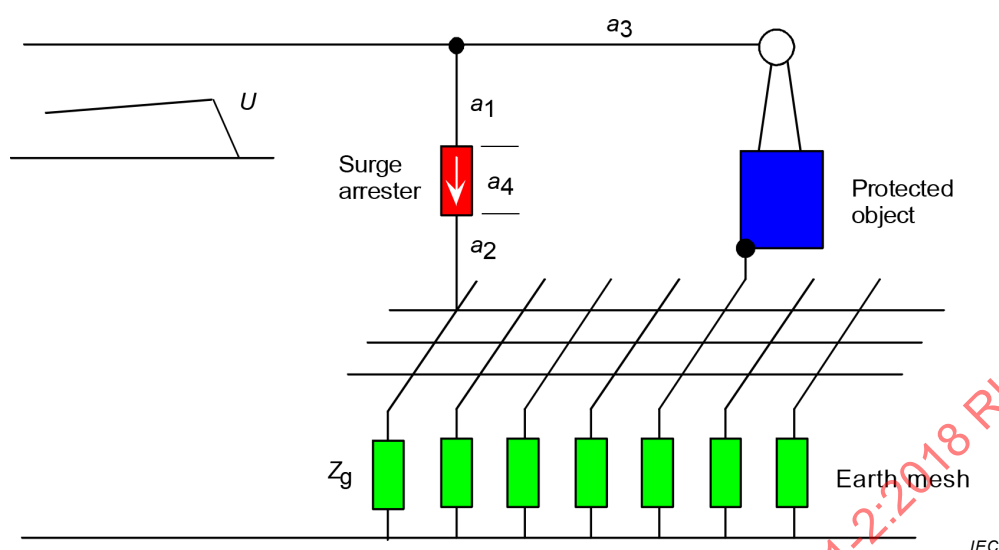
The values of the steepness shall be selected according to the lightning performance of the overhead lines connected to the station and on the adopted risk of failure in the substation. A complete treatment is given in Annex E.

The probability distribution of the representative lightning overvoltage amplitude at the substation can be determined by transient overvoltage calculations taking into account the lightning performance of the transmission lines, the travelling wave behaviour of overhead lines and substation and the performance of the equipment insulation and of the surge arresters dependent on the overvoltage amplitude and shape. References are given in Annex E.

As a general recommendation, the dependence of the insulation withstand on the overvoltage shape should also be considered in the determination of the representative amplitudes. This, in particular, applies to external insulation and to oil-paper insulation, for which the volt-time curve of the insulation may point to representative amplitudes substantially lower than the overvoltage peak values. For GIS or for solid insulation, this difference is negligible and the amplitude of the representative overvoltage is equal to the overvoltage peak.

A simplified method to estimate the representative lightning overvoltage amplitude probability distribution is given in Annex E. The assumed maximum value of the representative lightning overvoltage amplitude is either the truncation value of the probability distribution or a value obtained from experience in existing systems. Methods for the estimation of these values are also included in Annex E.

Recently, digital simulation is used in general. The numerical modelling of power facilities and equipment has become increasingly precise, enabling accurate calculation for lightning overvoltages. Technical guidance is provided in IEC TR 60071-4.

**Key**

- a_1 length of the lead connecting the surge arrester to the line
- a_2 length of the lead connecting the surge arrester to earth
- a_3 length of the phase conductor between the surge arrester and the protected equipment
- a_4 length of the active part of the surge arrester
- Z_g earthing impedance
- U impinging overvoltage surge

Figure 3 – Diagram for surge arrester connection to the protected object

4.3.4.6 Evaluation method of non-standard lightning overvoltage shape

The "representative overvoltage" stage in the insulation co-ordination procedure is specified to have a standard voltage shape, which is especially meaningful for a lightning impulse in the case of detailed analysis by digital computation. On this subject, recent researches have analysed field surges, clarified insulating characteristics for field real surges in comparison with those for the standard voltage shape in the lightning surge time region, and proposed the overvoltage evaluation method for GIS [14] and transformer [15]. These techniques have been discussed in CIGRE working groups, and adopted in the technical brochures [11], [16], [17].

The decay of the field overvoltage is generally large, making the insulation requirements not as severe as those of the standard voltage shape. Consequently, it could be possible in some cases to use lower withstand voltages (see Annex I).

4.3.5 Very-fast-front overvoltages [13]

Very-fast-front overvoltages (VFFO) originate from disconnector operations or faults within GIS due to the fast breakdown of the gas gap and the nearly undamped surge propagation within the GIS. Their amplitudes are rapidly dampened on leaving the GIS, for example at a bushing, and their front times are usually increased into the range of those of fast-front overvoltages.

The overvoltage shape is characterized by a fast increase of the voltage nearly to its peak value resulting in a front time below 0,1 μ s. This front is usually followed by an oscillation with frequencies above 1 MHz. Dominant frequency components may reach up to some tens of MHz.

For disconnector operations the VFFO amplitude depends on the disconnector construction and on the substation configuration. In the most unfavourable case, the maximum VFFO amplitude can reach 2,8 p.u.

VFFO due to faults within GIS can have amplitudes up to 1,6 times the breakdown voltages.

VFFO in UHV systems may be dangerous to the insulation of GIS, transformers and voltage transformers. The shape and the amplitude of the overvoltage depend on the kind of connection of the equipment to the GIS.

A representative overvoltage cannot be established because suitable standardizations are not available. Experience shows that very-fast-front overvoltages have no influence on the selection of rated withstand voltages up to system voltages of 800 kV.

Special care has to be taken for very-fast transients in GIS of UHV systems. Due to the decreasing ratio of lightning impulse withstand voltage to the system voltage, VFFO can become the limiting dielectric stress defining the dimensions of GIS. How to handle this situation and mitigation measures in respect to insulation co-ordination are described in Annex J.

5 Co-ordination withstand voltage

5.1 Insulation strength characteristics

5.1.1 General

In all materials, conduction is caused by the migration of charged particles. Conductors have large numbers of relatively free electrons, which will drift in an applied electric field, while insulating media have very few free electrons. When electric stress in an insulating medium is increased to a sufficiently high level, the resistivity along a path through the insulating medium will change from a high value to a value comparable to that of conductors. This change is called breakdown.

Breakdown takes place in three main stages:

- the initial ionization at a point or points;
- the growth of an ionized channel across the gap;
- the bridging of the gap and the transition to a self-sustaining discharge.

A number of factors influence the dielectric strength of the insulation. Such factors include:

- the magnitude, shape, duration and polarity of the applied voltage;
- the electric field distribution in the insulation: homogeneous or non-homogeneous electric field, electrodes adjacent to the considered gap and their potential;
- the type of insulation: gaseous, liquid, solid or a combination of these; the impurity content and the presence of local inhomogeneities;
- the physical state of the insulation: temperature, pressure and other ambient conditions, mechanical stress, etc. The history of the insulation may also have an importance;
- the deformation of the insulation under stress, chemical effects, conductor surface effects, etc.

Breakdown in air is strongly dependent on the gap configuration and on the polarity and wave shape of the applied voltage stress. In addition, relative atmospheric conditions affect the breakdown strength regardless of shape and polarity of applied stress. Relationships for the breakdown strength of air derived from laboratory measurements are referred to as the standard reference atmospheric conditions as defined by IEC 60060-1:

- temperature : 20 °C;
- pressure : 1 013 hPa (1 013 mbar);
- absolute humidity : 11 g/m³.

Laboratory measurements have also been made for non-standard conditions including low air density, high relative humidity, contamination, ice and snow, high temperatures and the presence of combustion particles.

For outdoor insulation, the effects of air density, humidity, rain, and surface contamination become particularly important. IEC 60060-1 defines test procedures for external insulation in dry and wet conditions. For internal gas insulation, such as metal-enclosed gas-insulated switchgear, the effect of the internal pressure and temperature as well as local inhomogeneities and impurities play a significant role.

In liquid insulation, particle impurities, bubbles caused by chemical and physical effects or by local discharges, can drastically reduce the insulation strength. It is important to note also that the amount of chemical degradation of the insulation can tend to increase with time. The same can apply to solid insulation. Its electric strength can be affected by mechanical stress.

The breakdown process is also statistical in nature and this should be taken into account. Due to the restoring feature of self-restoring insulation, its statistical response to stresses can be obtained by suitable tests. Therefore, self-restoring insulation is typically described by the statistical withstand voltage corresponding to a withstand probability of 90 %. For non-self-restoring insulation, the statistical nature of the strength cannot usually be found by testing and the assumed withstand voltage deemed to correspond to a withstand probability of 100 % is applied (see definition 3.23 of IEC 60071-1:2006).

Wind has an influence on insulation design, especially in the case of overhead lines employing free swinging insulator strings. Usually, the effect is only important in selecting gap lengths on the basis of power-frequency and switching impulse strengths.

Subclauses 5.1.2 to 5.1.5 give information on the different factors influencing the insulation response. For more detailed information, reference can be made to the CIGRE technical brochure [4].

5.1.2 Influence of polarity and overvoltage shapes

5.1.2.1 Influence of overvoltage polarity

In typical electrode geometries encountered in high-voltage applications, for the majority of cases the energized conductor is more highly stressed than the grounded conductor. For air insulation, if the more highly stressed electrode is positively charged, the gap breakdown voltage will be lower than if the more highly stressed electrode is negatively charged. This is because the propagation of ionization phenomena is more readily accomplished under positive stress than negative stress.

Where both electrodes are approximately equally stressed, two discharge processes will be involved with both positive and negative characteristics. If it is clear which polarity will be more severe for a particular insulation system and gap configuration, the design will be based on that polarity; otherwise both polarities shall be considered.

5.1.2.2 Influence of overvoltage shape

Under impulse stress, the breakdown voltage also in general depends on the shape of the impulse.

For slow-front impulses, the strength of external insulation depends more on the impulse front than on its tail. The tail becomes especially important only in the case of contamination on the surface of external insulation. The strength of internal insulation is assumed to be affected by the peak value only.

For external insulation, it is typical that for each gap length there is an impulse time-to-peak for which the breakdown voltage is a minimum (the critical time to peak). Usually, the

minimum is in the range of times-to-peak for slow-front overvoltages. The larger the gap length, the more pronounced is the minimum. For air gaps in range I, the effect is negligible and can be ignored. For air clearances to be used in range II, this minimum breakdown voltage is, to all intents and purposes, equal to the breakdown voltage at the standard 250 μ s time-to-peak. This means that the use of the withstand voltage of the insulation at the standard voltage shape 250/2 500 μ s results in a conservative insulation design for slow-front overvoltages. For some systems in which slow-front overvoltages have fronts much longer than the standard one, the higher insulation strength at these fronts may be advantageously utilized.

The breakdown voltage of external insulation under lightning impulse stress decreases with increasing tail duration. For withstand voltages, this decrease is neglected, and the breakdown voltage is assumed to be equal to that under the standard lightning impulse 1,2/50 μ s. However, some reduction in the insulation structure may be achieved, for example, in open-air substations protected by surge arresters, when the lightning overvoltage shape and its effect on the insulation strength is taken into account.

The lightning overvoltage shapes are analysed and the insulating characteristics of SF₆ gas and oil-filled transformer elements for these actual surges are clarified to convert them into the standard voltage shape (see 4.3.4.6).

5.1.3 Phase-to-phase and longitudinal insulation

The dielectric strength of phase-to-phase and longitudinal insulation structures depends on the relationship between the two voltage components at the two terminals. This dependence is very important for external insulation in range II or in three-phase metal-enclosed substations.

For external insulation in range II, the response of the insulation to phase-to-phase switching overvoltages depends on the value of α which correlates positive and negative voltage stress components (see Annex C); tests to verify the required withstand voltage shall therefore be so designed as to reflect this phenomenon. The representative overvoltage shape standardized in IEC 60071-1 is a combined overvoltage having two synchronous components of opposite polarity; the positive is a standard switching impulse, while the negative is an impulse with time-to-peak and time-to-half value not shorter than those of the positive component. For insulation affected by the relative value of the two components, therefore, the actual overvoltage amplitude shall be converted into the representative amplitude taking into account the insulation response characteristics (see 4.3.3.2 and Annex C where a particular example is given).

For longitudinal insulation structures, the voltage components are specified by the representative overvoltages (see Clause 4).

The values for the conventional deviation for the phase-to-earth insulation strength given in 5.1.5 may also be applied to the strength of the external phase-to-phase or the longitudinal insulation, when the 50 % flashover voltage is taken as the sum of the components applied to the two terminals.

5.1.4 Influence of weather conditions on external insulation

Flashover voltages for air gaps depend on the moisture content and density of the air. Insulation strength increases with absolute humidity up to the point where condensation forms on the insulator surfaces. Insulation strength decreases with decreasing air density. A detailed description of the effects of air density and absolute humidity is given in IEC 60060-1.

When determining the co-ordination withstand voltage, it should be kept in mind that most adverse conditions from the dielectric strength point of view (i.e. low absolute humidity, low air pressure and high temperature) do not usually occur simultaneously. In addition, at a given site, the corrections applicable for humidity and ambient temperature variations cancel each

other. Therefore, the estimation of the strength can usually be based on the average ambient conditions at the location. Extreme atmospheric conditions on site need special consideration.

For insulators, the possible reduction in the withstand voltage due to snow, ice, dew or fog should be taken into account.

5.1.5 Probability of disruptive discharge of insulation

No method is at present available for the determination of the probability of disruptive discharge of a single piece of non-self-restoring insulation. Therefore, it is assumed that the withstand probability changes from 0 % to 100 % at the value defining the withstand voltage.

For self-restoring insulation, the ability to withstand dielectric stresses caused by the application of an impulse of given shape can be described in statistical terms. The methods to be followed in the determination of the withstand probability curve are given in IEC 60060-1. For a given insulation, and for impulses of given shape and different peak values U , a discharge probability P can be associated with every possible value U , thus establishing a relationship $P = P(U)$. Usually, the function P is monotonically increasing with values of U . The resulting curve can be defined by three parameters:

- a) U_{50} : corresponding to the voltage under which the insulation has a 50 % probability to flashover or to withstand;
- b) Z : the conventional deviation which represents the scatter of flashover voltages. It is defined as the difference between the voltages corresponding to flashover probabilities 50 % and 16 % as shown in Equation (4):

$$Z = U_{50} - U_{16} \quad (4)$$

- c) U_{spec} : the truncation voltage. The maximum voltage below which a disruptive discharge is no longer possible. The determination of this value, however, is not possible in practical tests.

Usually, the function P is given by a mathematical function (cumulative probability distribution) which is fully described by parameters U_{50} , Z and U_{spec} . In the traditionally used Gaussian distribution, the value of U_{50} is also the mean, and the conventional deviation is obtained directly from Equation (4). The truncation point is not often considered for the sake of simplicity.

For application of the statistical method for insulation co-ordination for slow-front overvoltages, the use of the modified Weibull cumulative probability distribution given in Equation (5) has advantages with respect to the Gaussian distribution (advantages explained in Annex B). Equation (5) represents a Weibull cumulative function with parameters chosen to match a Gaussian cumulative probability function at the 50 % and 16 % probability of flashover and to truncate the distribution at $U_{50} - NZ$ (see Annex B).

$$P(U) = 1 - 0,5 \left(1 + \frac{x}{N} \right)^{\gamma} \quad (5)$$

where

x is the number of conventional deviations corresponding to U ;

N is the number of conventional deviations corresponding to the truncation voltage U_{spec} for which $P(U_{\text{spec}}) = 0$.

And

$$x = (U - U_{50}) / Z$$

At one conventional deviation of the Gaussian probability distribution (at $x = -1$), $P(U) = 0,16$ in Equation (5). If $N = 4$ is chosen, then the exact value of γ shall be 4,83 in Equation (5). Approximating this value to $\gamma = 5$ does not result in any appreciable errors so that the modified Weibull distribution proposed in this document is described in Equation (6).

$$P(U) = 1 - 0,5 \left(1 + \frac{x}{4} \right)^5 \quad (6)$$

Figure 4 illustrates this modified Weibull distribution together with the Gaussian distribution to which it is matched. Figure 5 shows the same distributions on Gaussian probability scales.

For statistical calculations of expected performance in the field, use should be made of detailed data obtained from field or laboratory tests. In the absence of such data, the following values for the conventional deviation derived from a large number of test results are recommended for statistical calculations:

- for lightning impulses: $Z = 0,03 U_{50}$ (kV), and
- for switching impulses: $Z = 0,06 U_{50}$ (kV)

The influence of weather conditions (refer to 5.1.4) is included in the values of derived deviations given above.

In IEC 60071-1, the parameter U_{10} (obtained from Equation (5)) corresponding to the withstand probability 90 % is used to describe the withstand probability distribution together with the deviation:

$$U_{10} = U_{50} - 1,3 Z \quad (7)$$

Annex B contains detailed information and statistical equations to be applied in the context of many identical insulations in parallel being simultaneously stressed.

Annex F contains guidance on the determination of the breakdown strength of air insulation under the different classification of overvoltage.

5.2 Performance criterion

According to definition 3.22 of IEC 60071-1:2006, the performance criterion to be required from the insulation in service is the acceptable failure rate (R_a).

The performance of the insulation in a system is judged on the basis of the number of insulation failures during service. Faults in different parts of the network can have different consequences. For example, in a meshed system, a permanent line fault or an unsuccessful reclosure due to slow-front surges is not as severe as a busbar fault or corresponding faults in a radial network. Therefore, acceptable failure rates in a network can vary from point to point depending on the consequences of a failure at each of these points.

Examples for acceptable failure rates can be drawn from fault statistics covering the existing systems and from design projects where statistics have been taken into account. For apparatus, acceptable failure rates R_a due to overvoltages are in the range of 0,001/year up to 0,004/year depending on the repair times. For overhead lines, acceptable failure rates due to lightning vary in the range of 0,1/100 km/year up to 20/100 km/year (the greatest number being for distribution lines). Corresponding figures for acceptable failure rates due to switching overvoltages lie in the range 0,01 to 0,001 per operation. Values for acceptable failure rates should be in these orders of magnitude.

5.3 Insulation co-ordination procedures

5.3.1 General

5.3.1.1 Overview

The determination of the co-ordination withstand voltages consists of determining the lowest values of the withstand voltages of the insulation meeting the performance criterion when subjected to the representative overvoltages under service conditions.

Two methods for co-ordination of insulation to transient overvoltages are in use: a deterministic and a statistical method. Many of the applied procedures, however, are a mixture of both methods. For example, some factors used in the deterministic method have been derived from statistical considerations or some statistical variations have been neglected in statistical methods.

5.3.1.2 Deterministic method

The deterministic method is normally applied when no statistical information obtained by testing is available on possible failure rates of the equipment to be expected in service.

With the deterministic method,

- when the insulation is characterized by its conventional assumed withstand voltage ($P_W = 100\%$), the withstand value is selected equal to the co-ordination withstand voltage obtained by multiplying the representative overvoltage (an assumed maximum) by a co-ordination factor K_C , accounting for the effect of the uncertainties in the assumptions for the two values (the assumed withstand voltage and the representative overvoltage), and
- when, as for external insulation, the insulation is characterized by the statistical withstand voltage ($P_W = 90\%$), K_C should account also for the difference between this voltage and the assumed withstand voltage.

With this method, no reference is made to possible failure rates of the equipment in service.

Typical examples are:

- insulation co-ordination of internal insulations against slow-front overvoltages, when the insulation is protected by surge arresters;
- surge arrester protection against lightning overvoltages for equipment connected to overhead lines, for which experience with similar equipment is available.

5.3.1.3 Statistical method

The statistical method is based on the frequency of occurrence of a specific origin, the overvoltage probability distribution belonging to this origin and the discharge probability of the insulation. Alternatively, the risk of failure may be determined combining overvoltage and discharge probability calculations simultaneously, shot by shot, taking into account the statistical nature of overvoltages and discharge by suitable procedures, for example using Monte Carlo methods.

By repeating the calculations for different types of insulations and for different states of the network the total outage rate of the system due to the insulation failures can be obtained.

Hence, the application of the statistical insulation co-ordination gives the possibility to estimate the failure frequency directly as a function of the selected system design factors. In principle, even the optimization of the insulation could be possible, if outage costs could be related to the different types of faults. In practice, this is very difficult due to the difficulty to evaluate the consequences of even insulation faults in different operation states of the network and due to the uncertainty of the cost of the undelivered energy. Therefore, it is

usually better to slightly overdimension the insulation system rather than optimize it. The design of the insulation system is then based on the comparison of the risks corresponding to the different alternative designs.

5.3.2 Insulation co-ordination procedures for continuous (power-frequency) voltage and temporary overvoltage

5.3.2.1 General

The co-ordination withstand voltage for the continuous (power-frequency) voltage is equal to the highest system voltage for phase-to-phase, and to this voltage divided by $\sqrt{3}$ for phase-to-earth insulations (i.e. equal to the assumed maximum value for the representative voltages given in 4.3.1) with a duration equal to the service life.

With the deterministic method, the co-ordination short-duration withstand voltage is equal to the representative temporary overvoltage. When a statistical procedure is adopted and the representative temporary overvoltage is given by an amplitude/duration distribution frequency characteristic (see 4.3.2), the insulation that meets the performance criterion shall be determined, and the amplitude of the co-ordination withstand voltage shall be equal to that corresponding to the duration of 1 min on the amplitude/duration withstand characteristic of the insulation.

5.3.2.2 Pollution

When contamination is present, the response of external insulation to power-frequency voltages becomes important and may dictate external insulation design. Flashover of insulation generally occurs when the surface is contaminated and becomes wet due to light rain, snow, dew or fog without a significant washing effect.

For the purpose of standardization in IEC TS 60815-1, five classes of characterizing site severity are qualitatively defined from very light to very heavy pollution as follows:

- very light;
- light;
- medium;
- heavy;
- very heavy.

Insulators shall continuously withstand the highest system voltage in polluted conditions with an acceptable risk of flashover. The co-ordination withstand voltages are taken equal to the representative overvoltages, and the performance criterion is satisfied choosing a suitable class of site severity. The long-duration power-frequency co-ordination withstand voltage shall correspond to the highest system voltage for phase-to-phase insulators and to this value divided by $\sqrt{3}$ for phase-to-earth insulators.

For the selection of suitable insulators, recommendations are given in IEC TS 60815-1 based on experiences, measurements and testing.

5.3.3 Insulation co-ordination procedures for slow-front overvoltages

5.3.3.1 Deterministic method

The deterministic method involves determining the maximum voltage stressing the equipment and then choosing the minimum dielectric strength of this equipment with a margin that will cover the uncertainties inherent in the determination of these values. The co-ordination withstand voltage is obtained by multiplying the assumed maximum value of the corresponding representative overvoltage by the deterministic co-ordination factor K_{cd} .

For equipment protected by surge arresters, the assumed maximum overvoltage is equal to the switching impulse protection level U_{ps} of the arrester. However, in such cases, a severe skewing in the statistical distribution of overvoltages may take place. This skewing is more pronounced the lower the protection level, as compared to the amplitudes of the prospective slow-front overvoltages, so that small variations of the insulation withstand strength (or in the value of the arrester protection level) can have a large impact on the risk of failure [4]. To cover this effect, it is proposed to evaluate the deterministic co-ordination factor K_{cd} dependent on the relation of the surge arrester switching impulse protection level U_{ps} to the 2 % value of the phase-to-earth prospective overvoltages U_{e2} . Figure 6 establishes this dependence.

For equipment not protected by surge arresters, the assumed maximum overvoltage is equal to the truncation value (U_{et} or U_{pt}) according to 4.3.3.2, and the deterministic co-ordination factor is $K_{cd} = 1$.

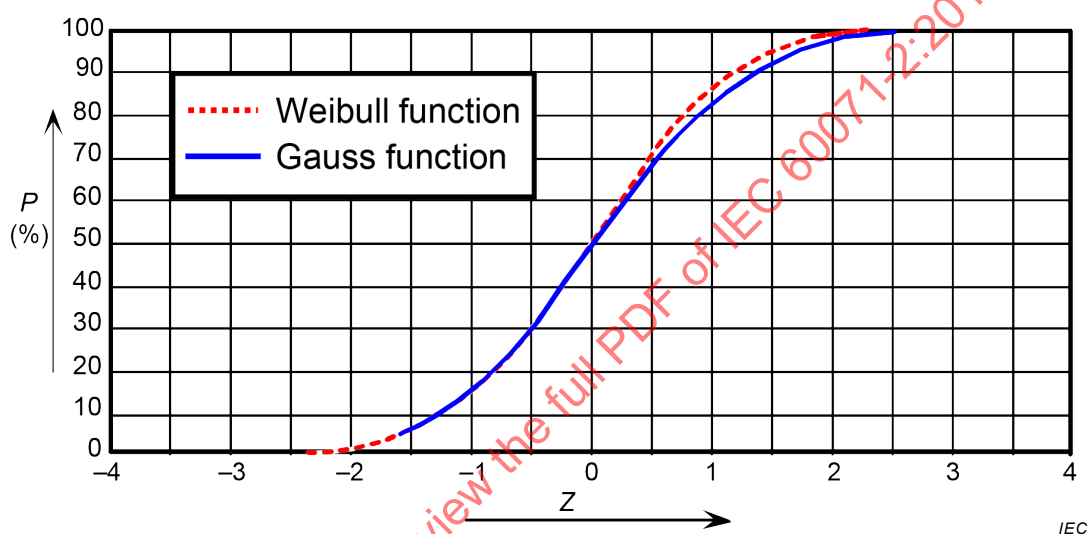


Figure 4 – Distributive discharge probability of self-restoring insulation described on a linear scale

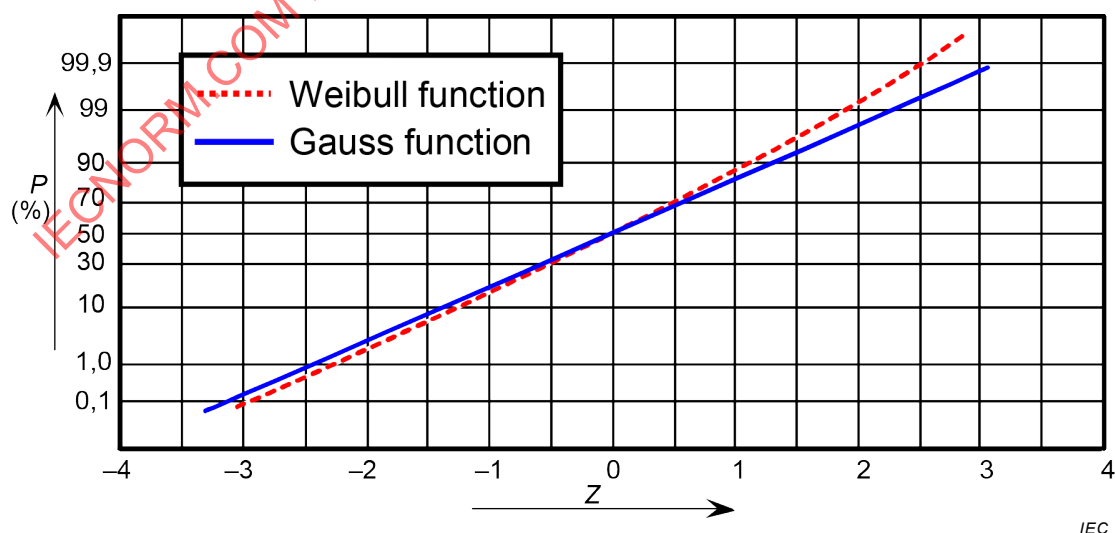
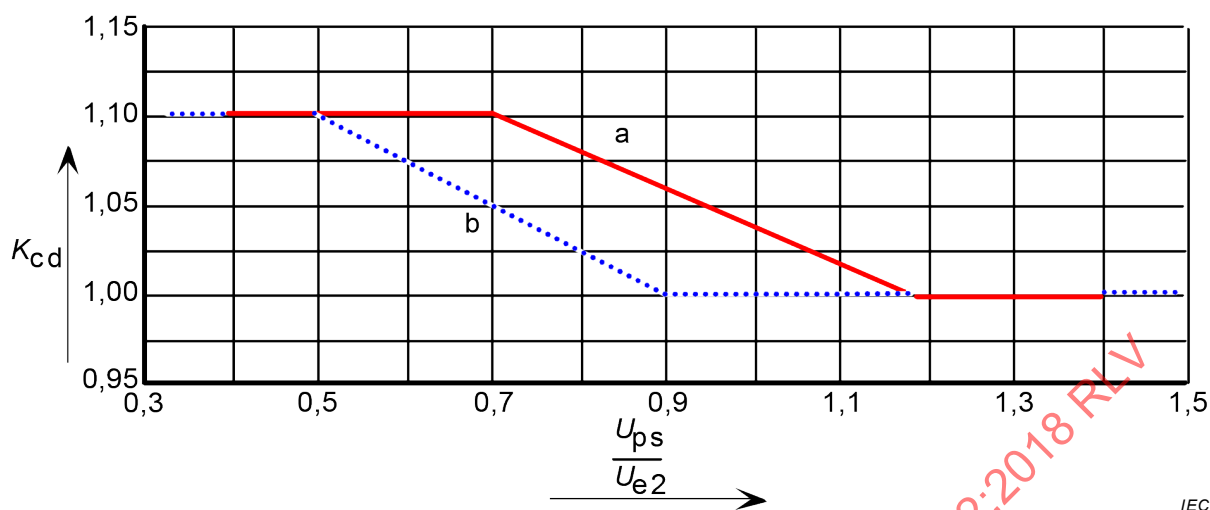


Figure 5 – Disruptive discharge probability of self-restoring insulation described on a Gaussian scale

**Key**

- a co-ordination factor applied to the surge arrester protection level to obtain the co-ordination withstand voltage phase-to-earth (applies also to longitudinal insulation);
- b co-ordination factor applied to twice the surge arrester protection level to obtain the co-ordination withstand voltage phase-to-phase.

Figure 6 – Evaluation of deterministic co-ordination factor K_{cd}

5.3.3.2 Statistical method (and corresponding risk of failure)

In applying the statistical method, it is first necessary to establish an acceptable risk of failure, as described in 5.2, based on technical and economic analysis and service experience.

The risk of failure gives the probability of insulation failure. The failure rate is expressed in terms of the expected average frequency of failures of the insulation (e.g. the number of failures per year) as a result of events causing overvoltage stresses. To evaluate this rate, the events giving rise to these overvoltages and their number have to be studied. Fortunately, the types of events that are significant in insulation design are sufficiently few in number to make the method practical.

The statistical method recommended in this document is based on peak value of the surges. The frequency distribution of overvoltages between phase and earth for a particular event is determined from the following assumptions:

- peaks other than the highest one in the shape of any given overvoltage are disregarded;
- the shape of the highest peak is taken to be identical to that of the standard switching impulse;
- the highest overvoltage peaks are taken to be all of the same polarity, namely the most severe for the insulation.

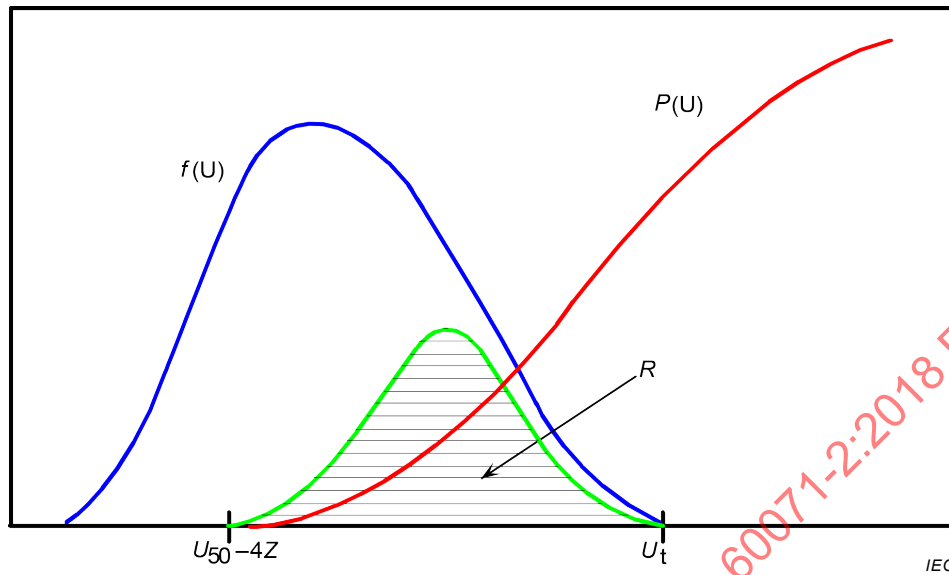
Once the frequency distribution of the overvoltages and the corresponding breakdown probability distribution of the insulation are given, the risk of failure of the insulation between phase and earth can be calculated as follows:

$$R = \int_0^{\infty} f(U) \times P(U) dU \quad (8)$$

where

$f(U)$ is the probability density of overvoltages;

$P(U)$ is the probability of flashover of the insulation under an impulse of value U (see Figure 7).



$$R = \int_{U_{50-4Z}}^{U_t} f(U) \times P(U) dU$$

where

$f(U)$ is the probability density of overvoltage occurrence described by a truncated Gaussian or a Weibull function;

$P(U)$ is the discharge probability of insulation described by a modified Weibull function;

U_t is the truncation value of the overvoltage probability distribution;

$U_{50} - 4Z$ is the truncation value of the discharge probability distribution.

Figure 7 – Evaluation of the risk of failure

If more than one independent peak occurs, the total risk for a phase can be calculated by taking into account the risk of failures for all peaks. For example, if a switching surge on a particular phase comprises three positive peaks leading to risks of failure R_1 , R_2 and R_3 , the phase-to-earth risk of failure for the switching operation is:

$$R = 1 - (1 - R_1) (1 - R_2) (1 - R_3) \quad (9)$$

If the overvoltage distribution is based on the phase-peak method (see 4.3.3.2.1), and the insulations in the three phases are the same, the total risk of failure is:

$$R_{\text{total}} = 1 - (1 - R)^3 \quad (10)$$

If the case-peak method (see 4.3.3.2.1) is used, the total risk is: $R_{\text{total}} = R$.

If one of the overvoltage polarities is substantially more severe for the insulation withstand, the risk values may be divided by two.

The risk of failure for the phase-to-earth and the phase-to-phase insulations can be determined separately in this simple way only if the distances between the two are large enough that the flashover to earth and between phases is not based on the same physical event. This is valid if the phase-to-earth and the phase-to-phase insulations have no common electrode. If they have a common electrode, the risk of failure is usually smaller than that calculated separately [6].

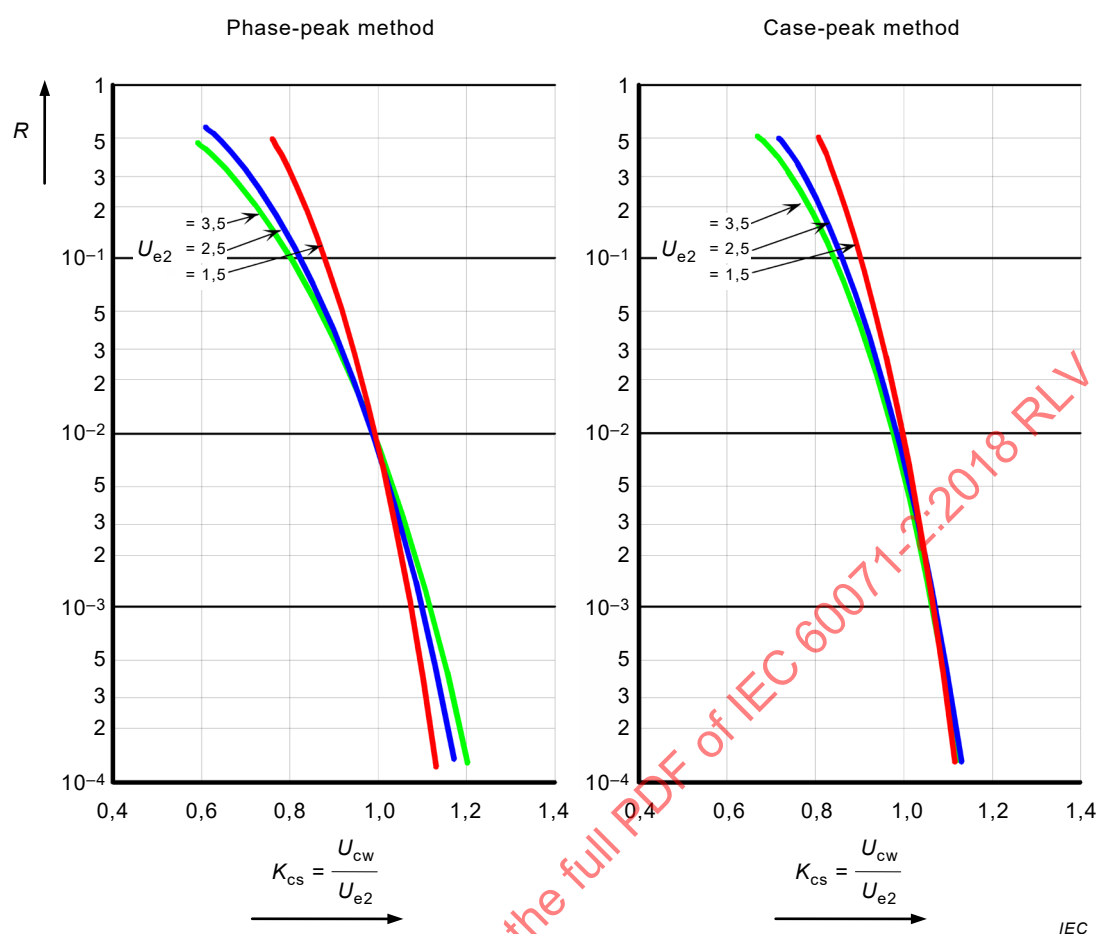
For the important case of the application of the statistical method to many identical parallel insulations, see detailed discussion in Annex B.

Simplified statistical method for slow-front overvoltages

The statistical method based on the amplitudes of the surges can be simplified if it is assumed that one can define the distributions of overvoltage and insulation strength by a point on each of these curves. The overvoltage distribution is identified by the statistical overvoltage, which is the overvoltage having a 2 % probability of being exceeded. The insulation strength distribution is identified by the statistical withstand voltage, which is the voltage at which the insulation exhibits a 90 % probability of withstand. The statistical co-ordination factor (K_{cs}) is then the ratio of the statistical withstand voltage to the statistical overvoltage.

The correlation between the statistical co-ordination factor and the risk of failure appears to be only slightly affected by changes in the parameters of the overvoltage distribution. This is due to the fact that the 2 % value chosen as a reference probability of the overvoltage falls in that part of the overvoltage distribution which gives the major contribution to the risk of failure in the range of risk considered.

Figure 8 shows an example of the relationship between the risk of failure and the statistical co-ordination factor for both the phase-peak and the case-peak methods outlined in Annex C, when the Gaussian distribution is applied for the stress and the modified Weibull distribution is applied for the strength. The curves take into account the fact that the conventional deviation is a function of the 2 % overvoltage value as given in Annex C. Extreme variations in the deviation of the insulation strength, markedly non-Gaussian distribution of overvoltage and, most of all, the shape of the overvoltage may cause the curve to be in error by as much as one order of magnitude. On the other hand, the curves show that a variation of one order of magnitude in the risk corresponds to only a 5 % variation in the electric strength.



Overvoltage parameters: see 4.3.3.2 and Annex C.

Strength parameters: see 5.1.5.

Figure 8 – Risk of failure of external insulation for slow-front overvoltages as a function of the statistical co-ordination factor K_{cs}

5.3.4 Insulation co-ordination procedures for fast-front overvoltages

5.3.4.1 Deterministic method

For fast-front lightning overvoltages, a deterministic co-ordination factor of $K_{cd} = 1$ is applied to the assumed maximum value of the overvoltages. This is because for lightning, the representative overvoltage includes probability effects. For fast-front switching overvoltages, the same relations apply as for slow-front overvoltages (see 5.3.3.1).

5.3.4.2 Statistical method

The statistical method recommended in this document is based on the probability distribution of the representative lightning overvoltages (see Annex E). As the frequency distribution of overvoltages is obtained by dividing their return rate by the total number of overvoltages and the probability density $f(U)$ is the derivative of the result, the risk of failure is calculated by the procedures already outlined in 5.3.3.2. The insulation failure rate is equal to the risk of failure multiplied by the total number of lightning overvoltages.

For internal insulation, the assumed withstand voltage has a withstand probability of 100 % (see definition 3.23 of IEC 60071-1:2006). The withstand probability at higher voltages is assumed to be 0 %. This means that the co-ordination withstand voltage is equal to the representative lightning overvoltage amplitude at a return rate equal to the adopted acceptable failure rate.

NOTE Fast-front overvoltages due to lightning are evaluated without taking into account the instantaneous power-frequency voltage. The combined stresses due to reversal of polarity are therefore neglected. This can be acceptable provided the power-frequency amplitude is small compared to that of the fast-front overvoltage. It may not be conservative for apparatus with oil paper internal insulation such as transformers in range II and the higher values of U_m in range I. Moreover, the internal (such as turn to turn) voltages in such apparatus due to stresses appearing at the terminals are not strictly considered in insulation co-ordination practice described in this document.

For the external insulation the conventional deviation of the discharge probability is usually small as compared to the dispersion of overvoltages. As a simplification, it can be neglected and the same equation as for the internal insulation applies.

6 Required withstand voltage

6.1 General remarks

The required withstand voltage, to be verified in standard type test conditions and at standard reference atmosphere, is determined taking into account all factors which may decrease the insulation in service, so that the co-ordination withstand voltage is met at the equipment location during the equipment life. To achieve this, two main types of correction factors shall be considered:

- a correction factor associated with atmospheric conditions;
- correction factors (called "safety factors") which take into account the differences between the actual in-service conditions of the insulation and those in the standard withstand tests.

6.2 Atmospheric correction

6.2.1 General remarks

For internal insulation, it may be assumed that the atmospheric air conditions do not influence the insulation properties.

The rules for the atmospheric correction of withstand voltages of the external insulation are specified in IEC 60060-1. These rules are based on measurements in altitudes up to 2 000 m and their application to higher altitudes should be made with care. For insulation co-ordination purposes, the following additional recommendations apply:

- a) for air clearances and clean insulators, the correction shall be carried out for the co-ordination switching and lightning impulse withstand voltages. For insulators requiring a pollution test, a correction of the long duration power-frequency withstand voltage is also necessary;
- b) for the determination of the applicable atmospheric correction factor, it may be assumed that the effects of ambient temperature and humidity tend to cancel each other. Therefore, for insulation co-ordination purposes, only the air pressure corresponding to the altitude of the location need to be taken into account for both dry and wet insulations.

NOTE This assumption can be considered as correct for insulator shapes for which rain does not reduce the withstand voltage to a high degree. For insulators with small shed distance, for which rain causes shed-bridging, this assumption is not completely true.

For further information regarding atmospheric and altitude correction, see Annex H.

6.2.2 Altitude correction

The correction factor K_a is based on the dependence of the atmospheric pressure on the altitude as given in ISO 2533:1975. The coordination withstand voltage U_{cw} has to be multiplied by K_a for the calculation of the required withstand voltage U_{rw} .

The correction factor can be calculated from:

$$K_a = e^{m \times \frac{H}{8150}} \quad (11)$$

where

H is the altitude above sea level (in meters);

m is as follows:

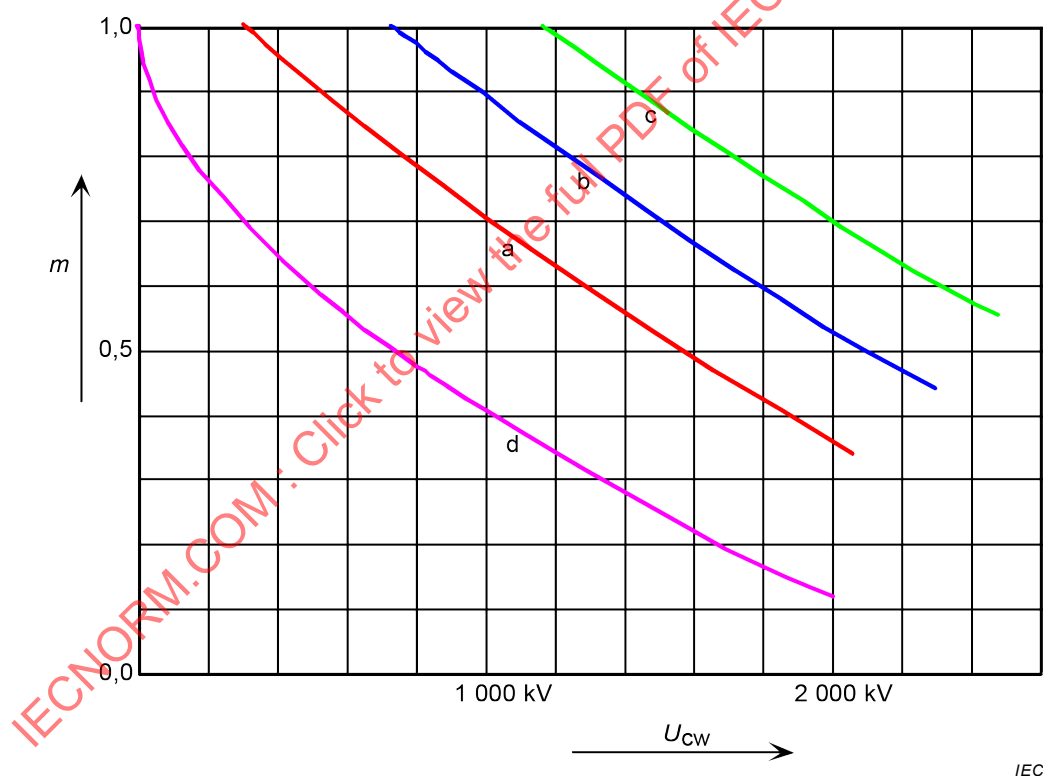
$m = 1,0$ for co-ordination lightning impulse withstand voltages;

m is according to Figure 9 for co-ordination switching impulse withstand voltages;

$m = 1,0$ for short-duration power-frequency withstand voltages of air-clearances and clean insulators.

NOTE The exponent m depends on various parameters, including minimum discharge path which is generally unknown at the specification stage. However, for insulation co-ordination purposes, the conservative estimates of m shown in Figure 9 may be used for the correction of co-ordination switching impulse withstand voltages. The determination of the exponent m is based on IEC 60060-1. In addition, for all types of insulation response, conservative gap factor values have been used (refer to Annex G).

For polluted insulators, the value of the exponent m is tentative. For the purposes of the long duration test and, if required, the short-duration power-frequency withstand voltage of polluted insulators, m may be as low as 0,5 for normal insulators and as high as 0,8 for anti-fog design.



Key

- a phase-to-earth insulation
- b longitudinal insulation
- c phase-to-phase insulation
- d rod-plane gap (reference gap)

For voltages consisting of two components, the voltage value is the sum of the components.

Figure 9 – Dependence of exponent m on the co-ordination switching impulse withstand voltage

6.3 Safety factors

6.3.1 General

The main factors of influence and related operating modes for electrical insulations are indicated in Annex A of IEC 60505:2011. They correspond to the following operational stresses:

- thermal stresses;
- electrical stresses;
- environmental stresses;
- mechanical stresses.

The factors to be applied compensate for

- the differences in the equipment assembly,
- the dispersion in the product quality,
- the quality of installation,
- the ageing of the insulation during the expected lifetime, and
- other unknown influences.

The relative weight of these factors and operating modes may vary between different types of equipment.

6.3.2 Ageing

The electrical insulation of all equipment ages in service owing to one or a combination of thermal, electrical, chemical or mechanical stresses.

For insulation co-ordination purposes, external insulations are not assumed to be subject to ageing. Exceptions are insulations containing organic materials, the ageing of which needs careful investigation, especially when used in outdoor conditions.

For internal insulations, ageing can be significant and should be covered by the safety factors given in 6.3.5.

6.3.3 Production and assembly dispersion

The rated withstand voltages are verified by a type test, often on a representative part of an assembly, or by a test relevant only for a part of the insulation system. As the equipment in service may differ from that in type tests due to different configurations or insulation conditions, the service withstand voltage of the equipment can be lower than the rated value.

For equipment fully assembled in the factory, this dispersion, for insulation co-ordination purposes, is negligibly small. For equipment assembled on site, the actual withstand voltage may be lower than the required withstand voltage, which shall be taken into account in the safety factors given in 6.3.5.

6.3.4 Inaccuracy of the withstand voltage

For external insulation, possible deviations of the test arrangement from the actual service arrangement and influences of the laboratory surroundings shall be taken into account in addition to the statistical inaccuracy involved in the selected type test procedure. Such deviations shall be covered by the safety factors given in 6.3.5.

For internal insulation for which a withstand probability of 100 % is assumed in 3.23 of IEC 60071-1:2006, an impulse type test with three impulses is usually carried out, and the

statistical uncertainty of this test shall be covered by the safety factor as given in 6.3.5 (see also 7.3.2).

6.3.5 Recommended safety factors (K_s)

If not specified by the relevant apparatus committees, the following safety factors should be applied:

- for internal insulation: $K_s = 1,15$;
- for external insulation: $K_s = 1,05$.

Safety factors different from the recommended values may be applied according to, as examples, special positive or negative service experience, improvements in technology, higher levels of quality control during manufacturing and assembly especially in higher voltage systems, or exceptionally conservative approaches in system studies.

7 Standard withstand voltage and testing procedures

7.1 General remarks

7.1.1 Overview

Tables 2 and 3 of IEC 60071-1:2006 and IEC 60071-1:2006/AMD1:2010 specify standard withstand voltages U_w for range I and range II, respectively. In both tables, the standard withstand voltages are grouped into standard insulation levels associated with standard values of highest voltage for equipment U_m .

In range I, the standard withstand voltages include the short-duration power-frequency withstand voltage and the lightning impulse withstand voltage. In range II, the standard withstand voltages include the switching impulse withstand voltage and the lightning impulse withstand voltage.

The standard insulation levels given in Tables 2 and 3 of IEC 60071-1:2006 and IEC 60071-1:2006/AMD1:2010 reflect the experience of the world, taking into account modern protection devices and methods of overvoltage limitation. The selection of a particular standard insulation level should be based on the insulation co-ordination procedure described in this document and should take into account the insulation characteristics of the particular equipment being considered.

7.1.2 Standard switching impulse withstand voltage

In Table 3 of IEC 60071-1:2006 and IEC 60071-1:2006/AMD1:2010, standard switching impulse withstand voltages associated with a particular highest voltage for equipment have been chosen in consideration of the following:

- a) for equipment protected against switching overvoltages by surge arresters:
 - the expected values of temporary overvoltages;
 - the characteristics of presently available surge arresters;
 - the co-ordination and safety factors between the protection level of the surge arrester and the switching impulse withstand voltage of the equipment;
- b) for equipment not protected against switching overvoltages by surge arresters:
 - the acceptable risk of disruptive discharge considering the probable range of overvoltages occurring at the equipment location;
 - the degree of overvoltage control generally deemed economical, and obtainable by careful selection of the switching devices and in the system design.

7.1.3 Standard lightning impulse withstand voltage

In Table 3 of IEC 60071-1:2006/IEC 60071-1:2006/AMD1:2010, standard lightning impulse withstand voltages associated with a particular standard switching impulse withstand voltage have been chosen in consideration of the following.

- a) For equipment protected by surge arresters, the low values of lightning impulse withstand level are applicable. They are chosen by taking into account the ratio of lightning impulse protection level to switching impulse protection level likely to be achieved with surge arresters, and by adding appropriate margins.
- b) For equipment not protected by surge arresters (or not effectively protected), only the higher values of lightning impulse withstand voltages shall be used. These higher values are based on the typical ratio of the lightning and switching impulse withstand voltages of the external insulation of apparatus (e.g. circuit-breakers, disconnectors, instrument transformers). They are chosen in such a way that the insulation design will be determined mainly by the ability of the external insulation to withstand the switching impulse test voltages.
- c) In a few extreme cases, provision should be made for a higher value of lightning impulse withstand voltage. This higher value should be chosen from the series of standard values given in 5.6 and 5.7 of IEC 60071-1:2006 and IEC 60071-1:2006/AMD1:2010.

In range I, the standard short-duration power-frequency or the lightning impulse withstand voltage should cover the required switching impulse withstand voltages phase-to-earth and phase-to-phase as well as the required longitudinal withstand voltage.

In range II, the standard switching impulse withstand voltage should cover the required short-duration power-frequency withstand voltage, and the continuous power-frequency voltage if no value is specified by the relevant apparatus committee.

In order to meet these general requirements, the required withstand voltages should be converted to those voltage shapes for which standard withstand voltages are specified using the test conversion factors given in 7.2. The test conversion factors are determined from existing results to provide a conservative value for the rated withstand voltages. They should, therefore, be used only in the specified direction.

IEC 60071-1 leaves it to the relevant apparatus committee to prescribe the long-duration power-frequency test intended to demonstrate the response of the equipment with respect to ageing of internal insulation or to external pollution (see also IEC 60507).

7.2 Test conversion factors

7.2.1 Range I

If adequate factors are not available (or specified by the relevant apparatus committee), suitable test conversion factors to be applied to the required switching impulse withstand voltages are given in Table 1. These factors apply to the required withstand voltages phase-to-earth as well as to the sum of the components of phase-to-phase and longitudinal withstand voltages.

Table 1 – Test conversion factors for range I, to convert required SIWV to SDWV and LIWV

Insulation	Short-duration power-frequency withstand voltage ^a	Lightning impulse withstand voltage
External insulation		
– air clearances and clean insulators, dry:		
• phase-to-earth	$0,6 + U_{rw} / 8\,500$	$1,05 + U_{rw} / 6\,000$
• phase-to-phase	$0,6 + U_{rw} / 12\,700$	$1,05 + U_{rw} / 9\,000$
– clean insulators, wet	0,6	1,3
Internal insulation		
– GIS	0,7	1,25
– liquid-immersed insulation	0,5	1,10
– solid insulation	0,5	1,00
U_{rw} is the required switching impulse withstand voltage in kV.		
^a The test conversion factors include a factor of $1/\sqrt{2}$ to convert from peak to RMS value.		

7.2.2 Range II

If adequate factors are not available (or specified by the relevant apparatus committee), suitable test conversion factors for the conversion of the required short-duration power-frequency withstand voltage to switching impulses are given in Table 2. They also apply to the longitudinal insulation.

Table 2 – Test conversion factors for range II to convert required SDWV to SIWV

Insulation	Switching impulse withstand voltage
External insulation	
– air clearances and clean insulators, dry	1,4
– clean insulators, wet	1,7
Internal insulation	
– GIS	1,6
– liquid-immersed insulation	2,3
– solid insulation	2,0
NOTE The test conversion factors include a factor of $\sqrt{2}$ to convert from RMS to peak value.	

7.3 Determination of insulation withstand by type tests

7.3.1 Test procedure dependency upon insulation type

The verification of the electric strength of insulation is achieved through tests. The type of test to be selected for a given equipment shall consider the nature of its insulation(s). Subclauses 3.4 and 3.5 of IEC 60071-1:2006 define the sub-division of insulation into self-restoring and non-self-restoring insulation. This constrains the selection of the test procedure to be adopted for a particular equipment from the list provided in 6.3 of IEC 60071-1:2006, and more fully described in IEC 60060-1.

The following information and guidance is given so as to aid the optimum selection of type tests from insulation co-ordination considerations. The fact that much equipment comprises a mixture of both self-restoring and non-self-restoring insulation is taken into account.

7.3.2 Non-self-restoring insulation

With non-self-restoring insulation, a disruptive discharge degrades the insulating property of the insulation, and even test voltages which do not cause a disruptive discharge may affect the insulation. For example, power-frequency overvoltage tests and impulse tests with polarity reversal may initiate treeing in polymeric insulation and give rise to gas generation in liquid and liquid-impregnated insulation. Non-self-restoring insulation is, for these reasons, tested by application of a limited number of test voltages at standard withstand level, i.e. by withstand procedure A, in 7.3.1.1 of IEC 60060-1:2010, in which three impulses are applied for each polarity, and the test is successful if no disruptive discharge occurs.

For insulation co-ordination purposes, equipment which passes this test should be deemed to have an assumed withstand voltage equal to the applied test voltage (i.e. the rated withstand voltage). Since the number of test impulses is limited and no failure is permitted, no useful statistical information regarding the actual withstand voltage of the equipment can be deduced.

Some equipment which contains both non-self-restoring and self-restoring insulation can be regarded, for test purposes, as non-self-restoring if disruptive discharge during the test would produce significant damage to the non-self-restoring insulation part (e.g. transformers tested with bushings having a higher standard impulse withstand voltage).

7.3.3 Self-restoring insulation

With self-restoring insulation, it is possible to apply a large number of test voltages, the number only being limited by testing constraints and not by the insulation itself, even in the presence of disruptive discharges. The advantage of applying many test voltages is that statistical information may be deduced for the insulation withstand. IEC 60060-1 standardizes three alternative methods leading to an estimation of the 90 % withstand voltage. For insulation co-ordination purposes, the up-and-down withstand method with seven impulses per group and at least eight groups is the preferred method of determining U_{50} . U_{10} can be deduced by assuming a value of conventional deviation (see 5.1.5) or the latter may be determined by a multiple level test. For an evaluation of the statistical significance of the test method, reference may be made to Annex A of IEC 60060-1:2010.

7.3.4 Mixed insulation

For equipment which has self-restoring insulation that cannot be tested separately from its non-self-restoring insulation (e.g. bushings and instrument transformers), a compromise in test method shall be made. This is necessary so as not to damage satisfactory non-self-restoring insulation while, at the same time, seeking to ensure that the test adequately discriminates between satisfactory and unsatisfactory self-restoring insulation. On the one hand, the non-self-restoring insulation part leads to few test voltage applications. On the other hand, the self-restoring insulation part leads to the need of many test voltage applications (for the purpose of selectivity). Experience shows that withstand test procedure B, in 7.3.1.2 of IEC 60060-1:2010 (15 impulses, up to two disruptive discharges permitted on self-restoring parts), is an acceptable compromise.

Its selectivity may be indicated as the difference between actual withstand levels which would result in probabilities of passing the test of 5 % and 95 %. Refer to Table 3.

Table 3 – Selectivity of test procedures B and C of IEC 60060-1

IEC test procedure	Number of impulses	% probability for passing test at U_{10}	Withstand level for 95 % probability to pass the test	Withstand level for 5 % probability to pass the test	Selectivity
B	15/2	82	$U_{5,5}$ ($U_w + 0,32 Z$)	U_{36} ($U_w - 0,92 Z$)	1,24 Z
C	3 + 9	82	$U_{4,6}$ ($U_w + 0,40 Z$)	U_{63} ($U_w - 1,62 Z$)	2,02 Z

Thus, an equipment tested using procedure B, which is on the borderline of being acceptable (rated and tested at its U_{10}), has a probability of passing the test of 82 %. A better equipment, having a withstand voltage U_{10} higher than the standard value U_w by 0,32 Z (rated and tested at its $U_{5,5}$), has a 95 % probability of passing the test. A poor equipment, having a withstand voltage lower than the standard value U_w by 0,92 Z (rated and tested at its U_{36}), has a 5 % probability of passing the test. This selectivity of test (1,24 Z) may be further quantified by assuming values for Z as 3 % and 6 % of U_{50} for lightning and switching impulses respectively. (It should be noted that Z cannot be determined from the test.) The selectivity of the 15/2 test is further illustrated in Figure 10 in comparison to the ideal test.

An alternative to the above test procedure is withstand test procedure C, in 7.3.1.3 of IEC 60060-1:2010, which is a modification of USA practice. In this procedure, three test impulses are applied and up to one disruptive discharge is permitted across self-restoring insulation, in which case a further nine impulses are applied and the test requirements are satisfied if no further disruptive discharge occurs. The selectivity of this procedure is compared with that of the 15/2 test in Table 3 and also in Figure 10.

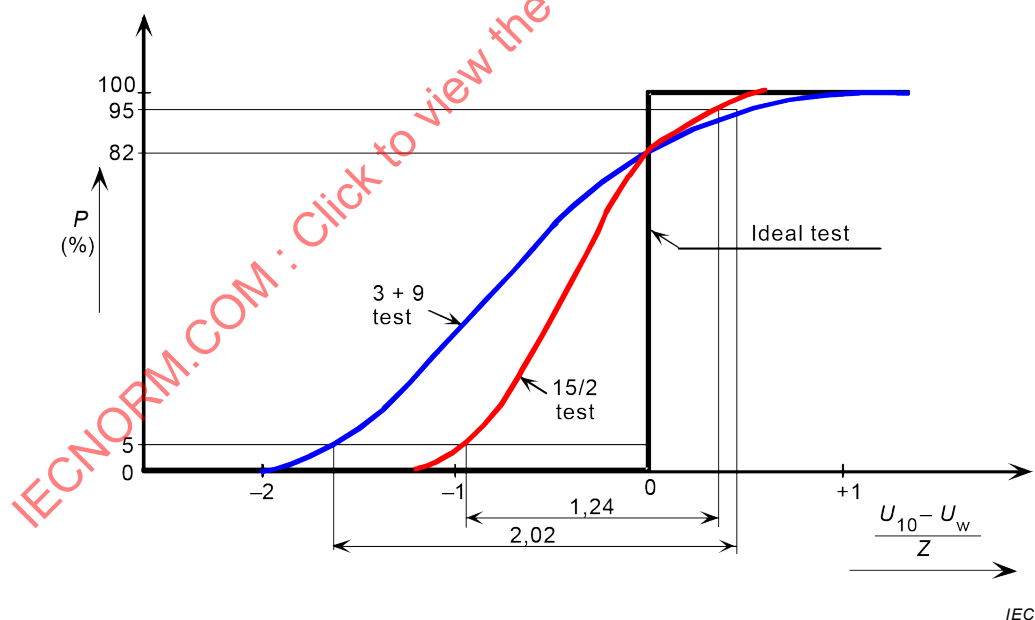


Figure 10 – Probability P of an equipment to pass the test dependent on the difference K between the actual and the rated impulse withstand voltage

7.3.5 Limitations of the test procedures

Since the recovery of insulation from a disruptive discharge is a time-dependent process, an adequate time interval between test voltage applications shall be permitted for the self-restoring insulation to fully recover its electric strength. Apparatus committees should specify the limits of acceptability (if any) of time intervals between test voltage applications which are dependent upon the type of insulation. Considerations should also be given to the possible

degradation of the non-self-restoring insulation by the repeated application of test voltages even without the occurrence of a disruptive discharge.

7.3.6 Selection of the type test procedures

In view of the foregoing, the following recommendations are made for tests performed for insulation co-ordination purposes:

- self-restoring insulation should be tested with the up-and-down withstand method (one of the methods described in withstand test procedure D, in 7.3.1.4 of IEC 60060-1:2010);
- non-self-restoring insulation should be tested with the three impulse withstand test (withstand test procedure A, in 7.3.1.1 of IEC 60060-1:2010);
- in general, equipment which comprises both self-restoring and non-self-restoring insulation (i.e. mixed insulation) should be tested with the 15/2 test (withstand test procedure B, in 7.3.1.2 of IEC 60060-1:2010). When, however, the risk of tree propagation in the non-self-restoring insulation is of prime concern, and the number of voltage applications is considered excessive, the 3 + 9 test (test procedure C, in 7.3.1.3 of IEC 60060-1:2010) is an acceptable alternative;
- also, where power-frequency tests are required for insulation co-ordination purposes, the short-duration power-frequency withstand tests (IEC 60071-1) should be applied to the insulation, whether self-restoring, non-self-restoring, or mixed.

7.3.7 Selection of the type test voltages

7.3.7.1 General

For equipment containing only external air insulation, the test is performed with the standard withstand voltage applying the atmospheric correction factors specified in IEC 60060-1.

For equipment containing only internal insulation, the test is performed with the standard withstand voltage only (without applying the atmospheric correction factors specified in IEC 60060-1).

For equipment containing both internal and external insulation, the atmospheric correction factor should be applied and the test carried out with the corrected value, provided that the corrected factor is between 0,95 and 1,05. When the correction factor is outside this range, the alternatives listed below are acceptable for insulation co-ordination purposes.

7.3.7.2 Test voltage of the external insulation higher than that of the internal insulation (atmospheric correction factor > 1,05)

The external insulation can only be correctly tested when the internal insulation is oversized. If not, the internal insulation should be tested with the standard value and, for the external insulation, the following alternatives may be considered by the technical apparatus committees or by agreement:

- the external insulation should only be tested on dummies;
- interpolation between existing results;
- estimation of the withstand voltages from the dimensions.

In general, a test of the external insulation is not necessary if the air clearances are equal to or larger than those given in IEC 60071-1.

For wet tests on vertical insulators, the insulator shape should meet certain additional requirements. Until supporting information is available, these requirements may be considered as being fulfilled if the insulator shape meets requirements of IEC TS 60815-1.

For power-frequency tests under wet conditions, no additional test of the external insulation is necessary if the clearances are larger than the rated power-frequency withstand voltage divided by 230 kV/m and the insulator shape meets the requirements of IEC TS 60815-1.

7.3.7.3 Test voltage of the external insulation lower than that of the internal insulation (atmospheric correction factor < 0,95)

The internal insulation can only be correctly tested when the external insulation is oversized. If not, the external insulation should be tested with the corrected values and, for the internal insulation, the following alternatives may be considered by the technical apparatus committees or by agreement:

- test of the internal insulation with one polarity (usually negative) impulse only;
- test of the internal insulation increasing the external insulation strength, for example by corona control electrodes of different gap sizes. The strengthening measure should not affect the behaviour of the internal insulation.

8 Special considerations for overhead lines

8.1 General remarks

Although the insulation co-ordination procedure for overhead line insulation follows the general philosophy of insulation co-ordination, the following special considerations shall be taken into account.

- Where the design employs free-swinging insulators, the dielectric strength of air clearances should take into account conductor movement.
- Insulator standards specify the dimensions of insulator units without making reference to a highest voltage for equipment or a highest system voltage. Consequently the insulation co-ordination procedure terminates with the determination of the required withstand voltage U_{rw} . The selection of a rated voltage in IEC 60071-1 is not necessary, and Tables 2 and 3 of IEC 60071-1:2006 and IEC 60071-1:2006/AMD1:2010 do not apply.
- The insulation performance of overhead lines has a large impact on the insulation performance of substations. The transmission line outage rate due to lightning primarily determines the frequency of re-energization operations, and the lightning performance rate close to the substation determines the frequency of fast-front overvoltages impinging on the substation.

8.2 Insulation co-ordination for operating voltages and temporary overvoltages

The operating voltage and the temporary overvoltages determine the required insulator string length and the shape of the insulator unit for the pollution site severity. In directly earthed neutral systems with earth fault factors of 1,3 and below, it is usually sufficient to design the insulators to withstand the highest system voltage phase-to-earth. For higher earth fault factors and especially in isolated or resonant earthed neutral systems, consideration of the temporary overvoltages may be necessary.

Where consideration shall be given to free-swinging insulators, the clearances should be determined under extreme swing conditions.

8.3 Insulation co-ordination for slow-front overvoltages

8.3.1 General

Slow-front overvoltages of interest for overhead lines are earth-fault overvoltages, energization and re-energization overvoltages. When establishing the acceptable failure rates it should be taken into account that

- an insulation failure due to earth-fault overvoltages causes a double phase-to-earth fault, and

- an insulation failure due to re-energization overvoltages causes an unsuccessful reclosure.

8.3.2 Earth-fault overvoltages

Earth-fault overvoltages should be taken into account in systems with high earth fault factors, i.e. for distribution lines or transmission lines in resonant earthed-neutral systems. The acceptable failure rates for these lines shall be selected in the order of magnitude of their two-phase lightning outage rate. As a guide, acceptable failure rates between 0,1 and 1,0 flashover/year are typical.

Special considerations are necessary for lines in range II where energization and re-energization overvoltages are normally controlled to low amplitudes, since in this case the slow-front overvoltage generated by earth faults may be more severe.

8.3.3 Energization and re-energization overvoltages

Energization overvoltages are of interest for all overhead lines, but specially in range II. Suitable acceptable failure rates are in the order of 0,005 to 0,05 flashover/year.

Re-energization overvoltages require attention for transmission lines when fast three-phase reclosing is applied (because of trapped charges). Acceptable failure rates of 0,005 to 0,05 flashover/year may be suitable.

Re-energization overvoltages can be disregarded when single-phase reclosing is used on transmission lines or for distribution lines in which the distribution transformers remain connected during the operation.

Slow-front overvoltages are one of the factors determining the air clearances and, for some type of insulators, the insulator fittings. Usually their importance is restricted to transmission lines in the higher system voltage range of 123 kV and above. Where free-swinging insulators are applied, air clearances for slow-front overvoltages are generally determined assuming moderate (mean) swing conditions. For distribution lines, the clearances are generally determined by the insulator (see 8.2) and slow-front overvoltages need not be considered.

8.4 Insulation co-ordination for lightning overvoltages

8.4.1 General

The lightning performance of overhead lines depends on a variety of factors, among which the most important are

- the lightning ground flash density,
- the height of the overhead line,
- the conductor configuration,
- the protection by shield wires,
- the tower earthing,
- the insulation strength, and
- the use of line surge arresters.

8.4.2 Distribution lines

For distribution lines, it should be assumed that each direct lightning flash to the line causes a flashover between phases with or without a flashover to earth. Protection by shield wires is useless because tower earthing and insulation strength cannot economically be improved to such a degree that back flashovers are avoided. The lightning performance of distribution lines, therefore, is largely determined by the ground flash density and the line height.

For distribution lines with unearthed crossarms (wood-pole lines), induced overvoltages from nearby strokes to earth have no importance. However, the high dielectric strength to earth causes overvoltage surges with high amplitudes impinging on the substation and, in such cases, consideration should be given for the appropriate choice of substation surge arresters (energy requirements).

For distribution lines with earthed crossarms, induced overvoltages may affect the required lightning impulse strength of the overhead line insulation.

8.4.3 Transmission lines

For transmission lines above 72,5 kV, induced voltages can be neglected and only direct flashes to the line determine the lightning performance. A general guide for a suitable target performance rate cannot be given because this rate would largely depend on the consequences of a lightning outage and the cost to improve shielding, earthing and insulation strength. It is possible, however, to design for a lower outage rate for the line section in front of the substation than for the rest of the line, in order to reduce the amplitudes and frequency of the overvoltage surges impinging on the substation and also to reduce the probability of occurrence of short-line faults (see IEC 62271-100).

9 Special considerations for substations

9.1 General remarks

9.1.1 Overview

The voltage stresses which can arise in a substation as shown in Figure 11 are described in the following subclauses 9.1.2 to 9.1.5.

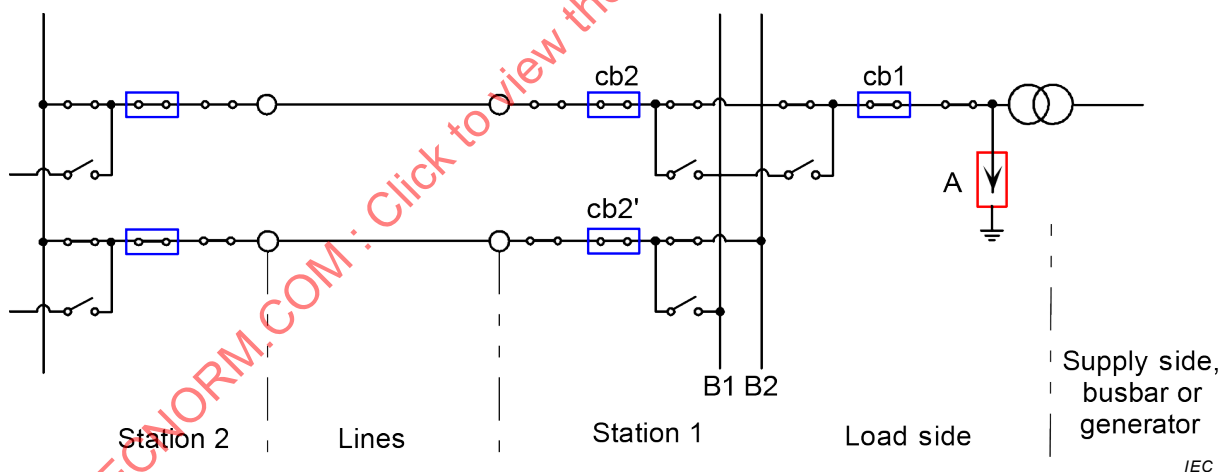


Figure 11 – Example of a schematic substation layout used for the overvoltage stress location

9.1.2 Operating voltage

It is assumed to be equal to the highest system voltage. All parts of the substation are equally stressed.

9.1.3 Temporary overvoltage

Earth faults on the load side stress all parts of one phase of the substation equally.

Load rejection overvoltages may arise in the substation mainly due to a fault in the distant substation (station 2). Depending on the protection scheme, either all or some parts between

circuit-breaker cb2 and the transformer will be stressed. For a fault in the substation itself (station 1), only the parts between circuit-breaker cb1 and the transformer are subjected to load rejection overvoltages.

Longitudinal overvoltage stresses may exist at circuit-breaker cb1 during synchronization if the transformer is connected to a generator. When busbar B2 is operating in a different system, the longitudinal insulation of the busbar disconnectors may be subjected to the operating voltage on busbar B2 and the load rejection overvoltage on busbar B1 in phase opposition.

9.1.4 Slow-front overvoltages

Overvoltages due to line energization or re-energization can have the high amplitudes of the receiving end only between the line entrance and the circuit-breaker cb2. The rest of the substation is subjected to the overvoltages at the sending end.

Overvoltage due to faults and fault clearing may occur in all parts.

9.1.5 Fast-front overvoltages

Lightning overvoltages may arise at all parts of the station; however, with different amplitudes depending on the distance to the arrester.

Fast-front switching overvoltages occur only on the switched section of the station (e.g. on busbar B2) or at one of the breakers, when they are switched by one of the busbar disconnectors.

The different steps of insulation co-ordination are shown in three selected examples in Annex G.

As the specification of suitable long-duration power-frequency test voltages is left to the technical apparatus committees, the verification of the required long-duration power-frequency withstand voltages is omitted from the examples.

At the initial stage, only one line can be in service and temporary overvoltages due to load rejection after an earth-fault should be considered.

When the transformers are energized via a long line, slow-front overvoltages can also stress transformer and busbar.

In GIS, very-fast-front overvoltages due to disconnector operations should be considered.

9.2 Insulation co-ordination for overvoltages

9.2.1 Substations in distribution systems with U_m up to 36 kV in range I

9.2.1.1 General

For equipment in this voltage range, IEC 60071-1 specifies standard rated short-duration power-frequency and lightning impulse withstand voltages.

As a general guide, it can be assumed that in the distribution voltage range the required switching impulse withstand voltages phase-to-earth are covered by the standard short-duration power-frequency withstand voltage. The required switching impulse withstand voltages phase-to-phase, however, have to be considered in the selection of the standard lightning impulse withstand voltage, or the short-duration power-frequency withstand voltage.

Provided that the slow-front phase-to-phase overvoltages have been accommodated, equipment designed to the lower standard lightning impulse withstand voltage values from IEC 60071-1:2006, Table 2, may be suitable for installations such as the following:

- a) systems and industrial installations not connected to overhead lines;
- b) systems and industrial installations connected to overhead lines only through transformers where the capacitance to earth of cables connected to the transformer low-voltage terminals is at least 0,05 μF per phase; when the cable capacitance to earth is insufficient, additional capacitors should be added on the transformer side of the switchgear, as close as possible to the transformer terminals, so that the combined capacitance to earth of the cables plus the additional capacitors is at least 0,05 μF per phase;
- c) systems and industrial installations connected directly to overhead lines, when adequate overvoltage protection by surge arresters is provided.

In all other cases, or where a very high degree of security is required, equipment designed to the higher rated lightning impulse withstand voltage value should be used.

9.2.1.2 Equipment connected to an overhead line through a transformer

Equipment connected to the low-voltage side of a transformer supplied on the high-voltage side from an overhead line is not directly subjected to lightning or switching overvoltages originating on the overhead line. However, due to electrostatic and electromagnetic transference of such overvoltages from the high-voltage winding to the low-voltage winding of the transformer, such equipment can be subjected to overvoltages which shall be taken into account in the insulation co-ordination procedure with the possible application of protection devices.

Analytical expressions for the electrostatic and electromagnetic terms of the transferred voltage are given in Annex D.

9.2.1.3 Equipment connected to an overhead line through a cable

Insulation co-ordination, in this case, is not only concerned with the protection of the substation equipment, but also of the cable.

When a lightning surge propagating along an overhead line impinges on a cable, it breaks up into a reflected wave and a transmitted wave, where the transmitted wave amplitude is substantially decreased as compared to that of the impinging surge. Subsequent reflections at each end of the cable, however, usually result in a substantial increase in the voltage along the cable above this initial value. In general, the higher standard rated lightning impulse withstand voltages from IEC 60071-1:2006, Table 2, should be selected and surge arresters installed at the line-cable junction. When wood poles are used in the overhead line and when only one line may be connected to the substation, additional arresters may be required at the cable entrance of the substation.

9.2.2 Substations in transmission systems with U_m between 52,5 kV and 245 kV in range I

For equipment in this voltage range, IEC 60071-1 specifies standard rated short-duration power-frequency and lightning impulse withstand voltages.

As a general guide, it can be assumed that in the transmission voltage range within range I, the required switching impulse withstand voltages phase-to-earth are covered by the standard short-duration power-frequency withstand voltage. The required switching impulse withstand voltages phase-to-phase, however, have to be considered in the selection of the lightning impulse withstand voltage or standard short-duration power-frequency withstand voltage for the equipment at the line entrance, or additional phase-to-phase switching impulse tests may be necessary for three-phase equipment.

For the selection of the lightning impulse withstand voltage, many considerations for the distribution voltage range also apply to the transmission voltage range within range I. However, as the variety of equipment and locations is not as great, it is recommended that the insulation co-ordination procedure be carried out for a number of representative substation-overhead line combinations using at least the simplified procedures described in Annex E.

9.2.3 Substations in transmission systems in range II

For equipment in this voltage range, IEC 60071-1 specifies standard rated switching and lightning impulse withstand voltages.

In this voltage range, the use of the statistical methods of insulation co-ordination should generally be applied. The frequency of overvoltages for both switching operations or faults and lightning events should be examined, carefully considering the location of the equipment in the substation (e.g. to distinguish between equipment at the sending or receiving end of energized lines). Furthermore, the deterministic insulation co-ordination method based on temporary overvoltages may result in standard withstand voltages that are too conservative and more accurate procedures should be applied, which take into account the actual overvoltage duration and the power-frequency voltage-time withstand characteristic of the insulation.

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Annex A (informative)

Determination of temporary overvoltages due to earth faults

The earth fault factor is at a given location of a three-phase system, and for a given system configuration, the ratio of the highest RMS phase-to-earth power frequency voltage on a healthy phase during a fault to earth affecting one or more phases at any point on the system to the RMS phase-to-earth power frequency voltage which would be obtained at the given location in the absence of any such fault (see definition 3.15 of IEC 60071-1:2006).

The earth fault factor is calculated using the complex impedances Z_1 and Z_0 of the positive and zero sequence systems, taking into account the fault resistance R . The following applies:

$Z_1 = R_1 + jX_1$: resistance and reactance of positive and negative sequence system;

$Z_0 = R_0 + jX_0$: resistance and reactance of zero sequence system;

(the earth fault factors are calculated for the location of the fault).

It should be observed that in extended resonant-earthed networks, the earth fault factor can be higher at other locations than the fault.

Figure A.1 shows the overall situation for $R_1 \ll X_1$ and $R = 0$

The range of high values for X_0/X_1 positive and/or negative, apply to resonant earthed or isolated neutral systems.

The range of low values of positive X_0/X_1 are valid for earthed neutral systems.

The range of low values of negative X_0/X_1 , shown hatched, is not suitable for practical application due to resonant conditions.

For earthed neutral systems, Figure A.2 to Figure A.5 show the earth fault factors as a family of curves applicable to particular values of R_1/X_1 .

The curves are divided into regions representing the most critical conditions by the following methods of presentation:

- Maximum voltage occurs on the phase which leads the faulted phase, during a phase-to-earth fault.
- Maximum voltage occurs on the phase which lags the faulted phase, during a phase-to-earth fault.
- Maximum voltage occurs on the unfaulted phases, during a phase-to-earth fault.

The curves are valid for fault resistance values giving the highest earth fault factors.

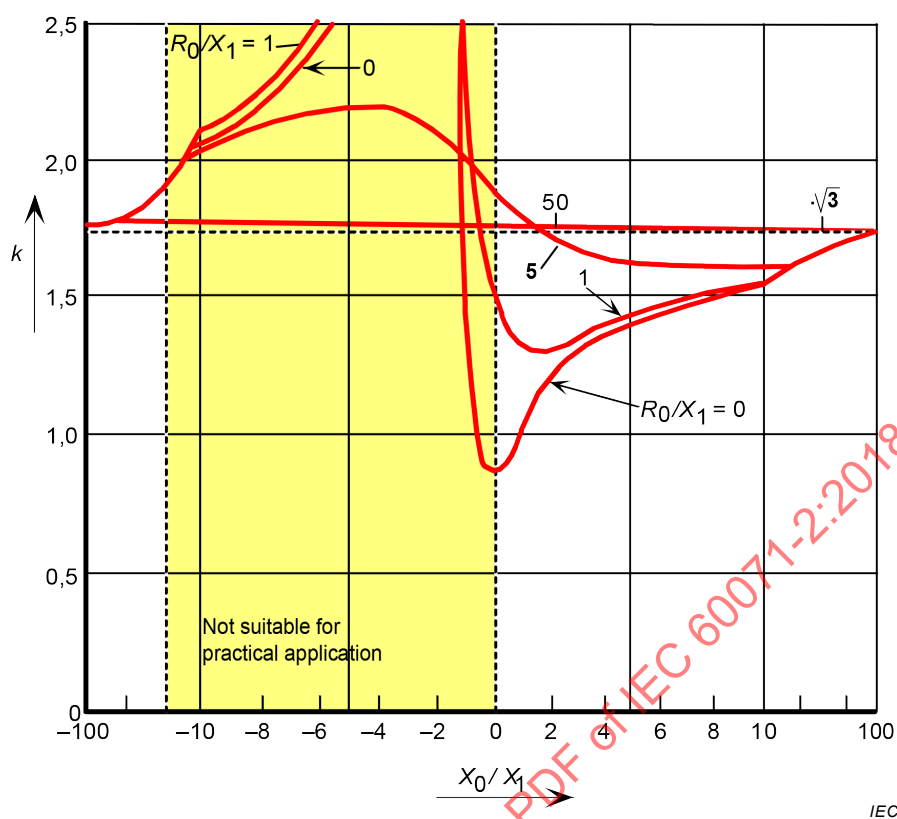


Figure A.1 – Earth fault factor k on a base of X_0/X_1 for $R_1/X_1 = R = 0$

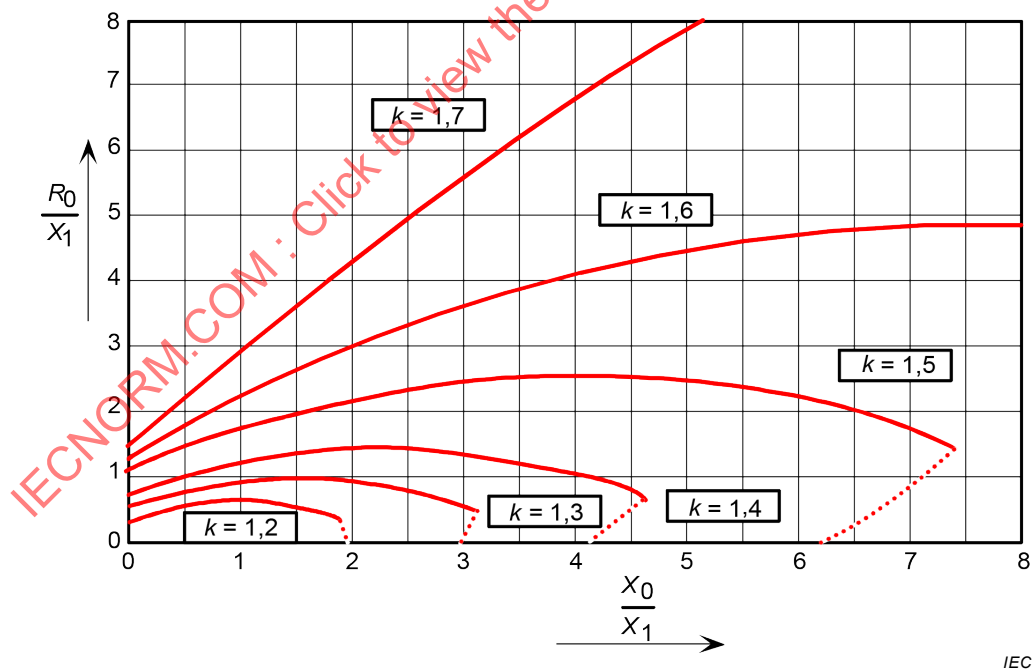


Figure A.2 – Relationship between R_0/X_1 and X_0/X_1 for constant values of earth fault factor k where $R_1 = 0$

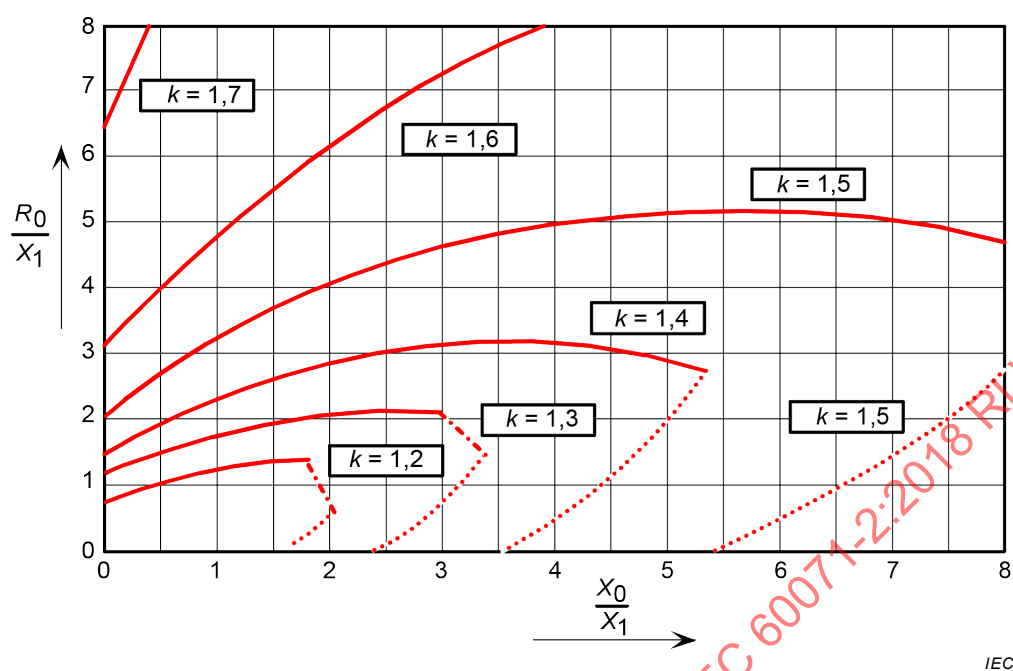


Figure A.3 – Relationship between R_0/X_1 and X_0/X_1 for constant values of earth fault factor k where $R_1 = 0,5 X_1$

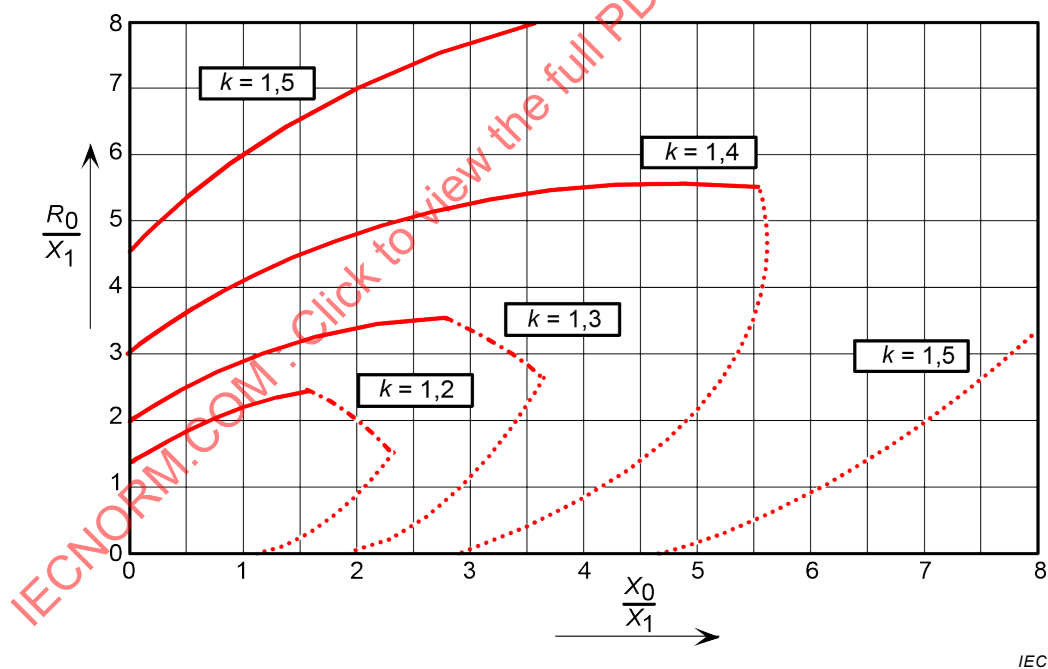


Figure A.4 – Relationship between R_0/X_1 and X_0/X_1 for constant values of earth fault factor k where $R_1 = X_1$

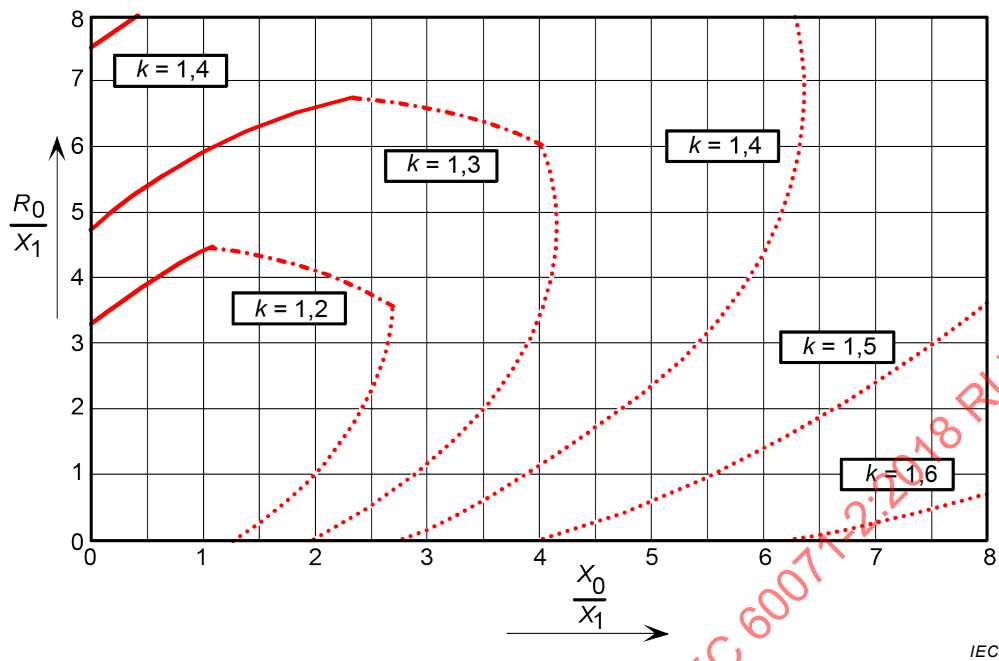


Figure A.5 – Relationship between R_0/X_1 and X_0/X_1 for constant values of earth fault factor k where $R_1 = 2X_1$

Annex B (informative)

Weibull probability distributions

B.1 General remarks

In the vast majority of literature dealing with external insulation, the disruptive discharge probability of the insulation as function of the peak value of the applied voltage $P(U)$ is represented by a Gaussian cumulative frequency distribution which is given by the following expression:

$$P(U) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^x e^{-\frac{1}{2}y^2} dy \quad (\text{B.1})$$

And

$$x = (U - U_{50}) / Z$$

where

U_{50} is the 50 % discharge voltage ($P(U_{50}) = 0,5$);

Z is the conventional deviation according to IEC 60061-1.

A fundamental observation, however, is that there is no physical support to the adoption of this function for $P(U)$. An evidence of this lack of support is that physically no discharge can occur below a minimum value of U . The function is therefore truncated at ($U_{\text{spec}} = U_{50} - 3 Z$) or at ($U_{\text{spec}} = U_{50} - 4 Z$), so that $P(U) = 0$ for $U \leq U_{\text{spec}}$. The main reason why Equation (B.1) was adopted is because it fitted reasonably well with the experimental results.

Also, the cumulative frequency distribution of the overvoltages is usually described by a Gaussian cumulative function $F(U)$ which is often truncated at ($U_{\text{et}} = U_{e50} + 3 S_e$) or at ($U_{\text{pt}} = U_{p50} + 3 S_p$) in order to represent an upper assumed limit for the overvoltages.

In order to account for these facts, this document recommends the use of Weibull probability functions both for the overvoltages and for the disruptive discharge of self-restoring insulation, because it offers the following advantages:

- the truncation values U_{spec} and U_{et} are mathematically included in the Weibull expression;
- the functions are easily evaluated by pocket calculators;
- the inverse functions $U = U(P)$ and $U_e = U_e(F)$ can be expressed mathematically and are easily evaluated by pocket calculators;
- the modified Weibull expressions are defined by the same parameters characterizing the two truncated Gaussian expressions: (U_{50} , Z and U_{spec}) for $P(U)$, and for example (U_{e2} , S_e and U_{et}) for $F(U_e)$;
- the disruptive discharge probability function of several identical insulations in parallel has the same expression as that of one insulation and its characteristics can be easily determined from those of the single insulation.

Annex B describes the derivation of the two modified functions from the Weibull cumulative probability distribution with three parameters, to be used for the representation of the disruptive discharge probability function of external insulation under switching and lightning impulses, and of the cumulative probability distribution of the peak values of the overvoltages occurring in a system.

B.2 Disruptive discharge probability of external insulation

The general expression for the Weibull distribution is:

$$P(U) = 1 - e^{-\left(\frac{U-U_0}{\beta}\right)^\gamma} \quad (\text{B.2})$$

where

U_0 is the truncation value;

β is the scale parameter;

γ is the shape parameter.

This expression can be suitably modified for the description of the discharge probability of an insulation with a truncated discharge probability by substituting the truncation value U_0 and the scale factor β :

$$U_0 = U_{50} - N Z \quad (\text{B.3})$$

$$\beta = NZ (\ln 2)^{-\frac{1}{\gamma}} \quad (\text{B.4})$$

which leads to the modified Weibull function:

$$P(U) = 1 - 0,5^{\left(1 + \frac{U-U_{50}}{ZN}\right)^\gamma} \quad (\text{B.5})$$

in which the constant N is equal to the number of conventional deviations below U_{50} corresponding to the truncation voltage ($P(U) = 0$) and the exponent is determined by the condition that ($P(U_{50} - Z) = 0,16$) resulting in:

$$\gamma = \frac{\ln \left[\frac{\ln(1 - 0,16)}{\ln 0,5} \right]}{\ln(1 - (1/N))} \quad (\text{B.6})$$

For external insulation, it is assumed that no discharge is possible (withstand probability = 100 %) at a truncation value ($U_{\text{spec}} = U_{50} - 4 Z$), i.e. for $N = 4$. Introducing $N = 4$ in Equation (B.6) results in an exponent of $\gamma = 4,80$, which can be approximated to $\gamma = 5$ without any significant error.

Introducing the normalized variable ($x = (U - U_{50}) / Z$) as for the Gaussian function, the adopted modified Weibull flashover probability distribution is then:

$$P(U) = 1 - 0,5^{\left(1 + \frac{x}{4}\right)^5} \quad (\text{B.7})$$

Figure 5 illustrates this modified Weibull distribution together with the Gaussian distribution to which it is matched. Figure 6 shows the same distributions on Gaussian probability scales.

If the same overvoltage stresses simultaneously M identical parallel insulations, the resulting flashover probability of the parallel insulations $[P'(U)]$ is given by Equation (B.8):

$$P'(U) = 1 - [1 - P(U)]^M \quad (\text{B.8})$$

Combining Equations (B.7) and (B.8), the flashover probability for M parallel insulations is:

$$P'(U) = 1 - 0,5^{M \left(1 + \frac{x}{4}\right)^5} \quad (\text{B.9})$$

Introducing the normalized variable ($x_M = (U - U_{50M})/Z_M$), the Equation (B.9) can be expressed as following:

$$P'(U) = 1 - 0,5^{\left(1 + \frac{x_M}{4}\right)^5} \quad (\text{B.10})$$

From Equations (B.9) and (B.10) is obtained:

$$1 + \frac{x_M}{4} = \sqrt[5]{M} \left(1 + \frac{x}{4}\right) \quad (\text{B.11})$$

In general, if the risk of failure of one insulation (R) is small (such as 10^{-5}), then the risk of failure of M identical parallel insulations stressed simultaneously can be approximated as the product of M and R .

Replacing in Equation (B.11) x and x_M by their respective extended definition, and because at the truncation point ($U_{50} - 4Z = U_{50M} - 4Z_M = U_{\text{spec}}$), the following relationships are obtained:

$$Z_M = \frac{Z}{\sqrt[5]{M}} \quad U_{50M} = U_{50} - 4Z \left(1 - \frac{1}{\sqrt[5]{M}}\right) \quad (\text{B.12})$$

These relationships are shown in Figure B.1 which gives the withstand characteristic of M parallel identical insulations related to the withstand characteristic of one insulation.

For example, applying preceding formulas for $M = 200$:

$$U_{50(200)} = U_{50} - 2,6Z$$

$$U_{10(200)} = U_{50(200)} - 1,3 Z_{200} = U_{50} - 3,1Z$$

As another example, for 100 parallel insulations, each one with $U_{50} = 1\,600$ kV and $Z = 100$ kV, then $Z_M = 100 / (100)^{1/5} = 39,8$ kV and $U_{50M} = 1359,2$ kV. Table B.1 completes this example giving the values of U and U_M for various flashover probabilities $P(U)$.

**Table B.1 – Breakdown voltage versus cumulative flashover probability –
Single insulation and 100 parallel insulations**

$P(U)$ (%)	50	16	10	2	1,	0,1	0 ^a
U (kV)	1 600	1 500	1 475	1 400	1 370	1 310	1 200
U_M (kV)	1 359	1 319	1 308	1 280	1 268	1 244	1 200

^a The truncation value remains constant.

Calculation of the risk of failure

To calculate the risk of failure for the preceding example, assume $U_{e2} = 1\,200$ kV and $S_e = 100$ kV. Then, for one insulator:

$$K_{cs} = U_{10} / U_{e2} = 1\,475 / 1\,200 = 1,23$$

and $R = 10^{-5}$

For 100 identical parallel insulations:

$$K_{cs} = 1\,308 / 1\,200 = 1,09$$

and $R = 10^{-3}$ (to compare to Figure 8)

As an approximation, one could calculate the risk of failure of M parallel insulations using the following equation, for $R < 0,1$:

$$R = M \phi \left[\frac{U_{e50} - U_{50}}{\sqrt{S_e^2 + Z^2}} \right] \quad (\text{B.13})$$

where

M is the number of simultaneously stressed insulations;

ϕ is the untruncated Gaussian integral function;

U_{e50} is the mean value of the overvoltage distribution, obtained as $U_{e2} - 2S_e$ according to Annex C (kV);

U_{50} is the 50 % flashover voltage determined as withstand voltage divided by $(1 - 1,3Z)$ (kV);

S_e is the conventional deviation of the overvoltage probability distribution (kV);

Z is the conventional deviation of the flashover probability (kV).

Then

$$R = 100 \phi ((1\,000 - 1\,600) / 140) = 100 \phi (-4,3) = 100 (10^{-5}) = 10^{-3}$$

which is the same result as above. For low risk values, the use of this equation may be too conservative.

B.3 Cumulative frequency distribution of overvoltages

To represent the cumulative frequency of overvoltages with a modified Weibull function, it is sufficient to change the sign of the voltages within the exponent of Equation (C.2) to take into account that the function shall be truncated for high-voltage values. For example, for phase-to-earth overvoltages:

$$F(U_e) = 1 - e^{-\left(\frac{U_{et} - U_e}{\beta}\right)^\gamma} \quad (\text{B.14})$$

With the assumptions made in Annex C that the truncation value ($U_{et} = U_{e50} + 3 S_e$) and the 2 % value is equal to ($U_{e2} = U_{e50} + 2,05 S_e$), the exponent of Equation (B.6) becomes

$\gamma = 3,07$, which can be approximated to $\gamma = 3$. The scale parameter with these assumptions becomes $\beta = 3,5 S_e$ to be used in Equation (B.14).

Alternatively, the frequency distribution of overvoltage can be expressed in a form similar to Equation (B.5) for the disruptive discharge:

$$F(U_e) = 1 - 0,5 \left[1 - \frac{1}{3} \left(\frac{U_e - U_{e50}}{S_e} \right)^3 \right]^3 \quad (\text{B.15})$$

With these factors, both equations (B.14) and (B.15) yield a probability of 2,2 % at the 2 % value, which is considered as sufficiently accurate.

If the case-peak method and the phase-peak method (for definition see 4.3.3.2.1) are compared, and the overvoltages at the three phases are statistically independent, then the probability distribution is:

$$F_{c-p} = 1 - (1 - F_{p-p})^3 = 1 - e^{-3 \left(\frac{U_{et} - U}{B} \right)^\gamma} \quad (\text{B.16})$$

where c – p and p – p refer to the case-peak and phase-peak method, respectively, and with the parameters $\gamma = 3$ et $\beta = 3,5 S_e$.

This means that the parameters β for the two methods follow the relation:

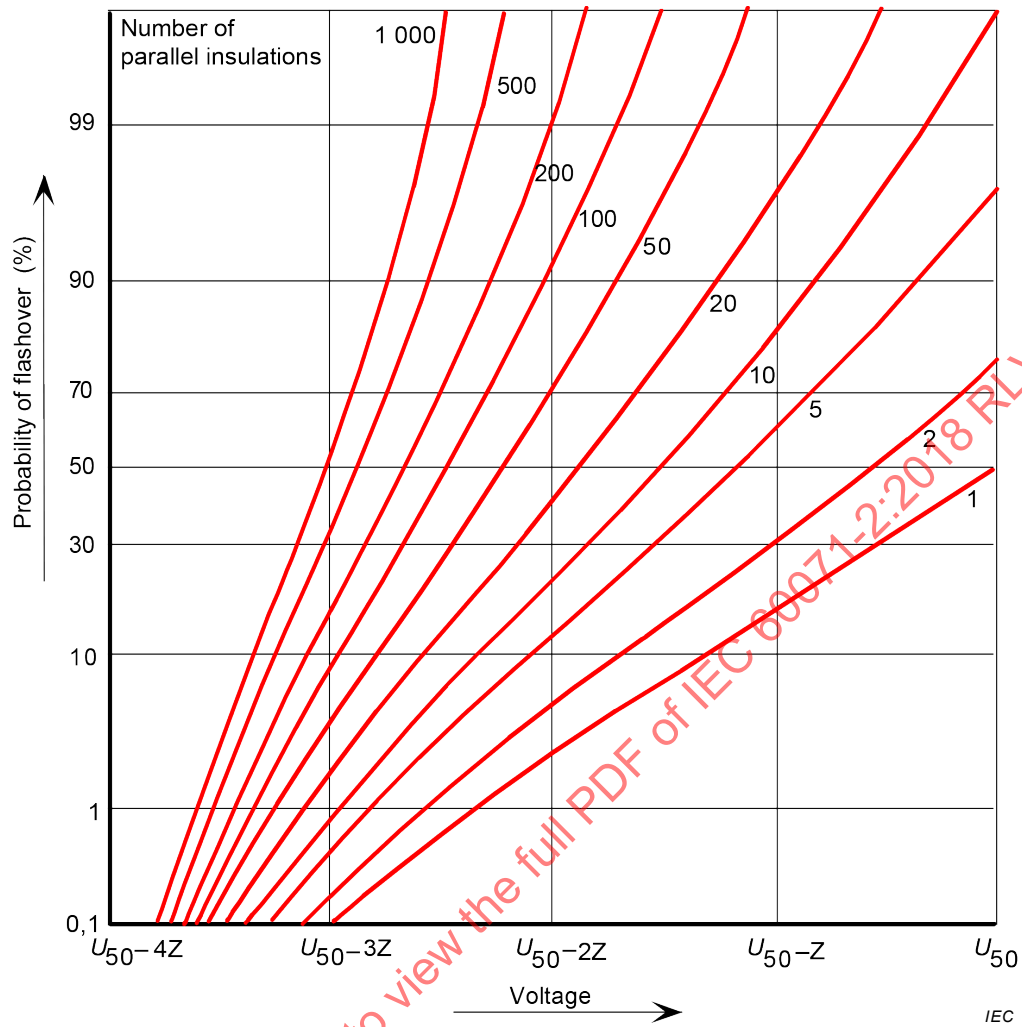
$$\beta_{c-p} = 3^{-1/3} \beta_{p-p} = 0,69 \beta_{p-p} \quad (\text{B.17})$$

and consequently, the relation between the deviations is:

$$S_{c-p} = 0,69 S_{p-p} \quad (\text{B.18})$$

and, as the truncation value should be the same for both methods:

$$u_{e2c-p} = 1,08 u_{e2p-p} - 0,08 \quad (\text{B.19})$$



U_{50} : 50 % flashover voltage of a single gap

Z: conventional deviation of a single gap

Figure B.1 – Conversion chart for the reduction of the withstand voltage due to placing insulation configurations in parallel

Annex C (informative)

Determination of the representative slow-front overvoltage due to line energization and re-energization

C.1 General remarks

The determination of the overvoltages due to energization and re-energization, the insulation response under these overvoltages and the consequences for the insulation co-ordination procedure for a phase-phase-earth insulation configuration have been investigated by CIGRE study committee 33 and been published [1], [6], [7], [8]. Although the principles reported there are still valid, their application has turned out to be complicated. Annex C, therefore, summarizes the results and introduces the simplifications which are considered necessary for the use of this document.

The principles are derived for the phase-peak method (defined in 4.3.3.2.1) in the evaluation of the overvoltages. The results and, in particular, the obtained simplifications, however, are also valid when the case-peak method is used

C.2 Probability distribution of the representative amplitude of the prospective overvoltage phase-to-earth

From the 2 % overvoltage values phase-to-earth (U_{e2} values from Figure 1), the representative probability distribution can be estimated:

Phase-peak method:

- 2 % value: U_{e2} ;
- deviation: $\sigma_e = 0,25 (U_{e2} - 1)$; (C.1)

- truncation value: $U_{et} = 1,25 U_{e2} - 0,25$; (C.2)

- it can be noted that if ($U_{e2} = U_{e50} + 2\sigma_e$), then ($U_{et} = U_{e50} + 3\sigma_e$).

Case-peak method:

- 2 % value: U_{e2} ;
- deviation: $\sigma_e = 0,17 (U_{e2} - 1)$; (C.3)

- truncation value: $U_{et} = 1,13 U_{e2} - 0,13$. (C.4)

As shown in Annex B, for the same switching operation, the truncation values obtained for the two methods are the same. Consequently, the 2 % values and the deviations shall differ.

Correct values for both methods can be obtained from studies. However, in view of the dispersion of the results, Figure 1 can be used for both methods.

C.3 Probability distribution of the representative amplitude of the prospective overvoltage phase-to-phase

In general, the insulation characteristic shall be taken into account in the evaluation of a three-phase overvoltage in order to determine the most critical instant from the overvoltage

shape (see Clause C.4). This most critical instant is sufficiently defined by one of the three following instants.

1) Instant of the positive peak of the phase-to-earth overvoltage

At this instant, the overvoltages are described by

- the positive peak at each terminal,
- the highest negative component from the two neighbouring terminals, given the highest stress between phases, and
- the lowest negative component from the two neighbouring terminals.

2) Instant of the negative peak of the phase-to-earth overvoltage

This instant is equivalent to the instant of the positive peak with reversed polarities.

3) Instant of the peak of the phase-to-phase overvoltage

At this instant the overvoltages are described by

- the phase-to-phase overvoltage peak between each couple of terminals,
- the positive and negative component of this overvoltage, and
- the component at the third terminal to earth.

In all instants, the third component is small. The overvoltage, therefore, can be described by two components on two phases with the third phase earthed. The probability distribution of the overvoltages is bivariate, because both components vary. In a bivariate probability distribution the usually used single voltage value is replaced by combinations of overvoltages, which all have the same probability density. These combinations form curves, which are ellipses, when Gaussian distributions are used to approximate the probability distribution of the components, with the special case of circles if the dispersions of the two distributions are equal. If Weibull distributions are used, the curves are similar to ellipses or circles.

Besides being the curve of constant probability density, a further characteristic of the curve is that each tangent to them defines a composite phase-to-phase overvoltage of constant probability. Figure C.1 shows an example from [7] corresponding to a tangent probability of 2 % for the three instants mentioned above. According to the evaluation of overvoltages only one of the three curves corresponds to the most critical instant for the insulation and only this curve is representative for the overvoltages.

In order to simplify and to take into account instants between the three selected ones, it is proposed in [7] to represent the three curves by a circle given in Figure C.2. This circle is fully defined by the positive and the equal negative peak of the phase-to-earth overvoltages and the peak of the phase-to-phase overvoltage. The circle has its centre at:

$$U_c^+ = U_c^- = \frac{U_p - \sqrt{2}U_e}{2 - \sqrt{2}} \quad (C.5)$$

and a radius:

$$R_u = \frac{2U_e - U_p}{2 - \sqrt{2}} \quad (C.6)$$

where the phase-to-earth overvoltage U_e and the phase-to-phase overvoltage U_p correspond to the same considered probability.

The phase-to-phase overvoltage probability distribution can be estimated as (refer to Figure 1 and Figure 2):

Phase-peak method:

- 2 % value: $U_{p2};$
- deviation: $\sigma_p = 0,25 (U_{p2} - 1,73);$ (C.7)
- truncation value: $U_{pt} = 1,25 U_{p2} - 0,43.$ (C.8)

Case-peak method:

- 2 % value: $U_{p2};$
- deviation: $\sigma_p = 0,17 (U_{p2} - 1,73);$ (C.9)
- truncation value: $U_{pt} = 1,14 U_{p2} - 0,24.$ (C.10)

C.4 Insulation characteristic

In the evaluation of three-phase overvoltages, the basic insulation characteristics have to be taken into account in order to determine the instant of the overvoltage transient which is most critical for the insulation (see 5.1.2). Figure C.3 shows two-phase terminals and the earth terminal of a complete insulation configuration in which the third phase is disregarded for simplification reasons. For the description of the dielectric strength of such a configuration two methods have been used.

- The positive component belonging to a given discharge probability is reported dependent on the negative component. With this description, an insulation characteristic is obtained as shown in Figure C.4 a) for the 50 % discharge probability.
- The total discharge voltage equal to the sum of the two components corresponding to a given discharge probability is reported dependent on a ratio α :

$$\alpha = U^- / (U^+ + U^-) = 1 / [1 + (U^+ / U^-)] \quad (C.11)$$

where

- U^+ is the positive component;
- U^- is the negative component.

The example of Figure C.4 a) then results in the dependency shown in Figure C.4 b).

The insulation characteristic is divided into three ranges (as shown in Figure C.4). Range "a" is the range of discharges from the positive terminal to earth. The negative component has little or no influence on the discharge probability. In range "b" the discharges occur between the terminals and the discharge probability depends on both components (α shall to be taken into account). Range "c" corresponds to range "a" for the discharges from the negative terminal to earth.

The discharge voltages in ranges "a" and "c" can be determined with the opposite terminal earthed, i.e. with a voltage component equal to zero. In range "b", however, the ratio of the components (or the ratio α) influences the result. This part of the insulation characteristic, which is responsible for the phase-to-phase flashover depends on the electrode configuration and the physical discharge process. Two different kinds of electrode configurations are of interest.

- Electrode configurations in which the discharges phase-to-earth and the discharges phase-to-phase occur at different parts of the configuration, for example when the radius of the electrodes is large compared to their clearance. The discharge between phases is exclusively determined by the total voltage between phases. The insulation characteristic

in range b decreases at 45° in Figure C.4 a) or is constant in Figure C.4 b). Such configurations exist in three-phase power transformers or in GIS.

- Electrode configurations in which the discharges phase-to-earth and the discharges phase-to-phase occur at the same part of the configuration. For these the insulation characteristic depends on the discharge process.

According to the discharge process, three groups can be distinguished.

a) Configurations with homogeneous or quasi-homogeneous electric field

The discharge voltage is equal to the corona inception voltage and the insulation characteristic can be obtained by field calculations. Such insulation configurations exist in three-phase enclosed GIS.

In spite of this, as the electrode dimensions are large compared to the clearances, the dielectric field between the phases is little influenced by the earth terminal and, therefore, determined by the total voltage. The insulation characteristic in range "b" is decreasing with about 45° in Figure C.4 a) and constant in Figure C.4 b).

b) Short air clearances with inhomogeneous electric field

The discharge voltage is substantially higher than the corona inception voltage. This discharge process corresponds to a streamer discharge, as a leader does not develop owing to the short air clearance. The discharge probability is determined by the sum of the two components, which means that the insulation characteristic in range "b" decreases with 45° in Figure C.4 a) or is constant in Figure C.4 b). The air clearances in range I of IEC 60071-1 can be associated with this group;

c) Long air clearances

In addition to the conditions mentioned for short air clearances, leader formation from the positive terminal takes place. This means that the dielectric field around the positive terminal is decisive and the positive component has a higher influence on the discharge than the negative. The insulation characteristic decreases by less than 45° [6]. Air clearances in range II of IEC 60071-1 can be associated with this group.

In summary, the insulation characteristic of a two-phase insulation configuration is described by

- the positive switching impulse withstand voltage phase-to-earth (range "a" in Figure C.4),
- the negative switching impulse withstand voltage phase-to-earth (range "c" in Figure C.4), and
- the insulation characteristic between phases (range "b" in Figure C.4) which can be described, for the representation of Figure C.4 a), by:

$$U^+ = U_0^+ - BU^- \quad (\text{C.12})$$

or, for the representation in Figure C.4 b), by:

$$U^+ + U^- = \frac{U_0^+}{1 - \alpha(1 - B)} \quad (\text{C.13})$$

The value of the constant B is:

In range I: all insulation types: $B = 1$;

In range II:

- internal insulation: $B = 1$;
- external insulation: $B < 1$.

Figure C.5 gives the angle ϕ ($B = \tan \phi$) dependent on the ratio of D/H_t .

IEC 60071-1 defines the representative overvoltage between phases as consisting of two components with equal amplitude and opposite polarity. This overvoltage is situated on the line $U^+ = U^-$ or $\alpha = 0,5$. The most critical stress on the insulation configuration depends on the insulation characteristic and, in particular, on the inclination B mentioned in Equation (C.12). The most critical stress is given by the voltage component at which the characteristic is tangent to the circle proposed as a simplification to describe the overvoltages. Figure C.2 shows that the most critical stress does not correspond with the representative overvoltage, if the inclination B is smaller than 1. In this case, the representative overvoltage shall be increased in order to test at $\alpha = 0,5$. This results in a new value for the phase-to-phase representative overvoltage U_{p2re} given by:

$$U_{p2re} = 2 (F_1 U_{p2} + F_2 U_{e2}) \quad (C.14)$$

The deviation value S_{pre} and the truncation value U_{ptre} are respectively given by Equations (C.15) and (C.16):

$$S_{pre} = 2 (F_1 S_p + F_2 S_e) \quad (C.15)$$

$$U_{ptre} = 2 (F_1 U_{pt} + F_2 U_{et}) \quad (C.16)$$

where:

$$F_1 = \frac{1}{2 - \sqrt{2}} \left[1 - \frac{\sqrt{1+B^2}}{1+B} \right]$$

$$F_2 = \frac{1}{2 - \sqrt{2}} \left[2 \frac{\sqrt{1+B^2}}{1+B} - \sqrt{2} \right]$$

If $B = 1$, i.e. for internal insulation and external insulations in range I, the representative phase-to-phase overvoltage is equal to the probability distribution of the phase-to-phase overvoltages. If $B < 1$, the representative phase-to-phase overvoltage varies between the phase-to-phase overvoltages for $B = 1$ and twice the phase-to-earth overvoltages for $B = 0$.

C.5 Numerical example

A phase-phase-earth insulation configuration typical for a system with $U_m = 765$ kV (1 p.u. = 625 kV) has an insulation strength between phases described by a constant $B = 0,6$. This results in the constants $F_1 = 0,463$ and $F_2 = 0,074$.

With the following phase-to-earth overvoltage parameters (phase-peak):

- $U_{e2} = (1,98 \text{ p.u.}) = 1\,238 \text{ kV};$
- $S_e = (0,25 \text{ p.u.}) = 156 \text{ kV};$
- $U_{et} = (2,225 \text{ p.u.}) = 1\,391 \text{ kV};$

the following phase-to-phase overvoltage parameters are derived:

- $U_{p2} = (3,366 \text{ p.u.}) = 2\,104 \text{ kV};$
- $S_p = (0,42 \text{ p.u.}) = 263 \text{ kV};$
- $U_{pt} = (3,778 \text{ p.u.}) = 2\,361 \text{ kV}.$

The representative overvoltage amplitude phase-to-earth is equal to the phase-to-earth overvoltage. The representative overvoltage amplitude phase-to-phase is derived from Equations (C.14) to (C.16) with the above-given constants:

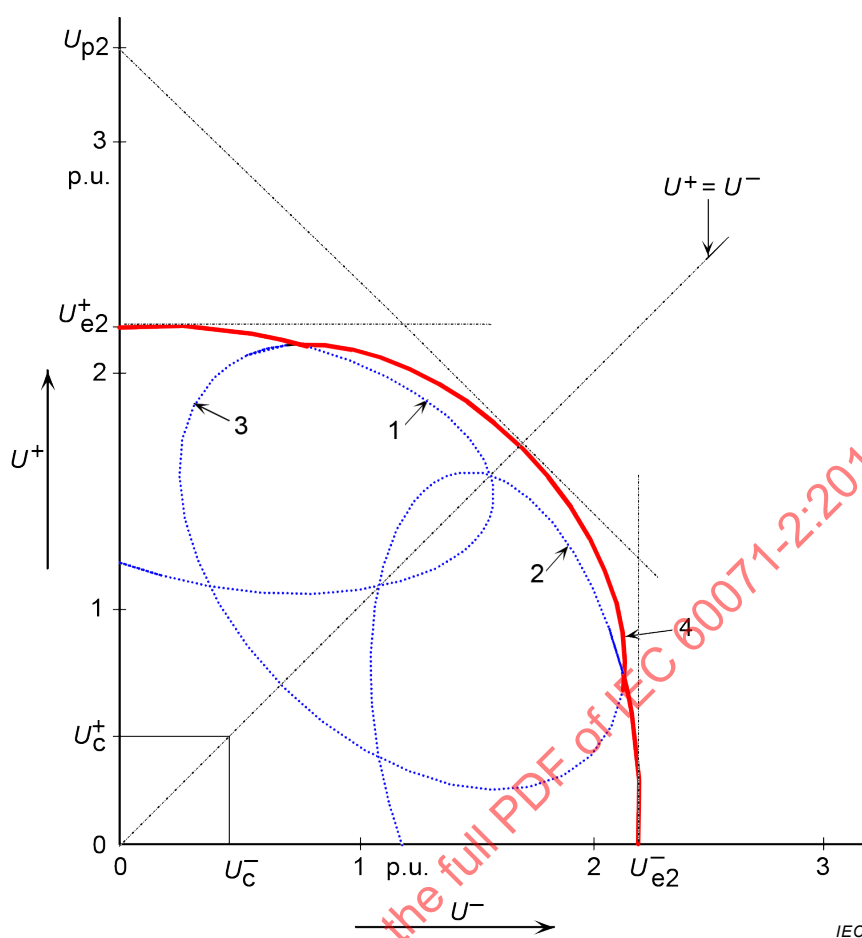
- $U_{p2re} = (3,41 \text{ p.u.}) = 2\,131 \text{ kV};$
- $S_{pre} = (0,44 \text{ p.u.}) = 266 \text{ kV};$
- $U_{ptre} = (3,828 \text{ p.u.}) = 2\,392 \text{ kV}.$

The required withstand voltages for $K_{cs} = 1,15$ are then:

- phase-to-earth: $U_w = U_{e2} \times 1,15 = 1\,424 \text{ kV};$
- phase-to-phase (nominal): $U_w = U_{p2} \times 1,15 = 2\,420 \text{ kV};$
- phase-to-phase (derived): $U_w = U_{p2re} \times 1,15 = 2\,451 \text{ kV}.$

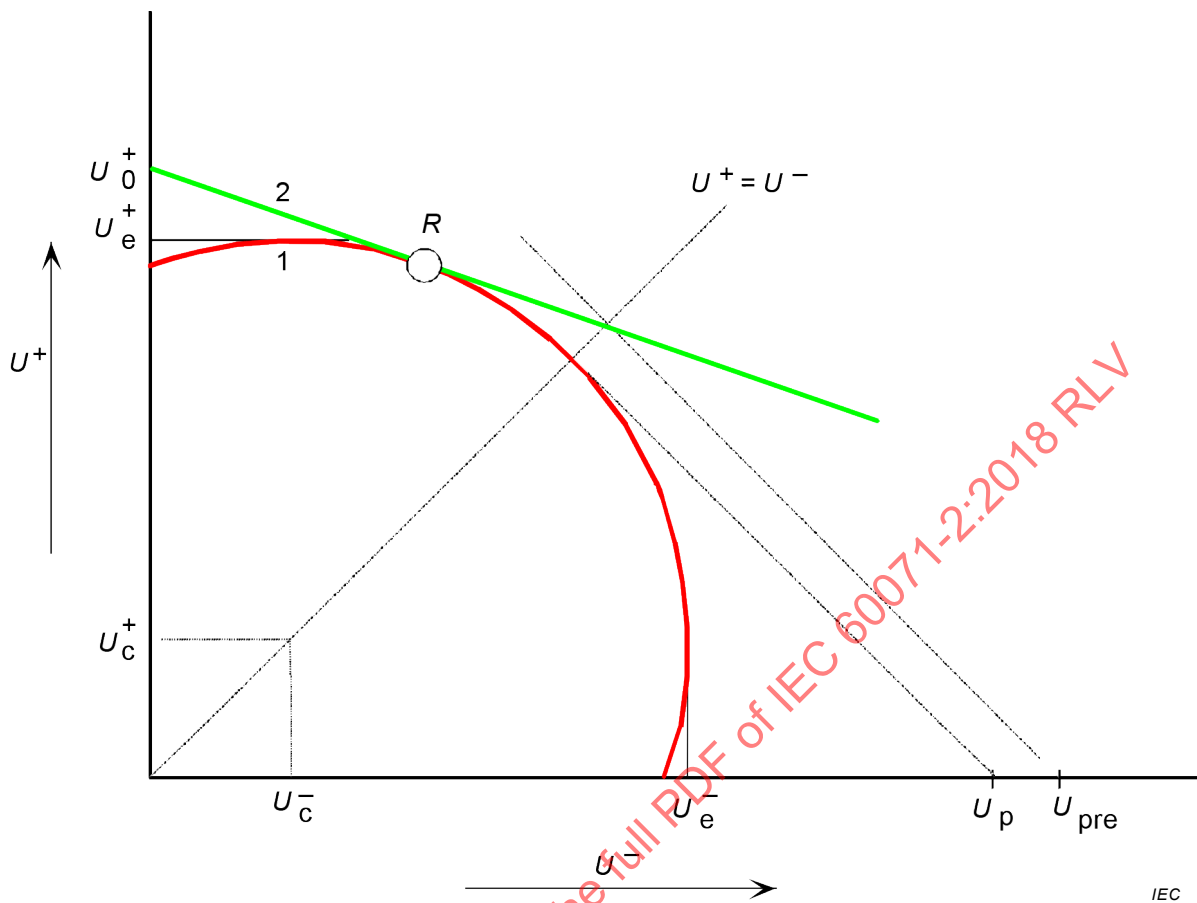
In IEC 60071-1:2006 and IEC 60071-1:2006/AMD1:2010, Table 3, provides standard withstand voltages of 1 425 kV phase-to-earth and 2 422 (1 425 $\times$ 1,7) kV phase-to-phase. While these values would adequately cover the nominal required withstand voltages, they would not cover the derived phase-to-phase required withstand voltage U_{p2re} of 2 451 kV. Therefore, the next highest standard withstand voltages of 1 550 kV phase-to-earth and 2 480 (1 550 $\times$ 1,6) kV phase-to-phase shall be selected, and the insulation shall be tested with positive and negative switching impulses of equal magnitude.

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**Key**

- 1 overvoltage at the instant of the positive phase-to-earth overvoltage peak
- 2 overvoltage at the instant of the negative phase-to-earth overvoltage peak
- 3 overvoltage at the instant of the phase-to-phase overvoltage peak
- 4 proposed simplification covering all instants

Figure C.1 – Example for bivariate phase-to-phase overvoltage curves with constant probability density and tangents giving the relevant 2 % values



Key

- 1 simplified overvoltage circle as given by the values for the phase-to-earth overvoltage $U_e^+ = U_e^-$ and for the phase-to-phase for the considered probability
- 2 50 % flashover characteristic of the insulation
- R most critical overvoltage stress

Figure C.2 – Principle of the determination of the representative phase-to-phase overvoltage U_{pre}

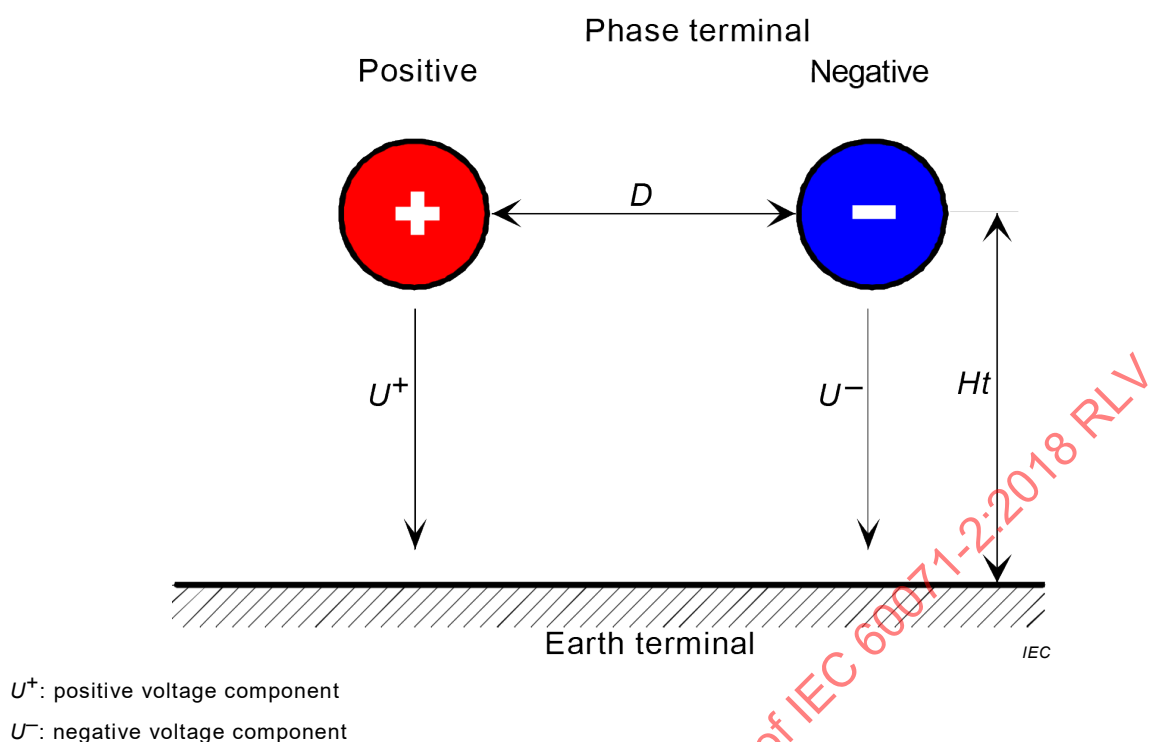
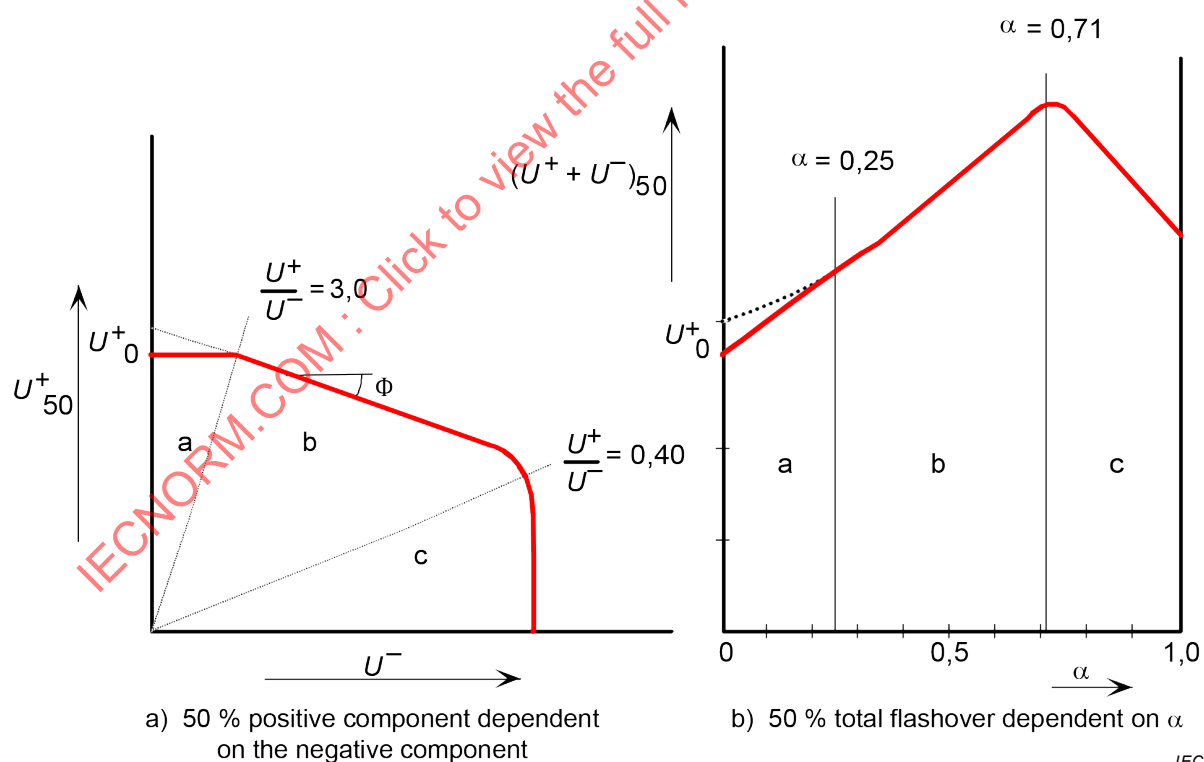


Figure C.3 – Schematic phase-phase-earth insulation configuration



Key

range a: flashover from positive phase terminal to earth

range b: flashover between phase terminals

range c: flashover from negative phase terminal to earth

Figure C.4 – Description of the 50 % switching impulse flashover voltage of a phase-phase-earth insulation

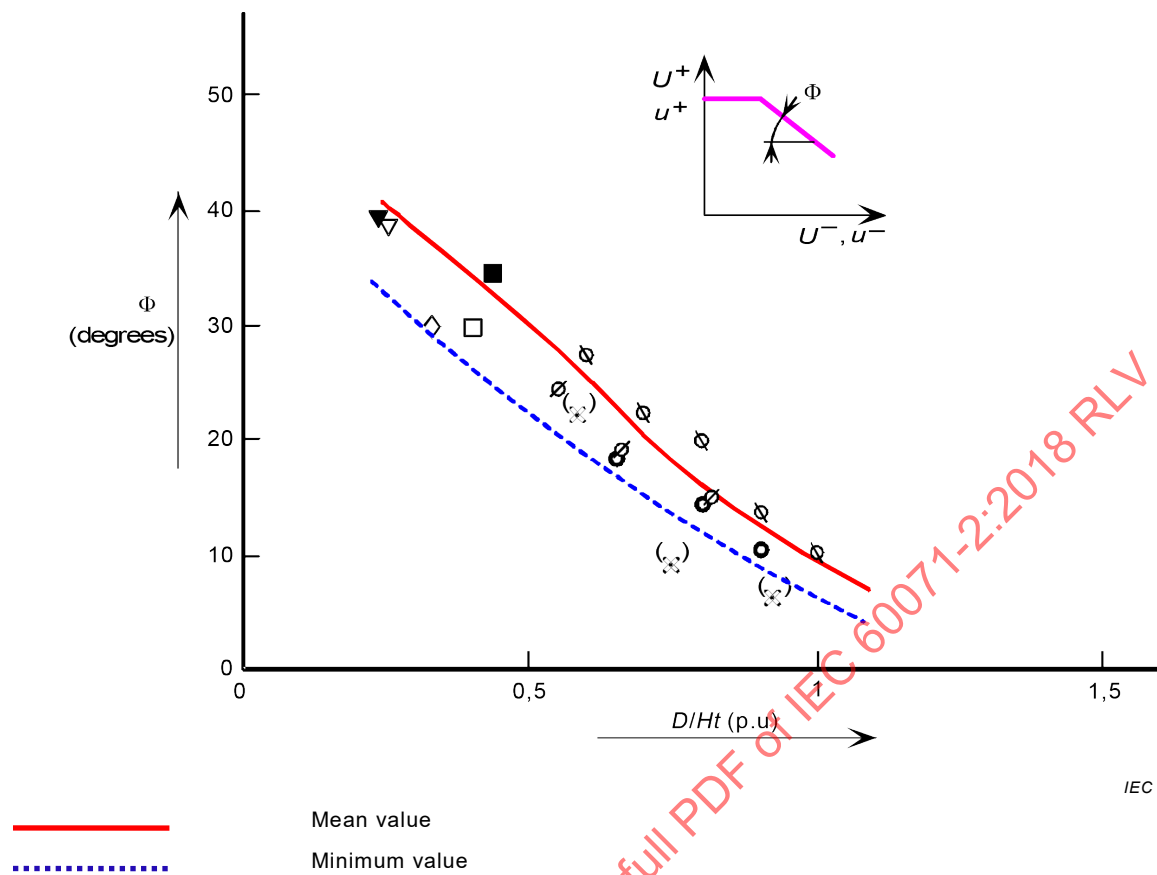


Figure C.5 – Inclination angle of the phase-to-phase insulation characteristic in range "b" dependent on the ratio of the phase-phase clearance D to the height H_t above earth

Annex D (informative)

Transferred overvoltages in transformers

D.1 General remarks

In some cases, the voltages and surges transferred through the transformer can be decisive when the overvoltage protection of the transformer is designed. A transformer connected to a high rating generator or motor with common circuit-breaker and protection is an example of such a case. Special cases are transformers whose one winding is permanently or occasionally (due to e.g. circuit-breaker operations) disconnected from the network.

The surges can be transferred through the transformer from one winding system to another. In certain cases the surge can be transferred also between the phases, which can increase the stress in an adjacent phase which is already being subjected to a direct surge. Problems are experienced with (for example) vacuum circuit-breaker switching a motor and in GIS with surges generated by disconnector operations.

The voltages transferred through the transformers are mainly fast-front or slow-front overvoltages. The transfer mode depends upon associated rates of change. In principle, the following transfer modes can come into question:

- electrostatic or capacitive transfer;
- oscillatory transfer through natural oscillations of primary and/or secondary circuits of the transformer (the earth capacitances and the self-inductances of the windings form the oscillation circuits);
- normal electromagnetic transfer which depends primarily on the turns ratio, leakage inductance and loading impedance of the transformer.

The oscillatory component is damped and superimposed on the electromagnetic transferred component. The oscillatory component is usually small and of secondary importance, if it is not magnified by resonance effects. Therefore, this transferring mechanism is not considered further here.

The transferred surge has usually both the capacitively and inductively transferred components which superimpose to the power-frequency voltage. The eventual voltage rise due to an earth fault have to be included in the power-frequency voltage. The capacitively transferred component lays typically in megahertz range and is seen first in the transferred surge. The inductively transferred component comes after the capacitive one. Its shape and amplitude change in time because the distribution of the voltage along the primary winding is time-dependent.

A special case of surge transference is the capacitively transferred neutral potential rise during earth faults and other unsymmetrical events in transformers where the turns ratio between the high-and low-voltage windings is exceptionally high (e.g. generator transformers or a transformer with a tertiary winding) and where the capacitance of the low-voltage side is low.

The magnitude of the transferred voltages depends on the construction of the transformer (especially the construction of the windings – disc, interleaved winding, etc. – and their order around the core legs as well as the leakage inductances), damping of the winding, capacitances of the transformer, turns (transformation) vector group, connection to the network, etc. In addition, the shape of the incoming surge has an important role.

Some of the constructional factors influencing the magnitude of transferred surges are difficult to calculate. Therefore, the most practical method to get a quantitative estimate for the

magnitude of these surges is to measure them, for example with recurrent surge measurement.

The following explains only the most important features of the overvoltage transference through transformers. Equations presented can be used only as a rough estimation of the surge magnitudes. "Primary" and "secondary" terms are used independently of the number of windings and in the direction of normal power transmission so that the surges come in the primary winding and are transferred from there to the secondary winding.

D.2 Transferred temporary overvoltages

The unsymmetry in the primary phase-to-earth voltages can cause phase-to-earth overvoltages in the secondary side if the secondary winding is with an isolated neutral and has a remarkably low rated voltage in respect to the primary winding. The most common cause of voltage unsymmetry is the earth fault. The magnitude of the transferred temporary overvoltage depends on the primary voltage during the earth fault, capacitance ratio of the transformer and on the eventual additional capacitors connected to the secondary side.

The maximum phase-to-earth overvoltage can be estimated from:

$$U_{2e} = \frac{C_{12}}{C_{12} + C_2} U_{1e} + \frac{U_{2N}}{\sqrt{3}} \quad (\text{D.1})$$

where

- U_{2e} is the secondary overvoltage caused by the earth fault in the primary;
- U_{1e} is the voltage in the neutral point of the primary winding during the earth fault;
- $U_{2N} / \sqrt{3}$ is the rated phase-to earth voltage in the secondary side;
- C_{12} is the capacitance between primary and secondary windings;
- C_2 is the phase-to-earth capacitance of the secondary winding and equipments connected to it.

The required capacitance values are obtained from the routine test protocols of the transformer.

The voltages should rigorously be added vectorially; however, arithmetic addition as given yields conservative results.

Too high overvoltages can occur if the phase-to-earth capacitance of the secondary winding is too low. For example, the standard power-frequency withstand voltages can be exceeded in the case of 110 kV transformers if the rated secondary voltage is 10 kV or less.

Another case leading to excessive capacitively transferred overvoltages is when the secondary winding with an isolated neutral is totally disconnected from the network during an earth fault on the primary side.

The magnitude of these overvoltages can be reduced with the help of additional capacitances which are connected between phase and earth in all phases on the secondary side. Often a capacitor of 0,1 μF is enough.

D.3 Capacitively transferred surges

Capacitively transferred surges are usually critical only when they are transferred from the high-voltage side to the low-voltage side.

The capacitively transferred surge can originate from the potential rise of the primary winding caused by incoming fast-front or slow-front overvoltages. They transfer to the secondary through the winding capacitance as in the case of unbalanced primary voltages but an important difference is caused by the fact that in the case of rapid primary voltage variations only those parts of the windings which are near the terminals take part in the surge transference. Therefore, in a general case, the distributed nature of the capacitances should be recognized by noting that the surge capacitance of a transformer winding is calculated from the distributed series and earth capacitances (C_s and C_e respectively) by:

$$C_{1in} = \sqrt{C_s C_e} \quad (D.2)$$

The value of C_e can be measured but the value of C_s has to be estimated on the basis of the construction of the windings. Therefore, only the manufacturer can give the value of the capacitance C_s .

NOTE The validity of the above calculation of C_{1in} is based on the assumption of a high initial distribution constant of the windings [9]. When high-voltage windings with much higher series capacitances (low distribution constant) are used, this approximation will be less accurate.

The surge capacitances form a capacitive divider (refer to Figure D.1) which can be used in the rough estimation of the magnitude of the capacitively transferred surges. When the effect of the power-frequency voltage is encountered, the resulting initial voltage spike on the open secondary side is given by:

$$U_{T2} = d_r h U_{T1} \quad (D.3)$$

where

h is the power-frequency voltage factor.

And the dividing ratio of the divider (d_r) is:

$$d_r = C_{1in} / (C_{1in} + C_{3in})$$

The dividing ratio d_r can range from 0,0 to at least 0,4. It can be estimated from the data available from the manufacturer of the transformer or measured by low-voltage impulse test. Delta connection of the low-voltage winding with a star connected high-voltage winding results in a further reduction in the value of parameter d_r .

The value of the factor h depends on the class of the voltage stress and on the type of transformer windings connections:

- for slow-front overvoltages, it is correct to assume $h = 1$ (no matter what the windings connections are);
- for fast-front overvoltages, $h > 1$ shall be used;
 - for star/delta or delta/star connections, $h = 1,15$ (rough estimate);
 - for star/star or delta/delta connections, $h = 1,07$ (rough estimate).

In the case of fast-front overvoltages, the value of U_{T1} can be the protection level of the arresters connected on the primary side. In the case of slow-front overvoltages, the value of U_{T1} can be the peak value of the phase-to-earth voltage stress (assuming the arresters will not react).

The magnitudes of capacitively transferred surges are damped due to the losses in the windings. This effect, as well as the load connected to the transformer, effectively reduces the magnitude of the capacitive spikes. Usually, these overvoltage spikes are critical only in the case of transformers with large step-down ratios and when only a small capacitance is connected to the secondary. Critical situations can arise if the incoming surge has a great

steepness or is chopped. Arresters connected to the secondary effectively limit the magnitudes of the capacitively transferred voltages. The protection can be further improved with additional capacitors, especially in the case of equipment which do not tolerate voltages with fast rising fronts (e.g. generators and motors) or if the capacitive ratio of the transformer is unfavourable, because otherwise the surge arresters on the secondary side might operate too frequently.

D.4 Inductively transferred surges

Inductive transfer of surges is usually the most important transfer mode and takes place already on moderate rates of voltage changes. Usually, an inductive surge transfer is associated with the transient behaviour of the surge voltages and currents in the primary winding when the initial distributions change in an oscillatory fashion towards the final voltage and current distributions. This means that the transferred surge is composed of several components which oscillate with different frequencies.

In this transfer mode, the transformer operates essentially in its normal mode and conventional power-frequency methods apply in the analysis of the magnitudes and shapes of the surges. Consequently, the derivation of equivalent circuits and equations for the voltage components is quite easy but, on the other hand, the determination of the values of the needed transformer parameters is complicated. Therefore, only simple approximative equations are often used for the determination of surge magnitudes. Consequently, direct measurements can give more reliable and accurate information on the magnitudes of the inductively transferred surges.

The magnitudes of the inductively transferred surges depend on

- the magnitude of the primary voltage (including the arrester operation),
- the duration of the incoming surge,
- the characteristics of the transformer (number of windings and turns ratio, short-circuit impedances, vector group),
- the surge impedances of the lines connected to the secondary, and
- the characteristics of the load.

The surge induced on the secondary side of a transformer may be estimated with the help of Equation (D.4):

$$U_{T2} = h q J w_{21} U_{T1} \quad (\text{D.4})$$

where

h is the factor defined under Equation (D.3);

q is the response factor of the secondary circuit to the transferred surge;

J is the factor dependent on the connection of the windings;

w_{21} is the ratio of transformer secondary to primary phase-to-phase voltage.

The response factor q basically determines the amplitude of the oscillation. The magnitude of q depends on the leakage inductance of the secondary winding, on the load connected to it as well as on the rate of rise of the incoming surge. Also, the order of the windings around the core legs influences (even reducing the value of q like the load in other windings) and makes the predetermination of q difficult.

In the following, some values are given to illustrate the situation in the case of transformers with disc windings. Manufacturers should be contacted in the case of transformers with other winding types.

Some typical values for q can be defined as following:

- if the transformer is connected to an overhead line without appreciable load, the value of q varies for fast-front surges from 0,3 to 1,3 when the rated voltage of the secondary winding varies from 245 kV to 36 kV;
- for switching surges on a similar system without appreciable load, the usual value is $q < 1,8$;
- if the transformer is connected to a cable, the usual value is $q < 1,0$, both for the fast-front and the slow-front surges.

Clearly higher values of q can result in the case of a three-winding transformer. Even values exceeding 1,7 to 2,0 have been recorded for such transformers.

Values of J for a surge on one phase only and for equal surges of opposite polarity on two phases are shown in Figure D.2 for eight different three-phase connections of the transformer. The figure is based on the assumption that the system voltage ratio is unity.

Inductively transferred surges from the high-voltage winding to the low-voltage one can be critical if

- the secondary voltage winding is not connected to the network,
- the secondary winding has a low rated voltage but a high rated power (e.g. generator transformers), and
- the winding is the tertiary of a three-winding transformer.

Inductively transferred surges can be dangerous for the phase-to-phase insulation of the delta-connected secondary windings, although all terminals of the transformer are equipped with surge arresters connected between phases and earth. Therefore, arresters connected between phases can also be necessary. High overvoltages can occur when the surge is transferred from the low-voltage winding to the high-voltage one, especially if resonance type voltage rises are caused.

The protection between phases and earth as well as between phases should be studied case by case. Necessary information should be required from the transformer manufacturer. Surge arresters connected between all phases and earth and also between the phases (when needed, e.g. star/delta connected transformers) usually give an adequate protection. Adding of extra capacitors does not usually reduce the inductively transferred overvoltages.

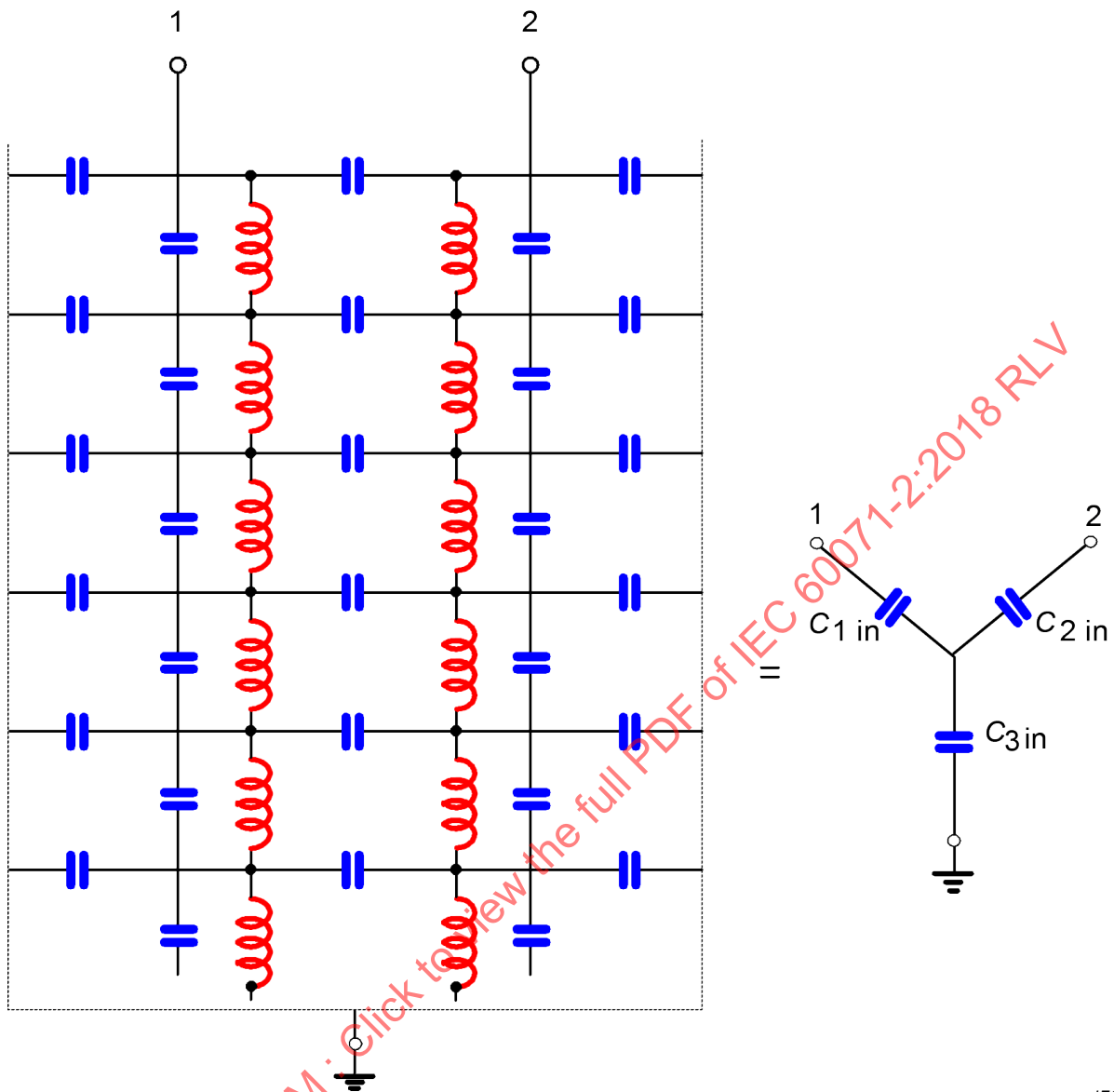


Figure D.1 – Distributed capacitances of the windings of a transformer and the equivalent circuit describing the windings

Case	Transformer connexion			Surge on one phase only $U_A = 1, U_B = U_C = 0$		Surges of opposite polarity on 2 phases $U_A = 1, U_B = -1, U_C = 0$	
	Higher-voltage winding	Lower-voltage winding	Tertiary	Higher-voltage winding	Lower-voltage winding	Higher-voltage winding	Lower-voltage winding
1	Y(e)	y(e)	(-, y)				
2	Y(e)	y(i)	(-, y)				
3	Y(e)	d	(-, y, d)				
4	Y(i)	y(e, i)	(-, y, d)				
5	Y(i)	d	(-, y, d)				
6	Y(i)	z(e, i)	(-, y, d)				
7	D	y(e, i)	(-, y, d)				
8	D	d	(-, y, d)				

IEC

Key

Y,y star-connected windings

D,d delta-connected windings

z Z-connected windings

 U_A, U_B, U_C overvoltage amplitudes at the high-voltage terminals A, B, C**Figure D.2 – Values of factor J describing the effect of the winding connections on the inductive surge transference**

Annex E (informative)

Lightning overvoltages

E.1 General remarks

The overvoltages in substations depend on amplitude and shape of the overvoltage impinging on the substation from the overhead line conductor as well as on the travelling wave behaviour of the substation itself. The frequency with which such impinging overvoltages occur is given by the lightning performance of the overhead line connected to the substation. For substations or parts of a substation to which no surge arrester is connected, the most important parameter is the amplitude of the impinging overvoltage; for substations protected by surge arresters, it is its steepness and the separation distance between surge arrester and the equipment under consideration.

The steepness of an impinging overvoltage surge is reduced mainly by corona damping effects on the overhead line [9]. This means that the steepness of the impinging surge can be only sufficient to cause a certain overvoltage amplitude if the lightning stroke hits the overhead line within a certain distance from the substation (see Clause E.2 for detailed explanations). For further strokes the steepness will be too low, irrespective of the amplitude of the surge.

The knowledge of this limit distance is of primary importance. In detailed digital overvoltage calculations using transient programs the overhead line should be carefully simulated over this distance. Recommendations for the necessary parameters to be included in such calculations are given in [9]. Furthermore, all simplifications which take into account the frequency of occurrence of the overvoltage amplitudes are based on similar considerations.

E.2 Determination of the limit distance (X_p)

E.2.1 Protection with arresters in the substation

E.2.1 contains more detailed information on surge arrester protection discussed in 4.3.4.5.

When more than one overhead line is connected to the substation, the original steepness (S) of the impinging surge can be divided by the number of lines (n). However, it is emphasized that the number of lines should correspond to the minimum number which reasonably remain in service taking into account possible outages during lightning storms.

Allowing for the fact that the steepness of the impinging surge reduces inversely with the travel distance on the overhead line, the steepness S of the impinging surge to be used in Equation (1) is approximately equal to:

$$S = 1 / (n K_{co} X) \quad (\text{E.1})$$

where

n is the number of overhead lines connected to the substation; if multi-circuit towers are involved and double-system back flashovers have to be taken into account, it is recommended to divide the number by two;

K_{co} is the corona damping constant according to Table E.1 ($\mu\text{s}/(\text{kV}\cdot\text{m})$);

X is the distance between struck point of lightning and substation (m).

NOTE Equation (E.1) has been derived with the assumption that the distances between the protected object and the connection points of the overhead lines result in travel times of less than half the front time of the impinging

surge. The lead between object and connection point, therefore, can be neglected in an approximate estimation. This approach is justified for determination of the limit distance in Equation (E.2) because here low steepnesses of the impinging surge are relevant. For the calculation of actual overvoltages resulting from an assumed impinging surge, this simplification may be not conservative.

The use of this steepness value in Equation (1) does not yield sufficiently accurate results for the calculation of overvoltage at the equipment. However, it is sufficient (and conservative) to estimate the limit distance X_p by:

$$X_p = 2t_s / [nK_{co} (U - U_{pl})] \quad (E.2)$$

where

U is the lowest considered overvoltage amplitude;

t_s is the longest travel time between any point in the substation to be protected and the closest arrester (μs);

U_{pl} is the lightning impulse protection level of the arrester.

For distances larger than X_p the steepness will be reduced such that the overvoltage at the equipment will in general be smaller than the assumed value U .

Table E.1 – Corona damping constant K_{co}

Conductor configuration	K_{co} $\mu s/(kV \cdot m)$
Single conductor	$1,5 \times 10^{-6}$
Double conductor bundle	$1,0 \times 10^{-6}$
Three or four conductor bundle	$0,6 \times 10^{-6}$
Six or eight conductor bundle	$0,4 \times 10^{-6}$

E.2.2 Self-protection of substation

Self-protection of the substation exists when the lightning overvoltage impinging the substation from the overhead line is decreased below the co-ordination withstand voltage by the reflections within the substation itself without any action of arresters. The fundamental requirement is that the number of lines connected to the substation is sufficiently large.

The necessary number of lines can be estimated by:

$$n \geq 4 \left[(U_{50}^- / U) \right] - 1 \quad (E.3)$$

where

n is the number of overhead lines;

U_{50}^- is the 50 % lightning impulse flashover voltage of the line insulation, negative polarity;

U is the overvoltage amplitude considered.

In addition, the impinging surge shall not cause too high overvoltages before the reflections from the additional lines act to decrease them. This requirement is fulfilled if the steepness of the impinging surge is so small due to corona damping effects on the line that the substation can be considered as a lumped element. This can be considered as valid when the lightning struck-point is beyond the limit distance:

$$X_p \geq 4 (t_s / K_{co} U) \quad (E.4)$$

where

t_s is the travel time to the most distant point from the substation busbar (μs).

An appreciable self-protection effect may be present in the case of GIS or cable-connected substations for which the reflections at the line entrance already decrease the overvoltage below the permitted value. This can be assumed as valid if:

$$U > (6Z_s / (Z_s + Z_L))U_{50}^- \quad (\text{E.5})$$

where

Z_s is the surge impedance of the substation;

Z_L is the surge impedance of the overhead line.

However, the distance between the lightning struck-point to the substation entrance may not be so small that the reflection from the substation interferes with the lightning. For this reason the following minimum limit distance is applicable:

- for shielding failures: $X_p = 1$ span;
- for back flashovers: $X_p = 2$ towers.

E.3 Estimation of the representative lightning overvoltage amplitude

E.3.1 General

As the full travelling wave calculation including the simulation of the overhead line performance is extremely difficult, a simplified procedure has been proposed in [9]. This procedure consists in calculating a lightning current with the desired return rate and calculating the overvoltage by travelling wave calculations in the substation including a short-line section equivalent circuit.

E.3.2 Shielding penetration

The lightning current determining the impinging surge is determined from the shielding penetration rate within the limit distance and its probability to be exceeded:

$$F(I) = F(I_m) + (R_t / R_p) \quad (\text{E.6})$$

where

$F(I_m)$ is the lightning current probability corresponding to the maximum shielding current;

R_t is the considered return rate;

R_p is the shielding penetration rate withing the limit distance.

NOTE The shielding penetration rate can be obtained from the shielding failure flashover rate by:

$$R_p = \frac{R_{sf}}{F(I_{cr}) - F(I_m)} \quad (\text{E.7})$$

where

R_{sf} is the shielding failure flashover rate;

$F(I_{cr})$ is the probability corresponding to the current causing line insulation flashover at negative polarity.

The currents corresponding to the probabilities can be obtained from the lightning stroke current probability distribution in the shielding failure range.

The amplitude of the impinging overvoltage surge is determined by Equation (E.8), and its steepness may be assumed to correspond to Equation (E.9):

$$U_l = Z_L I / 2 \quad (\text{E.8})$$

$$S = 1 / (K_{co} X_T) \quad (\text{E.9})$$

where

$$X_T = X_P / 4.$$

Its time to half-value should be 140 µs. If peak values higher than 1,6 times the negative flashover voltage of the line insulation are obtained, an impinging surge with this peak value should be used.

The impinging voltage surge is used to perform a travelling wave calculation within the substation and the representative overvoltages are obtained for this return rate for the various locations.

For some conductor bundles, the corona inception voltage can be very high, and the assumption of a linearly rising front can lead to an underestimation of the overvoltages. For such cases, a more suitable representation of the impinging surge front is recommended.

E.3.3 Back flashovers

The lightning current determining the design impinging surge is determined from the number of flashes to the overhead line tower and earth-wires within the limit distance and its probability to be exceeded is:

$$F(N) = R_t / R_f \quad (\text{E.10})$$

where

R_t is the considered return rate;

R_f is the flashing rate within the limit distance.

The voltage created at the tower footing impedance by this current is determined by its time response and current dependence. When the extension of the tower footing is within a radius of 30 m, the time response can be neglected and the tower footing impedance is:

$$R_{hc} = \frac{R_{lc}}{\sqrt{1 + \frac{I}{I_g}}} \quad (\text{E.11})$$

where

R_{lc} is the low current resistance;

I_g is the limit current (kA).

The limit current I_g represents the soil ionization and is evaluated by:

$$I_g = \frac{1}{2\pi} \frac{E_0 \rho}{R_{lc}^2} \quad (\text{E.12})$$

where

ρ is the soil resistivity (Ω·m);

E_0 is the soil ionization gradient (recommended value: 400 kV/m).

The amplitude of the design impinging surge is then given as:

$$U_1 = \frac{(1-c_f)R_{lc}I}{\sqrt{1+\frac{I}{I_g}}} \quad (\text{E.13})$$

where

c_f is the coupling factor between earth-wire and phase conductor.

Typical values of c_f are:

- $c_f = 0,15$ for single earth-wire lines;
- $c_f = 0,35$ for double earth-wire lines.

If amplitudes higher than 1,6 times the negative flashover voltage of the line insulation are obtained, an impinging surge with this amplitude should be used.

The design impinging surge has an exponentially decreasing tail with a time constant τ given by Equation (E.14) and a linear increasing front whose steepness S is given by Equation (E.15):

$$\tau = \frac{Z_e L_{sp}}{R_{lc} c} \quad (\text{E.14})$$

where

Z_e is the earth-wire surge impedance (typical values are 500 Ω for single earth-wire lines and 270 Ω for double earth-wire lines);

L_{sp} is the span length (m);

c is the light velocity (recommended value: 300 m/ μ s).

$$S = 1 / (K_{co} X_T) \quad (\text{E.15})$$

where

K_{co} is given by Equation (E.1);

X_T is given by Equation (E.9).

For travelling wave calculations in the considered substation, a single conductor of the length X_T and surge impedance equal to that of the phase conductors is connected to the substation. A voltage source with the internal impedance of the low current footing resistance R_{lc} is placed at the end of the conductor. It produces a voltage with the shape parameters of the impinging surge.

If the impinging surge amplitude is higher than 1,6 times the positive 50 % lightning impulse flashover voltage, the simplifications are no longer applicable and more careful studies may be recommendable. The same applies for tower footing extensions larger than 30 m in radius.

Two dependencies of the representative overvoltage amplitude on the return rate are obtained, one for shielding failures and one for back flashovers. The overall dependency is obtained by adding the return rates for a constant amplitude.

For some conductor bundles the corona inception voltage can be very high and the assumption of a linearly rising front can lead to an underestimation of the overvoltages. For such cases, a more suitable representation of the impinging surge front should be adopted.

E.4 Simplified method

A further simplification to the procedures described in Clauses E.2 and E.3 is to apply the basic principles given there, but to adopt the following assumptions:

- all lightning events within a certain distance from the substation cause higher overvoltages at the protected equipment than an assumed value, and all events outside this distance lower values;
- the overvoltage at the equipment can be calculated according to Equation (1) and Equation (E.1).

As mentioned already, both assumptions are not strictly valid. Firstly, not all events within a certain distance are equally severe. They depend on the lightning current or on the amplitude of the impinging overvoltage surge. Secondly, the overvoltages may be higher than that calculated with Equations (1) and (E.1). However, current practice of equipment protection by surge arresters has shown that both inaccuracies sufficiently cancel each other.

As regards the distance X to be applied in Equation (E.1), it has been shown that back flashovers do not occur at a tower close to the substation owing to the substation earth. The minimum value of X is one overhead line span length. The representative steepness S_{rp} to be applied in Equation (1), therefore, is equal to:

$$S_{rp} = 1 / [K_{co}(L_{sp} + L_t)] \quad (E.16)$$

And the overhead line section in which the lightning flashover rate is equal to the desired return rate [8] is equal to:

$$L_t = (R_t / R_{km})$$

where

R_t is the adopted overvoltage return rate (1/year);

R_{km} is the overhead line outage rate per year for a design corresponding to the first kilometre in front of the station (see Equation (E.16)) [usual unit: 1/(100 km·year); recommended unit: 1/(m·year)].

NOTE The equation is derived from the observation that back-flashovers do not occur at the tower close to the substation owing to the good substation earthing and that shielding failures do not occur in the first span of the overhead line. Therefore, there is a minimum travel length of the impinging surge which results in a maximum possible steepness. The analytical expression used in Equation (E.16) is an approximation to this observation. Alternatively, instead of the sum, the higher value of the span length or the length L_t can be used.

Thus, introducing S_{rp} in Equation (1) and putting $A = 2 / (K_{co} c)$ for transmission lines, the dependence of the representative lightning overvoltage on the return rate is obtained by:

$$U_{rp} = U_{pl} + \frac{A}{n} \frac{L}{L_{sp} + L_t} \quad (E.17)$$

where

U_{rp} is the representative lightning overvoltage amplitude (kV);

A is a factor given in Table E.2 describing the lightning performance of the overhead line connected to the station;

U_{pl} is the lightning impulse protection level of the surge arrester (kV);

- n is the minimum of lines connected to the substation ($n = 1$ or $n = 2$);
 L is the separation distance: $L = a_1 + a_2 + a_3 + a_4$ as shown on Figure 3 (m);
 L_{sp} is the span length (m);
 L_t is the overhead line length with outage rate equal to adopted return rate (m).

The co-ordination withstand voltage is obtained by replacing L_t by the line length L_a which yields an outage rate equal to the acceptable failure rate R_a :

$$L_a = R_a / R_{km} \quad (\text{E.18})$$

where

L_a is the overhead line section with outage rate equal to acceptable failure rate;

R_a is the acceptable failure rate for equipment.

And the co-ordination lightning impulse withstand voltage (U_{cw}) is equal to:

$$U_{cw} = U_{pl} + \frac{A}{n} \frac{L}{L_{sp} + L_a} \quad (\text{E.19})$$

For transmission lines, the factors A are obtained from Table E.2 and the corona damping constants K_{co} from Table E.1. For distribution systems, lightning overvoltages are usually multiphase and current sharing of the phase conductors has to be considered. For steel towers, the flashovers of more than one tower during a lightning stroke lead to a further reduction of the lightning overvoltages. For these lines, the factor A has been matched with the service practice.

GIS are, in general, better protected than open-air substations owing to a surge impedance much lower than that of the overhead lines. A generally valid recommendation for the estimation of the amelioration obtained for GIS as compared to open-air substations cannot be made. However, the use of the Equation (E.19) for the open-air substation results in conservative estimates of the co-ordination lightning impulse withstand voltage or of the protection range and a reduction of the ratio A/n to half the value used for outdoor stations is still suitable.

Table E.2 – Factor A for various overhead lines

Type of line	A (kV)
Distribution lines (phase-phase flashovers):	
– with earthed crossarms (flashover to earth at low voltage)	900
– wood-pole lines (flashover to earth at high voltage)	2 700
Transmission lines (single-phase flashover to earth)	
– single conductor	4 500
– double conductor bundle	7 000
– four conductor bundle	11 000
– six and eight conductor bundle	17 000
NOTE Values in this table are applicable in Equations (E.17) and (E.19).	

E.5 Assumed maximum value of the representative lightning overvoltage

For new stations, where lightning insulation performance of existing stations is known, the assumed maximum value of the representative overvoltage may be estimated by:

$$\frac{U_{rp2}}{U_{pl2}} = 1 + \left[\frac{n_1 L_2}{n_2 L_1} \frac{U_{pl1}}{U_{pl2}} \left(\frac{U_{rp1}}{U_{pl1}} - 1 \right) \right] \quad (\text{E.20})$$

where

U_{rp} is the assumed maximum representative overvoltage;

U_{pl} is the lightning impulse protection level of the surge arrester;

n is the minimum number of in-service overhead lines connected to the station;

And L is as follows (see Figure 3):

$$L = a_1 + a_2 + a_3 + a_4$$

The index 1 refers to the situation for which service experience has been satisfactory, and the index 2 to the new station situation.

Alternatively, the assumed maximum value can be obtained by assuming the return rate in Equation (E.16) equal to zero, thus leading to $L_t = 0$, and:

$$U_{rp} = U_{pl} + \frac{A}{n} \frac{L}{L_{sp}} \quad (\text{E.21})$$

Annex F (informative)

Calculation of air gap breakdown strength from experimental data

F.1 General

The intent of Annex F is not to provide the apparatus committees with a method to calculate air clearances. The purpose is rather to provide help to the user to estimate the size of equipment and the dielectric strength of air gaps for the purpose of determining the atmospheric correction factor.

It shall be noted that the equations provided here are based on experimental data and for the purposes of insulation co-ordination. For distances greater than 1 m, they can be assumed to give an approximate fit to these experimental results.

Discrepancies may be particularly significant for distances less than 1 m where the accuracy of the given equations is questionable.

F.2 Insulation response to power-frequency voltages

For air gap breakdown under power-frequency voltage, the lowest withstand voltage is obtained for the rod-plane gap configuration. The 50 % breakdown voltage for a rod-plane gap may be approximated by the following equation, for air gaps d up to 3 m:

$$U_{50RP} = 750 \sqrt{2} \ln(1 + 0,55 d^{1,2}) \quad (\text{kV crest, m}) \quad (\text{F.1})$$

The peak value of U_{50RP} under power-frequency voltage is about 20 % to 30 % higher than the corresponding value under positive switching impulse at critical front time. Withstand can be taken to be 90 % of U_{50} , based on an assumed conventional deviation of 3 % of U_{50} .

The influence of gap configuration on the strength is generally lower under power-frequency than under switching impulse:

- it is quite small for gaps up to about 1 m clearance;
- for gaps larger than 2 m, the strength can be evaluated according to the following equation (applicable to dry conditions):

$$U_{50} = U_{50RP} (1,35 K - 0,35 K^2) \quad (\text{F.2})$$

where

K is the gap factor (determined from switching impulse tests) as shown in Table F.1;

- for gaps between 1 m and 2 m, Equation (F.1) can be used with the knowledge that the results will be conservative.

When insulators are present, the flashover voltage can substantially decrease with respect to the reference case (the same air gap without insulators), especially in conditions of high humidity.

In general, discharges under power-frequency voltage and normal operating conditions and under temporary overvoltages will be caused by exceptional reductions in insulation withstand strength due to the severe ambient conditions or by aging of the insulation properties of the equipment.

The influence of rain on air gaps is negligible, especially for configurations presenting the lowest strength. However, rain can reduce the external dielectric strength of insulators, especially for post insulators with small distance between sheds. The degree of reduction depends on the rain rate, the insulator configuration and the conductivity of water.

Rain, together with pollution, can drastically reduce the insulation strength. The worst condition is usually caused by fog or light rain together with the polluted insulators (see 5.3.2.2). These conditions may in fact dictate the external insulation design. Comparative insulation contamination levels can be simulated by the equivalent salt deposit density (ESDD) in grams per square metre of NaCl. ESDD relates the steady-state conductivity of dissolved contaminant to an equivalent amount of dissolved NaCl. The determination of the ESDD requires an analysis of either performance of existing insulation in the area or statistical data gathered from on-site investigations.

Analysis of existing performance may be the more desirable but may not provide sufficient information if existing insulation never suffers pollution flashovers.

Analysis of statistical data requires several years of on-site monitoring as data is gathered by direct measurement of ESDD from washdown of exposed insulators or by other methods, for example leakage current measurement, chemical analysis or conductivity measurements.

NOTE The applicability of the concept of ESDD to non-ceramic insulators is not clear. The present research indicates that the phenomenon of surface hydrophobicity can be more important. The user is advised to use caution.

The statistical description of ambient conditions usually requires a greater amount of data. The statistical description of aging is even more difficult. Therefore, statistical procedures are not recommended in this document for estimation of the insulation response at power-frequency voltages.

F.3 Insulation response to slow-front overvoltages

Under stress from slow-front surges, a given self-restoring insulation exhibits an appreciably lower withstand voltage than under fast-front surges of the same polarity. As a result of numerous switching impulse tests, air gaps can be characterized by the minimum strength observed for the critical time-to-crest, as a function of the geometrical characteristics of the air gap which are mainly the gap spacing d and the electrode configuration. Among the different gaps of spacing d , the positively stressed rod-plane gap has the lowest strength and is used as a reference. For rod-plane gaps of length up to 25 m, experimental data for positive-polarity critical-front-time strength can be reasonably approximated by [10] [11]:

$$U_{50RP} = 1\,080 \ln(0,46 d + 1) \text{ (kV crest, m)} \quad (\text{F.3})$$

For standard switching impulses, the following equation provides a better approximation [11] [12]:

$$U_{50RP} = 500 d^{0,6} \text{ (kV crest, m)} \quad (\text{F.4})$$

Equations (F.3) and (F.4) are applicable to sea-level ($H = 0$). Therefore, correction for altitude is required when applying the insulation co-ordination procedure.

Insulators in the air gap generally decrease the breakdown strength, for positive slow-front impulses. For dry cap and pin insulators, the influence is small but can be important for post insulators.

For other gap configurations, a gap factor as described in Table F.1 is applied as follows:

$$U_{50} = K U_{50RP} \quad (F.5)$$

Note that for $K \geq 1,45$, the breakdown voltage under negative polarity may become lower than that for positive polarity.

For phase-to-phase configurations, a similar gap factor may be applied. In this case however, the gap factor is influenced not only by the gap configuration, but also by the ratio α defined as the peak negative component divided by the sum of the peak negative and positive components (see Annex C).

Table F.2 gives typical values of gap factor for usual phase-to-phase gap geometries for $\alpha = 0,5$ and $\alpha = 0,33$.

NOTE For any given gap configuration, actual gap factors can only be determined accurately by testing.

F.4 Insulation response to fast-front overvoltages

Under fast-front impulse stress, the negative polarity breakdown strength of a rod-plane gap configuration is much higher than that with positive polarity stress. Furthermore, the gap strength when plotted against the gap clearance is non-linear with negative polarity while it is linear with positive polarity. For standard lightning impulses applied to rod-plane gaps from 1 m up to 10 m, the experimental data for positive polarity strength may be approximated by:

$$U_{50RP} = 530 d \text{ (kV crest, m)} \quad (F.6)$$

In general, the gap factors applicable to switching impulse are not directly useable for lightning impulse strength. However, experimental results have shown that for positive polarity the breakdown gradient for a general air gap in per unit of the breakdown gradient for a rod-plane gap increases linearly with switching impulse gap factor for positive impulse stress. The gap factor K_{ff}^+ for fast-front lightning impulses of positive polarity can be approximated in terms of the switching impulse gap factor as follows:

$$K_{ff}^+ = 0,74 + 0,26 K \quad (F.7)$$

For the purpose of estimating the breakdown strength of overhead line insulator strings for negative polarity, in order to determine the magnitude of surges impinging on a substation, the following equation may be used:

$$U_{50} = 700 d \text{ (kV crest, m)} \quad (F.8)$$

The formulas (F.6) and (F.8) are applicable to sea-level ($H = 0$). Therefore, correction for altitude is required when applying the insulation co-ordination procedure.

For configurations such as conductor-upper structure and conductor-crossarm, the influence of the insulators on the strength is negligible so that the strength of these configurations is close to that of air gaps.

For other unusual configurations and particularly when large clearances are involved (like in range II), specific testing is advised for accurate results. For these configurations, the presence of insulators between the electrodes can play an important role on the discharge process, thus also heavily affecting the value of U_{50} . The degree of influence depends on insulator type (capacitance between units, distance between metal parts along the insulator set). A lower influence is to be expected for insulators with few metal parts (e.g. post insulators, long rod, composite). The generalization of the results similar to that made for configurations without insulators is not easy when cap and pin insulators are included in the

gap. It can be stated however that the influence of cap and pin insulators is reduced when the stress on the first insulator at both extremities of the string is reduced using shielding rings. It is also reduced for more practical configurations with insulators at both extremities less stressed than in the case of rod-plane gaps.

For air gaps, the conventional deviation is about 3 % of U_{50} under positive impulses and about 5 % of U_{50} under negative impulses. When insulators are present, the conventional deviation is increased reaching a maximum of 5 % to 9 % in connection with cases presenting the largest reduction of U_{50} . In other cases, a value close to that of air gaps is applicable.

The influence of rain on a flashover voltage is generally secondary, both in the case of air gaps and insulator strings.

For fast-front overvoltages, the time-to-breakdown is markedly influenced by the amplitude of the applied impulse relative to the breakdown voltage. For impulses close to the value of U_{50} , flashover occurs on the tail of the standard impulse. As amplitude is increased, time to flashover decreases giving rise to the well-known volt-time curve.

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Table F.1 – Typical gap factors K for switching impulse breakdown phase-to-earth (according to [1] and [4])

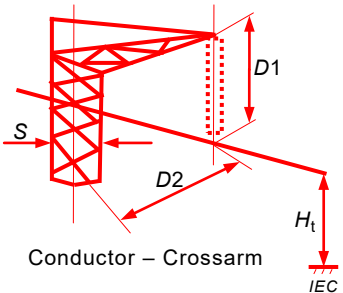
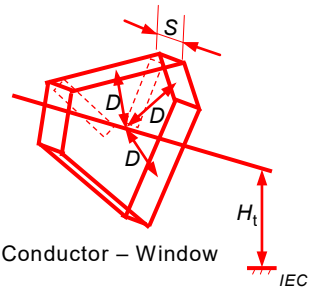
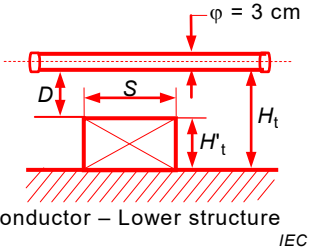
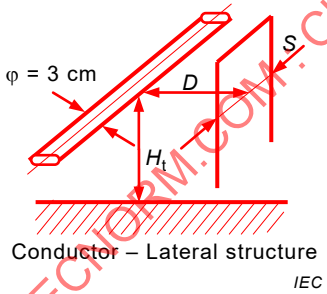
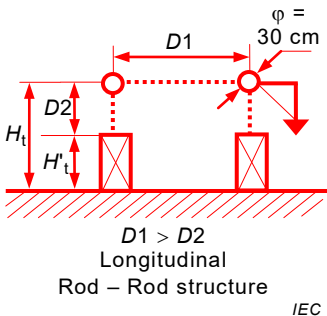
Gap type	Parameters	Typical range	Reference value	
 Conductor – Crossarm IEC	K	1,36 to 1,58	1,45	
	$D2 / D1$	1 to 2	1,5	
	$H_t / D1$	3,34 to 10	6	
	$S / D1$	0,167 to 0,2	0,2	
 Conductor – Window IEC	K	1,22 to 1,32	1,25	
	H_t / D	8 to 6,7	6	
	S / D	0,4 to 0,1	0,2	
 Conductor – Lower structure IEC	K	1,18 to 1,35	1,15 Conductor-plane	1,47 Conductor-rod
	H'_t / H_t	0,75 to 0,75	0	0,909
	H'_t / D	3 to 3	0	10
	S / D	1,4 to 0,05	-	0
 Conductor – Lateral structure IEC	K	1,28 to 1,63	1,45	
	H_t / D	2 to 10	6	
	S / D	1 to 0,1	0,2	
 $D1 > D2$ Longitudinal Rod – Rod structure IEC	K	1,03 to 1,66	1,35	
	H'_t / H_t	0,2 to 0,9	0	
	$D1 / H_t$	0,1 to 0,8	0,5	

Table F.2 – Gap factors for typical phase-to-phase geometries

Configuration	$\alpha = 0,5$	$\alpha = 0,33$
Ring-ring or large smooth electrodes	1,80	1,70
Crossed conductors	1,65	1,53
Rod-rod or conductor-conductor (along the span)	1,62	1,52
Supported busbars (fittings)	1,50	1,40
Asymmetrical geometries	1,45	1,36
NOTE According to [1] and [4].		

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Annex G (informative)

Examples of insulation co-ordination procedure

G.1 Overview

The insulation co-ordination procedure includes determining the voltage stresses from all origins on equipment and the corresponding electric strength required based on acceptable margins of protection or acceptable levels of performance. These margins (or levels) are mostly empirical.

As described in Figure 1 of IEC 60071-1:2006, there are in fact four main steps in this insulation co-ordination procedure, which can be identified as follows:

- step 1: determination of the representative overvoltages (U_{rp});
- step 2: determination of the co-ordination withstand voltages (U_{cw});
- step 3: determination of the required withstand voltages (U_{rw});
- step 4: determination of the standard withstand voltages (U_w).

These main steps, with associated links connecting them, will be illustrated in some examples contained in Annex G. Not only will the required standard withstand voltages be determined but also the calculation related to phase-to-ground and phase-to-phase clearances will be illustrated, as applicable.

The representative overvoltages are not, strictly speaking, the overvoltages that occur in the system but are overvoltages that represent the same electric stress on the equipment as the actual overvoltages. Thus, if the assumed actual overvoltage has a shape different from the test shape, the representative overvoltage may have to be modified accordingly so that the tests truly verify the insulation strength.

In matching the voltage stresses with the electric strength, one has to take into account the various types of voltage stresses and the corresponding response of the insulation. This involves making a distinction between self-restoring (external) insulation and non-self-restoring (internal) insulation. For non-self-restoring insulation, the stress-strength co-ordination is made using deterministic methodology whereas for self-restoring insulation a statistical methodology can be used where this is convenient. The following examples attempt to present all these considerations.

G.2 Numerical example for a system in range I (with nominal voltage of 230 kV)

G.2.1 General

The system analysed corresponds to that shown in Figure 11. The process of insulation co-ordination is applied to station 1 assumed to be a new station.

For equipment in range I, IEC 60071-1 specifies short-duration power-frequency and lightning impulse withstand voltages.

The evaluation of the required slow-front (switching) withstand voltages is followed by their conversion into equivalent power-frequency and fast-front (lightning) withstand voltages. The example showed in Clause G.2 includes such a conversion procedure.

For normal systems in range I, the insulation co-ordination procedure leads to the general philosophy of specifying one standard insulation level (a set of standard withstand voltages) applicable phase-to-phase and phase-to-earth.

This is illustrated in the first part of the example (G.2.2) where no "abnormal" operating condition is considered.

However, as a second part of the example (G.2.3), to show the importance of considering stresses from all origins and their influence on this general philosophy, such special operating conditions (consisting of capacitor switching at station 2) are considered.

In the third part of this example (G.2.4), flow charts summarize intermediate and final results obtained along the different steps of the insulation co-ordination procedure.

For the purpose of this example, one will assume the following basic data:

- the highest system voltage is $U_s = 245$ kV;
- the pollution level is heavy (refer to 5.3.2.2);
- the altitude is $H = 1\,000$ m.

G.2.2 Part 1: no special operating conditions

G.2.2.1 Step 1: determination of the representative overvoltages – values of U_{rp}

G.2.2.1.1 Power-frequency voltage

For the insulation co-ordination procedure, the most important reference voltage is the maximum continuous operating voltage U_s . For the system analysed, while the nominal voltage is 230 kV, the value of U_s is confirmed to be 245 kV (RMS, phase-to-phase). The system, including compensation, is designed to operate at or below this limit. Obviously, the installed equipment should have a U_m equal to or greater than U_s .

The new station 1 is to be located adjacent to a major thoroughfare where salt, spread on the road in winter, can be expected to lead to heavy pollution. Because of this environment, the performance requirements of external insulation at power-frequency will be met by specifying an artificial pollution test corresponding to pollution level "heavy" in 5.3.2.2. According to IEC TS 60815-1, the minimum creepage distance recommended for insulators is 25 mm/kV.

G.2.2.1.2 Temporary overvoltages

One source of temporary overvoltages is earth faults (refer to 4.3.2.2) giving rise to phase-to-earth overvoltages. System studies have been made taking into account the system neutral grounding characteristics, and the earth fault factor has been found to be $k = 1,5$ (such a figure is just for the purpose of the example; in fact, a value of 1,5 is rather unusual at a voltage level of 230 kV where a value not greater than 1,3 is normally expected). The corresponding phase-to-earth representative overvoltage is $U_{rp} = 212$ kV.

Another source of temporary overvoltages is load rejection (refer to 4.3.2.3) which produces overvoltages affecting both phase-to-phase and phase-to-earth insulation. Analysis and system studies have shown that generator overspeed and regulation combine to produce overvoltages of 1,4 p.u. at station 1 (which is also rather high) which results in phase-to-earth and phase-to-phase representative overvoltages of $U_{rp} = 198$ kV and $U_{rp} = 343$ kV.

As mentioned in 4.3.2.6, an earth fault can combine with load rejection to give rise to other overvoltage amplitudes. In this example, such a combination does not occur because after load rejection, the system configuration has changed: circuit-breakers at station 1 have opened, external infeeds are gone, and the earth fault factor (k) at station 1 has been reduced below 1 (with the delta/grounded Y generator step-up transformer).

The representative temporary overvoltages are the highest obtained considering all possible sources:

- phase-to-earth: $U_{rp} = 212 \text{ kV}$;
- phase-to-phase: $U_{rp} = 343 \text{ kV}$.

G.2.2.1.3 Slow-front overvoltages

System studies have confirmed that slow-front overvoltages from remote lightning strokes (refer to 4.3.3.6) are not a problem in the system under consideration. On the other hand, slow-front overvoltages due to earth faults need to be considered only in systems with resonant neutral earthing (refer to 4.3.3.3), which is not the case in this example.

For the determination of the representative overvoltages, it may be necessary to distinguish between equipment at the line entrance which can be in the open-end condition during energization or re-energization at remote end (station 1), and equipment on the source side at the local end (station 2) which will be affected in a different way and by different stresses.

1) Particular surges affecting line entrance equipment (at station 1)

System studies using the phase-peak method (refer to Annex C) have shown that line re-energization from station 2 can result in 2 % overvoltages at the open-end line entrance at station 1 of $u_{e2} = 3,0 \text{ p.u.}$ and $u_{p2} = 4,5 \text{ p.u.}$ The representative overvoltages for external line entrance equipment, before applying surge arresters, are the truncation values of these overvoltage distributions. As shown in Annex C:

- $u_{et} = 1,25 u_{e2} - 0,25 \Rightarrow u_{et} = 700 \text{ kV}$;
- $u_{pt} = 1,25 U_{p2} - 0,43 \Rightarrow u_{pt} = 1\,039 \text{ kV}$.

2) Surge affecting all equipment (at station 1)

All the equipment located in station 1 is subjected to slow-front overvoltages due to local line energization and re-energization. However, these sending end surges are much lower than at the receiving end: for station 1, system studies result in $u_{e2} = 1,9 \text{ p.u.}$ and $u_{p2} = 2,9 \text{ p.u.}$ Corresponding values are $U_{et} = 425 \text{ kV}$ and $U_{pt} = 639 \text{ kV}$.

3) Surge arresters at the line entrance (at station 1)

To control the possible severe overvoltages originating from remote re-energization, metal-oxide surge arresters are installed at the line entrance (refer to 4.3.3.8), identical to those planned for transformer protection. The rating of these arresters is such that they can sustain the worst temporary overvoltage cycle (amplitude and duration). Their protection characteristics are:

- switching impulse protection level: $U_{ps} = 410 \text{ kV}$;
- lightning impulse protection level: $U_{pl} = 500 \text{ kV}$.

As explained in 4.3.3.8, with the use of surge arresters, the slow-front representative overvoltages can be directly given by U_{ps} (phase-to-earth) or $2 U_{ps}$ (phase-to-phase) if these protection values are lower than the corresponding maximum slow-front overvoltage stresses (U_{et} and U_{pt} values). This is the case for any stress except for line entrance equipment, phase-to-phase, so that the representative slow-front overvoltages are:

- phase-to-earth: $U_{rp} = 410 \text{ kV}$ for any equipment;
- phase-to-phase:
 - $U_{rp} = 639 \text{ kV}$ for any equipment except at line entrance;
 - $U_{rp} = 820 \text{ kV}$ for equipment at line entrance.

G.2.2.1.4 Fast-front overvoltages

In this example, only fast-front overvoltages from lightning have to be considered. A simplified statistical approach will be used which leads directly to the co-ordination withstand voltage (step 2 below), bypassing the need for a representative overvoltage.

G.2.2.2 Step 2: determination of the co-ordination withstand voltages – values of U_{cw}

G.2.2.2.1 General

According to Clause 5, different factors have to be applied to the previously determined values of representative overvoltages. These factors, which may vary with the shape of the considered overvoltage, take into account the adopted performance criteria (the economic or operational rate of failure which is acceptable) and the inaccuracies in the input data (e.g. arrester data).

G.2.2.2.2 Temporary overvoltages

For this class of overvoltages, the co-ordination withstand voltage is equal to the representative temporary overvoltage (refer to 5.3.2). In other words, the co-ordination factor K_c is equal to 1. Therefore:

- phase-to-earth: $U_{cw} = 212 \text{ kV}$;
- phase-to-phase: $U_{cw} = 343 \text{ kV}$.

G.2.2.2.3 Slow-front overvoltages

The deterministic approach is used. With such an approach, one shall take into account that surge limitation by an arrester distorts the statistical distribution of these surges, creating a significant bulge in the probability distribution of surges at about the arrester protection level (refer to 5.3.3.1). Therefore, small uncertainties related to the arrester protection characteristic or to equipment strength could lead to an abnormally high increase in the failure rate. Figure 4 takes this into account by applying a deterministic co-ordination factor K_{cd} to the arrester protection level to obtain the U_{cw} values.

For line entrance equipment:

- phase-to-earth: $U_{ps}/U_{e2} = 410/600 = 0,68 \Rightarrow K_{cd} = 1,10$;
- phase-to-phase: $2 U_{ps}/U_{p2} = 820/900 = 0,91 \Rightarrow K_{cd} = 1,00$.

For all other equipment:

- phase-to-earth: $U_{ps}/U_{e2} = 410/380 = 1,08 \Rightarrow K_{cd} = 1,03$;
- phase-to-phase: $2 U_{ps}/U_{p2} = 820/580 = 1,41 \Rightarrow K_{cd} = 1,00$.

The resulting co-ordination withstand voltages are $K_{cd} \times U_{rp}$:

For line entrance equipment:

- phase-to-earth: $U_{cw} = 1,1 \times 410 \Rightarrow U_{cw} = 451 \text{ kV}$;
- phase-to-phase: $U_{cw} = 1,0 \times 820 \Rightarrow U_{cw} = 820 \text{ kV}$.

For all other equipment:

- phase-to-earth: $U_{cw} = 1,03 \times 410 \Rightarrow U_{cw} = 422 \text{ kV}$;
- phase-to-phase: $U_{cw} = 1,0 \times 639 \Rightarrow U_{cw} = 639 \text{ kV}$.

G.2.2.2.4 Fast-front overvoltages

A statistical approach is used (refer to 5.3.4.2), and more specifically, a simplified statistical approach (refer to Clause E.4). Here, the factor to be applied to U_{rp} is based on experience with particular line construction and on the calculated effect due to the separation between the arrester and the protected equipment.

One determines the length L_a of overhead line with an outage rate equal to the acceptable failure rate R_a . Then, taking account of the separation distance L , the number of lines n entering the station, and the span length L_{sp} , one calculates the effective protection level of the arrester, which is the desired value U_{cw} .

For this example, the following data are available: many arresters with a lightning protection level of 500 kV are located at different places (at line entrance and near the transformers). The maximum separation distance for internal insulation is 30 m; for external insulation, it is 60 m. Two steel tower lines characterized by $A = 4\,500$ (refer to Table E.2) and with a span length of 300 m are connected to the station. The lightning performance for such lines is one outage per 100 km per year. For the equipment to be installed in station 1, an acceptable failure rate is defined as 1 in 400 years.

Using Equation (E.18), the value of $L_a = 0,25$ km is found. Introducing the value of L_a and other parameters in Equation (E.19), the co-ordination withstand voltage is found:

- for internal insulation:

$$U_{cw} = 500 + [(4\,500 / 2) \times 30 / (300 + 250)] \Rightarrow U_{cw} = 622 \text{ kV};$$

- for external insulation:

$$U_{cw} = 500 + [(4\,500 / 2) \times 60 / (300 + 250)] \Rightarrow U_{cw} = 745 \text{ kV}.$$

Fast-front overvoltages affect the phase-to-phase and the phase-to-earth insulations in the same way.

G.2.2.3 Step 3: determination of the required withstand voltages – values of U_{rw}

G.2.2.3.1 General

The required withstand voltages are obtained by applying to the co-ordination withstand voltages two correction factors (refer to Clause 6): factor K_a which takes into account the altitude of the installation, and a safety factor K_s .

G.2.2.3.2 Safety factor

The recommended values for the safety factor K_s are defined in 6.3.5. The factor K_s is applicable to any type of overvoltage shape (temporary, slow-front, fast-front), phase-to-phase and phase-to-earth:

- for internal insulation: $K_s = 1,15$;
- for external insulation: $K_s = 1,05$.

G.2.2.3.3 Atmospheric correction factor

The altitude correction factor K_a is defined in 6.2.2 (Equation (11)). The factor K_a is applicable to external insulation only and its value depends on the overvoltage shape (via parameter m in Equation (11)).

For power-frequency withstand, short-duration tests on polluted insulators are required, and:

$$\Rightarrow m = 0,5.$$

For switching impulse withstand, the value of m is a function of the co-ordination withstand voltage according to Figure 9:

- phase-to-earth: $U_{cw} = 451 \text{ kV} \Rightarrow m = 0,94;$
- phase-to-phase: $U_{cw} = 820 \text{ kV} \Rightarrow m = 1,00.$

For lightning impulse withstand: $\Rightarrow m = 1,00.$

The installation is at an altitude $H = 1\,000 \text{ m}$. The corresponding values of K_a are:

- for power-frequency withstand: $K_a = 1,063$ (phase-to-phase and phase-to-earth);
- for switching impulse withstand: $K_a = 1,122$ (phase-to-earth),
 $K_a = 1,130$ (phase-to-phase);
- for lightning impulse withstand: $K_a = 1,130$ (phase-to-phase and phase-to-earth).

G.2.2.3.4 Required withstand voltages

The values for the required withstand voltages are obtained from: $U_{rw} = U_{cw} K_s K_a$, with U_{cw} values found in step 2 (G.2.2.2) and K_s and K_a values found in step 3 (G.2.2.3).

1) For temporary overvoltages

- external insulation:
 - phase-to-earth $\Rightarrow U_{rw} = 212 \times 1,05 \times 1,063 \Rightarrow U_{rw} = 237 \text{ kV},$
 - phase-to-phase $\Rightarrow U_{rw} = 343 \times 1,05 \times 1,063 \Rightarrow U_{rw} = 383 \text{ kV};$
- internal insulation:
 - phase-to-earth $\Rightarrow U_{rw} = 212 \times 1,15 \Rightarrow U_{rw} = 243 \text{ kV},$
 - phase-to-phase $\Rightarrow U_{rw} = 343 \times 1,15 \Rightarrow U_{rw} = 395 \text{ kV}.$

2) For slow-front overvoltages

For line entrance equipment:

- external insulation:
 - phase-to-earth $\Rightarrow U_{rw} = 451 \times 1,05 \times 1,122 \Rightarrow U_{rw} = 531 \text{ kV},$
 - phase-to-phase $\Rightarrow U_{rw} = 820 \times 1,05 \times 1,13 \Rightarrow U_{rw} = 973 \text{ kV}.$

For other equipment:

- external insulation:
 - phase-to-earth $\Rightarrow U_{rw} = 422 \times 1,05 \times 1,122 \Rightarrow U_{rw} = 497 \text{ kV},$
 - phase-to-phase $\Rightarrow U_{rw} = 639 \times 1,05 \times 1,13 \Rightarrow U_{rw} = 758 \text{ kV}.$
- internal insulation:
 - phase-to-earth $\Rightarrow U_{rw} = 422 \times 1,15 \Rightarrow U_{rw} = 485 \text{ kV},$
 - phase-to-phase $\Rightarrow U_{rw} = 639 \times 1,15 \Rightarrow U_{rw} = 735 \text{ kV}.$

3) For fast-front overvoltages:

- external insulation:
 - phase-to-earth $\Rightarrow U_{rw} = 745 \times 1,05 \times 1,13 \Rightarrow U_{rw} = 884 \text{ kV},$
 - phase-to-phase $\Rightarrow U_{rw} = 745 \times 1,05 \times 1,13 \Rightarrow U_{rw} = 884 \text{ kV}.$
- internal insulation:
 - phase-to-earth $\Rightarrow U_{rw} = 622 \times 1,15 \Rightarrow U_{rw} = 715 \text{ kV},$
 - phase-to-phase $\Rightarrow U_{rw} = 622 \times 1,15 \Rightarrow U_{rw} = 715 \text{ kV}.$

G.2.2.4 Step 4: conversion to withstand voltages normalized for range I

G.2.2.4.1 General

In range I, the insulation level is normally described by a set of two values as shown in Table 2 of IEC 60071-1:2006: a short-duration power-frequency withstand voltage and a lightning impulse withstand voltage. Table 1 gives the test conversion factor to be applied to the required withstand voltage for slow-front overvoltage to get such an equivalent set of values.

G.2.2.4.2 Conversion to short-duration power-frequency withstand voltage (SDWV)

For line entrance equipment:

- external insulation:
 - phase-to-earth $\Rightarrow$ $SDWV = 531 \times (0,6 + 531 / 8\,500) = 352 \text{ kV};$
 - phase-to-phase $\Rightarrow$ $SDWV = 973 \times (0,6 + 973 / 12\,700) = 658 \text{ kV}.$

For other equipment:

- external insulation:
 - phase-to-earth $\Rightarrow$ $SDWV = 497 \times (0,6 + 497 / 8\,500) = 327 \text{ kV};$
 - phase-to-phase $\Rightarrow$ $SDWV = 758 \times (0,6 + 758 / 12\,700) = 500 \text{ kV};$
- internal insulation:
 - phase-to-earth $\Rightarrow$ $SDWV = 485 \times 0,5 = 243 \text{ kV};$
 - phase-to-phase $\Rightarrow$ $SDWV = 735 \times 0,5 = 367 \text{ kV}.$

G.2.2.4.3 Conversion to lightning impulse withstand voltage (LIWV)

For line entrance equipment:

- external insulation:
 - phase-to-earth $\Rightarrow$ $LIWV = 531 \times 1,30 = 690 \text{ kV};$
 - phase-to-phase $\Rightarrow$ $LIWV = 973 \times (1,05 + 973 / 9\,000) = 1\,127 \text{ kV}.$

For other equipment:

- external insulation:
 - phase-to-earth $\Rightarrow$ $LIWV = 497 \times 1,30 = 646 \text{ kV};$
 - phase-to-phase $\Rightarrow$ $LIWV = 758 \times (1,05 + 758 / 9\,000) = 860 \text{ kV};$
- internal insulation:
 - phase-to-earth $\Rightarrow$ $LIWV = 485 \times 1,10 = 534 \text{ kV};$
 - phase-to-phase $\Rightarrow$ $LIWV = 735 \times 1,10 = 808 \text{ kV}.$

G.2.2.5 Step 5: selection of standard withstand voltage values

Table G.1 summarizes values $U_{rw(s)}$ of minimum required withstand voltages obtained from system studies (results in step 3) which become minimum test values to be applied to verify these withstands in terms of short-duration power-frequency, switching impulse and lightning impulse tests. In range I, the required switching impulse withstand voltage is normally covered by a standard short-duration power-frequency test or by a standard lightning impulse test. In Table G.1, values obtained after such conversions are indicated under $U_{rw(c)}$ (results from step 4). In this example, converted values for a lightning impulse test are retained so that converted values for a short-duration power-frequency test need no more consideration.

Table G.1 – Summary of minimum required withstand voltages obtained for the example shown in G.2.2

Values of U_{rw} kV		External insulation				Internal insulation	
		Line entrance equipment		Other equipment			
		$U_{rw(s)}$	$U_{rw(c)}$	$U_{rw(s)}$	$U_{rw(c)}$	$U_{rw(s)}$	$U_{rw(c)}$
Short-duration power-frequency (RMS)	phase-earth	237	352	237	327	243	243
	phase-phase	383	658	383	500	395	367
Switching impulse (peak)	phase-earth	531		497	—	485	—
	phase-phase	973	—	758	—	735	—
Lightning impulse (peak)	phase-earth	884	690	884	646	715	534
	phase-phase	884	1127	884	860	715	808
NOTE The figures are obtained from part 1 (G.2.2), without capacitor switching at remote station (station 2).							

Standard voltages to be defined for the purpose of the short-duration power-frequency and lightning impulse tests have to be selected taking into account results shown in bold characters in Table G.1 (highest value of minimum withstand required $U_{rw(s)}$ or converted value $U_{rw(c)}$) and standard values proposed in IEC 60071-1:2006 and IEC 60071-1:2006/AMD1:2010, 5.6 and 5.7. Normally, specified voltages are chosen in such a way as to correspond to a standard insulation level as defined in 3.36 of IEC 60071-1:2006 and shown in Table 2 of IEC 60071-1:2006.

Standardized values of 395 kV (for short-duration power-frequency) and 950 kV (for lightning impulse) correspond to such a standard insulation level for a system with $U_m = 245$ kV; these values will cover any insulation, phase-to-earth and phase-to-phase, except the phase-to-phase external insulation at line entrance for which a 1 127 kV minimum withstand value is required. However, in this example, three-phase equipment is not installed at line entrance so that a minimum phase-to-phase clearance can be specified instead of testing. According to IEC 60071-1, a clearance of 2,35 m between phases would be required for line entrance equipment, corresponding to a standard lightning impulse withstand voltage of 1 175 kV. A minimum phase-to-earth and phase-to-phase clearance of 1,9 m is required for any other external insulation not located at line entrance. These clearances are solely based on insulation co-ordination requirements.

It will be noted that, for external phase-to-earth insulation, the high value specified for the short-duration power-frequency test (395 kV) is well above minimum requirement related to temporary overvoltages (237 kV). However, a 395 kV value corresponds to the standard insulation level having the required lightning withstand level of 950 kV. Refinements in studies could lead to lower requirements by one step for the phase-to-earth external insulation (360 kV/850 kV).

For the internal insulation, the selection of the same standard insulation level as for external insulation could be considered as leading to too much margin with respect to required lightning withstand voltages (715 kV phase-to-earth and 808 kV phase-to-phase). Other choices, considering the economic issue, are possible (refer to 5.10 of IEC 60071-1:2006 and IEC 60071-1:2006/AMD1:2010): specification of a lightning impulse withstand voltage of 850 kV, phase-to-phase and phase-to-earth; or 750 kV phase-to-earth with a special phase-to-phase test at 850 kV. However, the short-duration power-frequency test at a minimum value of 395 kV shall be kept. Even if acceptable, the final issue related to these other choices would lead to a rated insulation level not corresponding to a standard insulation level as defined in IEC 60071-1.

G.2.3 Part 2: influence of capacitor switching at station 2

This second part of the example exposed in Clause G.2 deals with an additional slow-front overvoltage possibility originating from capacitor bank switching done at station 2 (remote station). All the other stresses considered in part 1 are present at their same values, with the same arrester implementation at station 1.

Results from system studies show that all equipment at station 1 (including line entrance equipment in normal operating closed condition) is subjected to severe voltage surges due to capacitor bank energization at station 2. These surges propagate and, due to amplification phenomenon (resonance at given frequencies), show the following maximum amplitudes at station 1:

- phase-to-earth:
 - $U_{e2} = 500$ kV;
 - $U_{et} = 575$ kV;
- phase-to-phase:
 - $U_{p2} = 750$ kV;
 - $U_{pt} = 852$ kV.

For the open-end line entrance equipment, the highest slow-front surges are those related to line re-energization described in part 1. But for all other equipment, the slow-front surges governing the insulation co-ordination procedure are now related to capacitor bank switching in station 2, which are higher than surges originating from local energization and re-energization (described in part 1). Hereafter, only this type of stress (new slow-front surges) is dealt with, conclusions for the other types of stress (temporary and fast-front overvoltages) remaining the same as discussed in part 1.

Values of representative slow-front overvoltages U_{rp} are now controlled by the surge arrester protection characteristic because $U_{ps} < U_{et}$ and $2 U_{ps} < U_{pt}$, so that:

- phase-to-earth: $U_{rp} = 410$ kV;
- phase-to-phase: $U_{rp} = 820$ kV.

To obtain the slow-front co-ordination withstand voltages U_{cw} , a deterministic co-ordination factor K_{cd} is applied to U_{rp} values by following the same procedure described in part 1:

- phase-to-earth: $U_{ps} / U_{e2} = 410 / 500 = 0,82 \Rightarrow K_{cd} = 1,10 \Rightarrow U_{cw} = 451$ kV;
- phase-to-phase: $2 U_{ps} / U_{p2} = 820 / 750 = 1,09 \Rightarrow K_{cd} = 1,00 \Rightarrow U_{cw} = 820$ kV.

The values for the safety factor K_s and for the atmospheric correction factor K_a keep approximately the same values as in part 1 so that the resulting required withstand voltages U_{rw} are:

- external insulation:
 - phase-to-earth $\Rightarrow U_{rw} = 451 \times 1,05 \times 1,122 \Rightarrow U_{rw} = 531$ kV;
 - phase-to-phase $\Rightarrow U_{rw} = 820 \times 1,05 \times 1,13 \Rightarrow U_{rw} = 973$ kV;
- internal insulation:
 - phase-to-earth $\Rightarrow U_{rw} = 451 \times 1,15 \Rightarrow U_{rw} = 518$ kV;
 - phase-to-phase $\Rightarrow U_{rw} = 820 \times 1,15 \Rightarrow U_{rw} = 943$ kV.

The required withstand voltages for slow-front surges are converted into short-duration power-frequency and lightning impulse withstand voltages (refer to part 1 for detailed information).

Conversion to short-duration power-frequency withstand voltage (SDWV):

- external insulation:
 - phase-to-earth $\Rightarrow$ SDWV = $531 \times (0,6 + 531 / 8\,500)$ = 352 kV;
 - phase-to-phase $\Rightarrow$ SDWV = $973 \times (0,6 + 973 / 12\,700)$ = 658 kV;
- internal insulation:
 - phase-to-earth $\Rightarrow$ SDWV = $518 \times 0,5$ = 259 kV;
 - phase-to-phase $\Rightarrow$ SDWV = $943 \times 0,5$ = 472 kV.

Conversion to lightning impulse withstand voltage (LIWV):

- external insulation:
 - phase-to-earth $\Rightarrow$ LIWV = $531 \times 1,30$ = 690 kV;
 - phase-to-phase $\Rightarrow$ LIWV = $973 \times (1,05 + 973 / 9\,000)$ = 1 127 kV;
- internal insulation:
 - phase-to-earth $\Rightarrow$ LIWV = $518 \times 1,10$ = 570 kV;
 - phase-to-phase $\Rightarrow$ LIWV = $943 \times 1,10$ = 1 037 kV.

Table G.2 reflects the minimum withstand (or test) values required to take into account the different overvoltage stresses related to part 2 of the example exposed in Clause G.2. Minimum values required for the short-duration power-frequency and lightning impulse withstand tests are shown in bold characters.

Table G.2 – Summary of required withstand voltages obtained for the example shown in G.2.3

Values of U_{rw} kV		External insulation				Internal insulation	
		Line entrance equipment		Other equipment			
		$U_{rw(s)}$	$U_{rw(c)}$	$U_{rw(s)}$	$U_{rw(c)}$	$U_{rw(s)}$	$U_{rw(c)}$
Short-duration power-frequency (RMS)	phase-earth	237	352	237	352	243	259
	phase-phase	383	658	383	658	395	472
Switching impulse (peak)	phase-earth	531	—	531	—	518	—
	phase-phase	973	—	973	—	943	—
Lightning impulse (peak)	phase-earth	884	690	884	690	715	570
	phase-phase	884	1127	884	1127	715	1037
NOTE The figures are obtained from part 2, with capacitor switching at remote station (station 2).							

A comparison between Table G.2 and Table G.1 shows the impact of slow-front overvoltages due to capacitor switching at station 2, mainly on phase-to-phase switching impulse requirements and on the resulting equivalent minimum testing values.

For external insulation, including longitudinal insulation, the same standard insulation level defined in part 1 (395 kV/950 kV) is also applicable here, no phase-to-phase test being required if a 2,35 m phase-to-phase clearance (corresponding to a standard lightning impulse withstand voltage of 1 175 kV) is adopted for all external equipment (not only at line entrance as for part 1).

For internal insulation, a standard insulation level applicable phase-to-phase and phase-to-earth of 460 kV/1 050 kV, corresponding to $U_m = 245$ kV, can be chosen (refer to Table 2 of IEC 60071-1:2006). This corresponds to one standard insulation level higher than in part 1 of this example, and is due to the switching of a capacitor at the remote station. Lower, phase-

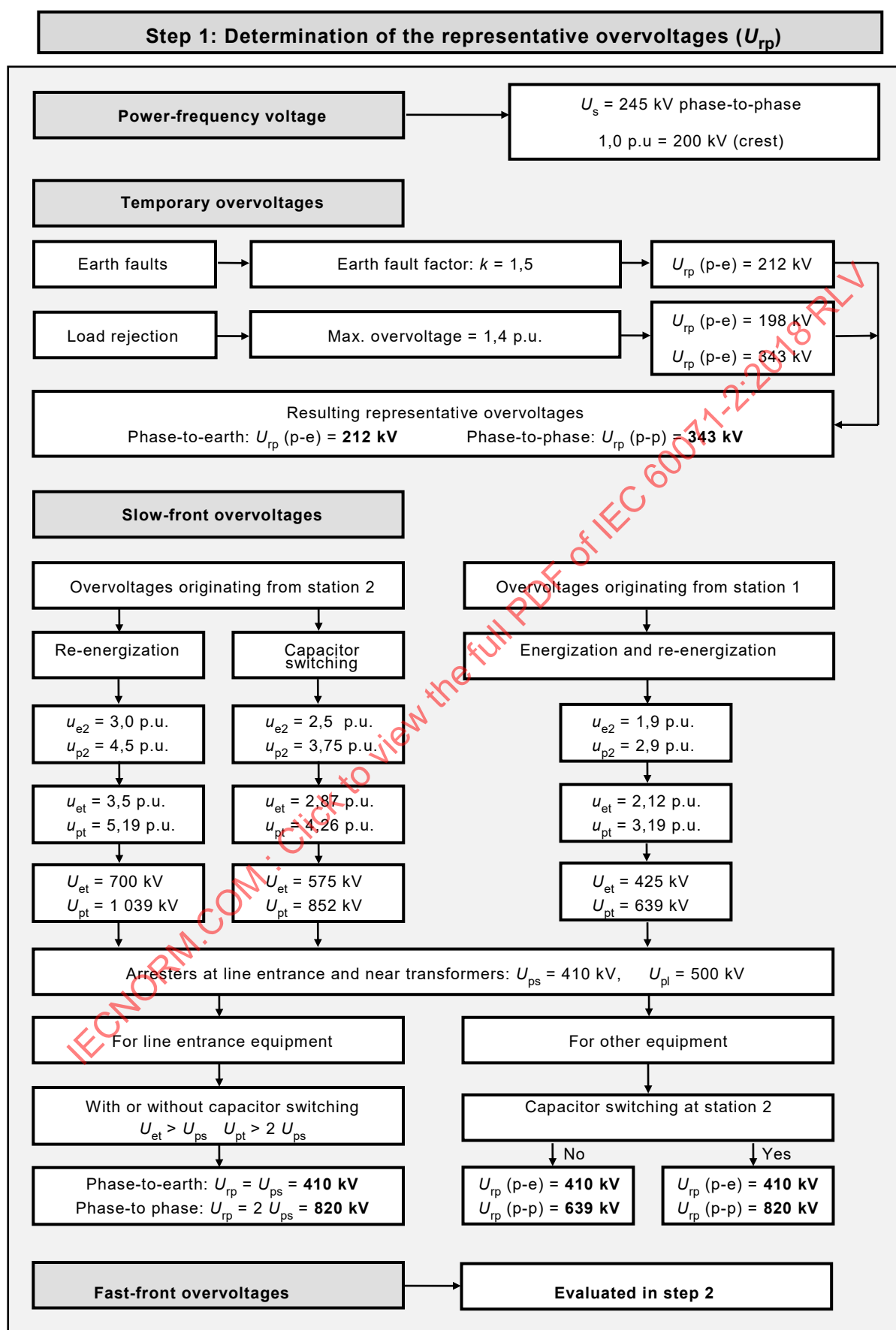
to-earth insulation levels, as discussed in part 1, could be retained but in any case a special phase-to-phase test at 1 050 kV would be required.

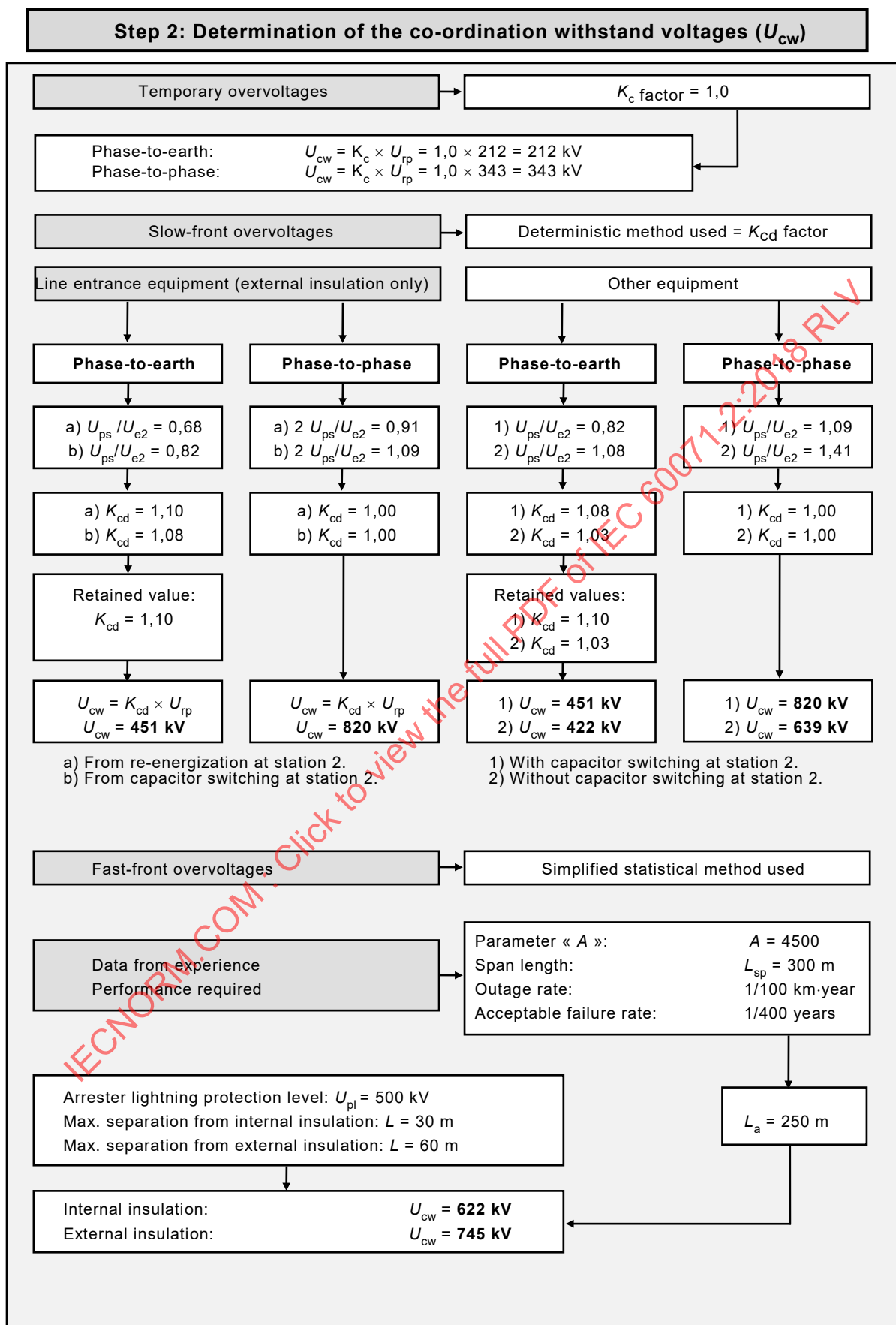
G.2.4 Part 3: flow charts related to the example of Clause G.2

The following flow charts summarize the insulation co-ordination procedure and the results obtained along the different steps. The flow charts include results obtained without (part 1) or with (part 2) capacitor switching at station 2.

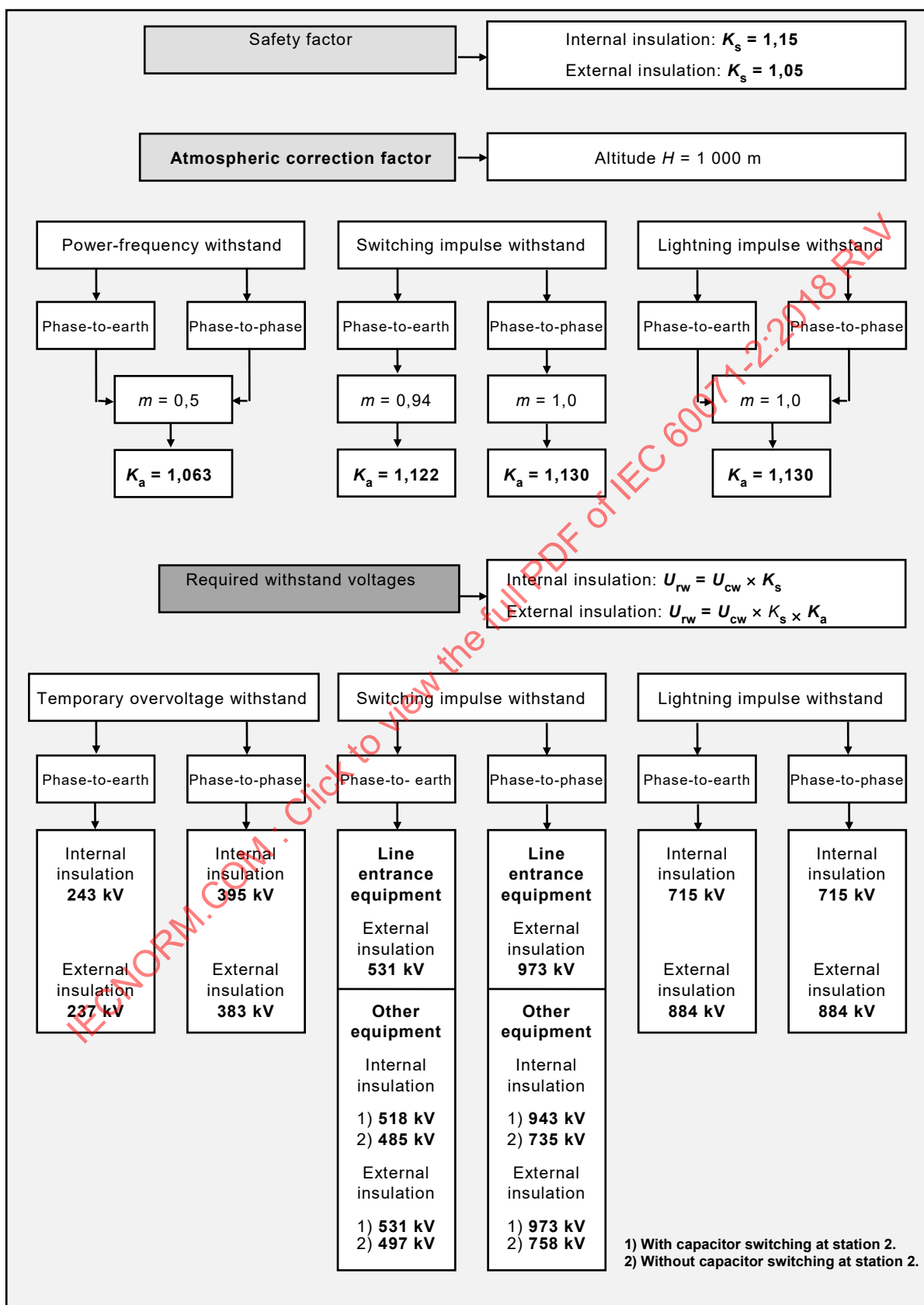
It should be noted that this example does not consider any means of mitigation to reduce the severe slow-front overvoltage surges from capacitor switching. As mentioned in 4.3.3.7, such measures could be considered, such as the use of closing resistors at the remote station to obtain a substantial reduction of slow-front stresses with a consequent reduction of withstand levels to be selected. This implies the necessity for additional system studies taking into account the presence of the means of mitigation and, on the basis of the new representative stresses found, to restart the insulation co-ordination procedure. For the particular example discussed here, this would lead to a reduction of some of the requirements obtained (inscribed under the flow chart of step 5 below), such as the phase-to-phase lightning impulse withstand voltage for internal insulation and the phase-to-phase clearance for external insulation.

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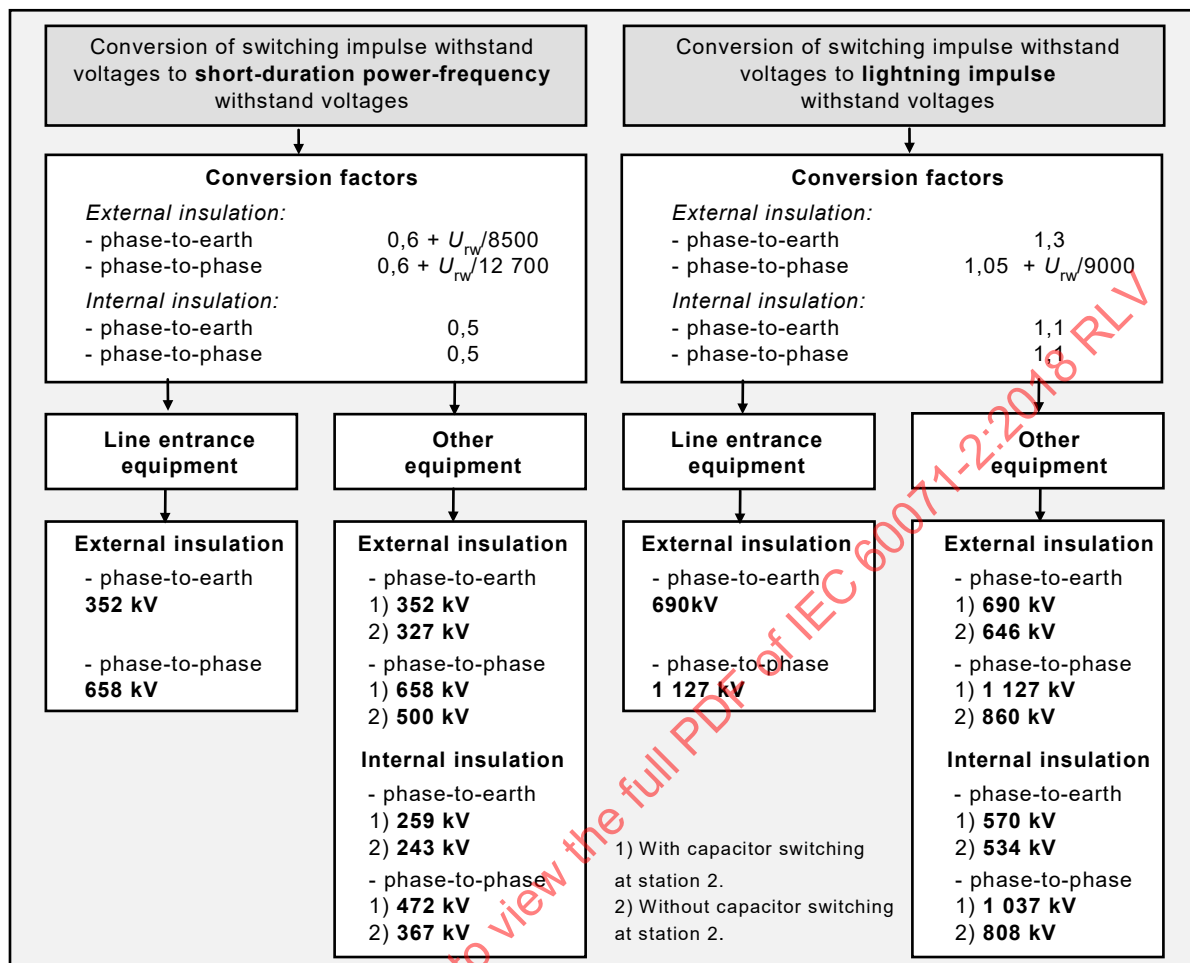




Step 3: Determination of the required withstand voltages (U_{rw})



Step 4: Conversion to withstand voltages normalized for range I



Step 5: Selection of standard withstand voltage values

	<u>Without</u> capacitor switching at remote station. Refer to explanations related with Table G.1	<u>With</u> capacitor switching at remote station. Refer to explanations related with Table G.2
<u>Standard insulation level:</u>	395 kV/950 kV Applicable to any insulation	395 kV/950 kV External insulation 460 kV/1 050 kV Internal insulation
<u>External insulation</u> No phase-to-phase test required if clearances are:		
- for line entrance equipment:	2,35 m	2,35 m
- for other equipment:	1,90 m	2,35 m
<u>Internal insulation</u> Minimum standard lightning impulse level:		
- phase-to-earth:	750 kV	750 kV
- phase-to-phase:	850 kV	1 050 kV

G.3 Numerical example for a system in range II (with nominal voltage of 735 kV)

G.3.1 General

For the purpose of this example, one will assume the following basic data:

- the highest system voltage is: $U_s = 765$ kV;
- the pollution level is low to medium (refer to 5.3.2.2);
- the altitude is: $H = 1\,000$ m.

The altitude level is here assumed so as to cover all possible locations. The pollution level is assumed sufficiently mild that the standard insulation levels (and clearances) can be determined by the voltage stresses (usually the slow-front overvoltages for systems in range II).

Considerations of tower design such as conductor size and phase-to-phase spacing do not fall into the category of insulation co-ordination procedure. Only the phase-to-earth clearance results from the insulation co-ordination procedure since it depends on the slow-front overvoltages (in range II). Lightning considerations may dictate the type of overhead ground wires and counterpoise wires but this is generally the result of a separate study based on keraunic levels. Thus the transmission line design is not usually specified in terms of standard insulation levels but rather in terms of tower dimensions.

G.3.2 Step 1: determination of the representative overvoltages – values of U_{rp}

G.3.2.1 General

The representative temporary and slow-front overvoltages are usually determined from system studies (transient network analyser or digital simulation or a combination of both). For this example, results from such studies confirmed the following values:

- temporary overvoltages: $U_{rp} = 660$ kV (RMS, phase-to-earth);
- slow-front overvoltages: $U_{e2} = 1\,200$ kV (peak, phase-to-earth; phase-peak method).

G.3.2.2 Power-frequency and temporary overvoltages

The high level of temporary overvoltage (1,5 p.u.) is associated with situations involving long lines radially fed after a major load rejection. For systems in range II, the two standard withstand voltages normally specified are the lightning and the switching impulse levels. The conversion of the required short-duration power-frequency withstand voltage into an equivalent required switching impulse withstand voltage is discussed under step 4 (G.3.5) of this example.

G.3.2.3 Slow-front overvoltages

The slow-front overvoltage is related to line reclosing and is limited to about 2,0 p.u. by the use of closing resistors implemented on line circuit breakers.

The surge arrester rating is also determined from these same system studies (normally from the temporary overvoltage characteristics: amplitude and duration) and, for the particular case of this example, the following protection levels were determined:

- switching impulse protection level: $U_{ps} = 1\,300$ kV (peak value);
- lightning impulse protection level: $U_{pl} = 1\,500$ kV (peak value).

G.3.2.4 Fast-front overvoltages

The simplified statistical method for fast-front overvoltages will be used, leading directly to the co-ordination withstand voltage.

In this step and those that follow, only the phase-to-earth insulation is considered. Phase-to-phase insulation co-ordination will be treated at the end of the example as a separate item (see G.3.7).

G.3.3 Step 2: determination of the co-ordination withstand voltages – values of U_{cw}

G.3.3.1 General

The co-ordination withstand voltage is obtained by applying a co-ordination factor (K_c) to the representative overvoltages, this factor being either K_{cd} for the deterministic method or K_{cs} for the statistical method. Thus the determination of the co-ordination withstand voltages shall be carried out for internal insulation (such as transformers) and external insulation separately.

G.3.3.2 U_{cw} for internal insulation

G.3.3.2.1 General

In this step, the determination of U_{cw} for internal insulation is carried out for power-frequency, slow-front and fast-front overvoltages.

G.3.3.2.2 U_{cw} for temporary overvoltages

For this class of overvoltages, the co-ordination withstand voltage is equal to the representative temporary overvoltage (refer to 5.3.2). In other words, the co-ordination factor $K_c = 1$. Therefore:

- phase-to-earth: $U_{cw} = 660$ kV.

G.3.3.2.3 U_{cw} for slow-front overvoltages

For equipment protected by surge arresters, the maximum slow-front overvoltage (and thus the slow-front representative overvoltage) is equal to the switching-impulse protection level of the surge arrester, namely 1 300 kV.

This value of 1 300 kV shall be adjusted by the co-ordination factor K_{cd} to account for the skewing of the statistical distribution of the slow-front overvoltages as discussed in 5.3.3.1. It can be seen from Figure 4 that for a ratio of $U_{ps} / U_{e2} = 1,08$ (1 300 / 1 200) the value of K_{cd} is 1,03. Hence, the co-ordination withstand voltage for slow-front surges is 1 340 kV:

- representative slow-front overvoltage: $U_{rp} = 1\,300$ kV;
- deterministic co-ordination factor: $K_{cd} = 1,03$ kV;
- co-ordination withstand voltage: $U_{cw} = 1\,340$ kV.

G.3.3.2.4 U_{cw} for fast-front overvoltages

For equipment protected by surge arresters, the maximum fast-front overvoltage (and thus the fast-front representative overvoltage) is equal to the lightning-impulse protection level of the surge arrester, namely 1 500 kV.

However, to this value of 1 500 kV, one shall add a voltage equal to $AL/(n(L_{sp} + L_a))$ according to Equation (E.19) to take into account the separation distance L between the surge arrester and the protected equipment, as explained in 4.3.4.5.

The parameters are obtained as follows:

- A : from Table E.2 (for an assumed four conductor bundle) is 11 000;
- n : the minimum number of connected overhead lines is assumed equal to two for this example;
- L : is equal to $a_1 + a_2 + a_3 + a_4$ according to Figure 3; is assumed equal to 40 m for this example;

- L_{sp} : length of the first line span is assumed equal to 400 m for this example;
- L_a : length of overhead line section with flashover rate equal to the acceptable failure rate. If the acceptable failure rate is assumed to be 1/(500 year) or 0,002/year and the line lightning flashover rate is 0,15/(100 km·year), then L_a is 1,3 km.

Then, the separation term $AL/(n(L_{sp} + L_a))$ is 130 kV.

- Representative fast-front overvoltage: $U_{rp} = 1\,500$ kV.
- Correction value for separation: 130 kV.
- Co-ordination withstand voltage: $U_{cw} = 1\,630$ kV.

G.3.3.3 U_{cw} for external insulation

G.3.3.3.1 General

Determination of the co-ordination withstand voltage for external insulation is carried out for slow-front overvoltages using the statistical method because of the nature of the insulation. A statistical method could also be applied to fast-front overvoltages but this is generally not necessary for voltages in range II; refer to G.3.3.3.3 below.

G.3.3.3.2 U_{cw} for temporary overvoltages

These are the same as for the internal insulation (G.3.3.2.2).

G.3.3.3.3 U_{cw} for slow-front overvoltages

The value of the statistical co-ordination factor K_{cs} comes from choosing a risk of failure of the insulation that has been proven from experience to be acceptable. The relation between the risk of failure R and K_{cs} is shown in Figure 8 and, for a usually acceptable value of R in the range of 10^{-4} , the value of K_{cs} is 1,15. Hence the co-ordination withstand voltage is $U_{cw} = 1\,200$ kV $\times$ 1,15 = 1 380 kV:

- statistical overvoltage: $U_{e2} = 1\,200$ kV;
- statistical co-ordination factor: $K_{cs} = 1,15$;
- co-ordination withstand voltage: $U_{cw} = 1\,380$ kV.

G.3.3.3.4 U_{cw} for fast-front overvoltages

The determination of the co-ordination withstand voltage for fast-front overvoltage is not necessary since the lightning impulse withstand voltage of the minimum clearances that result from the switching impulse withstand voltage will be far in excess of those that should be determined solely by the lightning impulse withstand voltage required for the non-self-restoring insulation.

G.3.4 Step 3: determination of the required withstand voltages – values of U_{rw}

G.3.4.1 General

The required withstand voltage is obtained by applying a safety factor K_s to the co-ordination withstand voltage as explained in 6.3.5. The values of K_s are given as:

- for internal insulation: $K_s = 1,15$;
- for external insulation: $K_s = 1,05$.

For external insulation, an atmospheric correction factor K_a is also applied (refer to G.3.4.3 below).

G.3.4.2 U_{rw} for internal insulation

The values of U_{rw} for internal insulation are as follows:

- U_{cw} for temporary overvoltages: $U_{cw} = 660 \text{ kV}$;
- safety factor: $K_s = 1,15$;
- U_{rw} for temporary overvoltages: $U_{rw} = 759 \text{ kV}$;
- U_{cw} for slow-front overvoltages: $U_{cw} = 1\,340 \text{ kV}$;
- safety factor: $K_s = 1,15$;
- U_{rw} for slow-front overvoltages: $U_{rw} = 1\,540 \text{ kV}$;
- U_{cw} for fast-front overvoltages: $U_{cw} = 1\,630 \text{ kV}$;
- safety factor: $K_s = 1,15$;
- U_{rw} for fast-front overvoltages: $U_{rw} = 1\,875 \text{ kV}$.

G.3.4.3 U_{rw} for external insulation

For power-frequency, the atmospheric correction factor is determined assuming a short-duration power-frequency test on polluted insulators is required, for which $m = 0,5$ and assuming $H = 1\,000 \text{ m}$, $K_a = 1,063$.

Hence, $U_{rw} = 660 \times 1,063 \times 1,05 = 737 \text{ kV}$:

- U_{cw} for temporary overvoltages: $U_{cw} = 660 \text{ kV}$;
- atmospheric correction factor: $K_a = 1,063$;
- safety factor: $K_s = 1,05$;
- U_{rw} for temporary overvoltage: $U_{rw} = 737 \text{ kV}$.

The atmospheric correction factor K_a for slow-front overvoltages is based on the assumed altitude as explained in 6.2.2 and Equation (11). For $H = 1\,000 \text{ m}$ and $m = 0,6$ (from Figure 9), then $K_a = e^{0,07} = 1,07$. Hence $U_{rw} = 1\,380 \text{ kV} \times 1,07 \times 1,05 = 1\,550 \text{ kV}$:

- U_{cw} for slow-front overvoltages: $U_{cw} = 1\,380 \text{ kV}$;
- atmospheric correction factor: $K_a = 1,07$;
- safety factor: $K_s = 1,05$;
- U_{rw} for slow-front overvoltages: $U_{rw} = 1\,550 \text{ kV}$.

G.3.5 Step 4: conversion to switching impulse withstand voltages (SIWV)

Referring to 7.1, the required short-duration power-frequency withstand voltages are converted to an equivalent switching impulse withstand voltage (SIWV), according to Table 2.

- For internal insulation: $\text{SIWV} = 759 \times 2,3 = 1\,746 \text{ kV}$.
- For external insulation: $\text{SIWV} = 737 \times 1,7 = 1\,253 \text{ kV}$.

G.3.6 Step 5: selection of standard insulation levels

G.3.6.1 General

The standard withstand voltages U_w are obtained from the required withstand voltages by choosing the next highest value from the standard values listed in IEC 60071-1.

G.3.6.2 U_w for internal insulation

For the temporary overvoltage stresses, a switching withstand voltage of $1\,750 \text{ kV}$ would be required according to step 4. Considering this last requirement, many options are available. At first, a value of $1\,750 \text{ kV}$ is not standardized in IEC 60071-1, the highest one being $1\,550 \text{ kV}$, so that a switching test at such a value would be considered as a special one. Another option is to realize an alternative test, as mentioned in 5.4 of IEC 60071-1:2006, to verify the withstand of internal insulation to power-frequency. For this example, an applied voltage test at a minimum value of 660 kV (1,5 p.u.) for a minimum duration of 1 min is required. It is

recommended to refer to standards issued by the relevant apparatus committee (as for power transformers) which give more detailed information relative to such a test. For instance, to avoid saturation, such a test is performed with a source whose frequency is three or four times the nominal frequency. Also, fixed values are recommended for voltages and durations associated with the different cycles involved in such a test (such as 1,7 p.u. during 7 200 periods followed by 1,5 p.u. for 1 h).

- U_{rw} for slow-front overvoltages: $U_{rw} = 1\,540$ kV.
- Standard switching-impulse withstand voltage: $U_w = 1\,550$ kV.
- U_{rw} for fast-front overvoltages: $U_{rw} = 1\,875$ kV.
- Standard lightning impulse withstand voltage: $U_w = 1\,950$ kV.

G.3.6.3 U_w for external insulation

The lightning impulse withstand voltage of 1 950 kV would apply to the external insulation of equipment protected by arresters, such as transformers and shunt reactors.

In the case of equipment remotely located from the surge arresters such as current transformers, circuit-breakers, disconnectors and busbar, the separation distance (see 4.3.4.5) has a greater impact and for this example it is decided to choose one step higher in the lightning impulse withstand voltage. Hence, for this equipment the standard lightning-impulse withstand voltage is $U_w = 2\,100$ kV.

- U_{rw} for slow-front overvoltages: $U_{rw} = 1\,550$ kV.
- Standard switching impulse withstand voltage: $U_w = 1\,550$ kV.
- Standard lightning impulse withstand voltage (protected equipment): $U_w = 1\,950$ kV.
- Standard lightning impulse withstand voltage (unprotected equipment): $U_w = 2\,100$ kV.

The standard switching impulse withstand voltage of 1 550 kV is more than sufficient to cover the required switching impulse withstand voltage of 1 253 kV converted from the power-frequency requirements (external insulation).

G.3.7 Considerations relative to phase-to-phase insulation co-ordination

The phase-to-phase dielectric strength of the external insulation of three-phase equipment is usually tested with equal impulses of positive and negative polarity. The actual test values are determined from a consideration of the positive and negative slow-front overvoltages (which are the most critical) as explained in Clause C.4. Based on G.3.7, the assumption is made that $B = 0,6$ from which $F_1 = 0,463$ and $F_2 = 0,074$. In this example, the value of B ($B = \tan \phi$) comes from Figure C.5 which gives an inclination angle $\phi \cong 30^\circ$ for the considered three-phase equipment (height above earth $\cong 16$ m and phase-to-phase distance $\cong 8$ m). The required test voltages are obtained as follows:

- phase-to-earth slow-front overvoltage: $U_{e2} = 1\,200$ kV;
- phase-to-phase slow-front overvoltage: $U_{p2} = 2\,040$ kV.

The phase-to-earth slow-front overvoltage was determined in G.3.2. The phase-to-phase slow-front overvoltage is found from Figure 2: at $U_{e2} = 1,92$ p.u., the ratio of U_{p2}/U_{e2} is 1,7 which gives $U_{p2} = 2\,040$ kV. Equation (C.14) gives the phase-to-phase representative overvoltage:

$$U_{p2-re} = 2 (F_1 U_{p2} + F_2 U_{e2}) = 2\,067 \text{ kV.}$$

The co-ordination phase-to-phase withstand voltage is obtained applying a co-ordination factor $K_{cs} = 1,15$:

$$U_{p-cw} = K_{cs} U_{p2-re} = 2\,377 \text{ kV.}$$

The required phase-to-phase withstand voltage is based on an altitude correction factor $K_a = 1,07$ and a safety factor $K_s = 1,05$ (the same procedure as for phase-to-earth insulation, see G.3.4):

$$U_{p-rw} = K_a K_s U_{p-cw} = 2\,670 \text{ kV}.$$

Test values are thus specified as $\pm 1\,335 \text{ kV}$ but, as these are not standard values, the test itself is not a standard test since there is very little three-phase equipment at the 735 kV level.

For the temporary overvoltage, we have a representative overvoltage of 660 kV phase-to-earth from step 1 yielding a phase-to-phase voltage of 1 143 kV. This results in the same value for the co-ordination withstand voltage since $K_c = 1,0$ as in step 2. Applying the safety factors and atmospheric correction factors, we obtain the required withstand voltages:

- internal insulation: $U_{rw} = 1\,143 \times 1,15 = 1\,314 \text{ kV}$;
- external insulation: $U_{rw} = 1\,143 \times 1,063 \times 1,05 = 1\,276 \text{ kV}$.

These are converted into phase-to-phase switching impulse withstand voltages (SIWV):

- internal insulation: $SIWV = 1\,314 \times 2,3 = 3\,022 \text{ kV}$;
- external insulation: $SIWV = 1\,276 \times 1,7 = 2\,169 \text{ kV}$.

The previously determined switching impulse test voltage of 2 670 kV is adequate to cover the external insulation power-frequency requirement but not the internal insulation. Special measures as described in G.3.6.2 would be required.

G.3.8 Phase-to-earth clearances

The required phase-to-earth clearance for switching impulses can be obtained from IEC 60071-1 and a standard switching impulse withstand voltage of 1 550 kV.

For the conductor-structure configuration (slow-front gap factor $K = 1,35$), the minimum clearance is 4 900 mm. For the rod-structure configuration (slow-front gap factor $K < 1,15$), the minimum clearance is 6 400 mm. The lightning impulse withstand voltage of such clearances can be estimated from the equations given in Annex F. Using Equation (F.7) to obtain the equivalent fast-front gap factors, we obtain:

- conductor-structure: $K_{ff}^+ = 0,74 + 0,26 \times 1,35 = 1,05$;
- rod-structure: $K_{ff}^+ = 0,74 + 0,26 \times 1,15 = 1,04$.

Using $K_{ff}^+ = 1,04$ to be conservative, we obtain from Equations (F.6) and (F.7):

- $U_{50RP} = K_{ff}^+ 530 d = 1,04 \times 530 \times 4,9 = 2\,700 \text{ kV}$; and
- $LIWV = U_{50RP} - 1,3 Z = U_{50RP} (1 - 1,3 z) = 2\,700 (1 - 1,3 \times 0,03) = 2\,595 \text{ kV}$,

which is well above the standard lightning impulse withstand voltage of 2 100 kV from G.3.6.3.

G.3.9 Phase-to-phase clearances

The required phase-to-phase clearance can be obtained from Equation (C.12) which states that $U_0^+ = U^+ + BU^-$ where U_0^+ is an equivalent phase-to-earth voltage that represents the effect of a positive voltage on one phase (U^+) and a negative voltage on the other phase (U^-). From the work carried out in G.3.7, with the values of $U^+ = U^- = 1\,335 \text{ kV}$ and with $B = 0,6$, one can find U_0^+ as:

$$U_0^+ = 1\,335 \times 1,6 = 2\,136 \text{ kV}$$

The corresponding value of U_{50} is given by $U_{50} = U_{10} / 0,922 = 2\,317 \text{ kV}$; d is obtained from Equations (F.3) and (F.5), and for gap factors $K = 1,62$ (parallel conductor configuration) and $K = 1,45$ (rod-conductor configuration):

$$2\,317 = K\,1\,080 \ln(0,46\,d + 1)$$

from which phase-to-phase clearances are:

- conductor-conductor: $d = 6,0 \text{ m}$;
- rod-conductor: $d = 7,4 \text{ m}$.

From IEC 60071-1, a standard phase-to-earth switching impulse withstand voltage of 1 550 kV leads to standard phase-to-phase minimum clearances of 7,6 m (conductor-conductor) and 9,4 m (rod-conductor). Therefore, use of the above-calculated clearances would require a special test.

G.4 Numerical example for substations in distribution systems with U_m up to 36 kV in range I

G.4.1 General

For equipment in this voltage range, IEC 60071-1 specifies standard rated short-duration power-frequency and lightning impulse withstand voltages. The selection of these values is illustrated in Table G.3 for $U_m = 24 \text{ kV}$, where the values are examples and not valid for general application.

For the purpose of this example, one will assume the following basic data:

- the highest system voltage is: $U_s = 24 \text{ kV}$;
- the pollution level is: light;
- the altitude is: $H = 1\,000 \text{ m}$.

The altitude level here is assumed to cover all possible locations.

G.4.2 Step 1: determination of the representative overvoltages – values of U_{rp}

G.4.2.1 Power-frequency and temporary overvoltages

Owing to the neutral earthing practice, the highest overvoltages phase-to-earth originate from earth faults. Values up to the highest system voltage are frequent. In this example, the representative temporary overvoltage is the assumed maximum value equal to the highest system voltage 24 kV.

Overvoltages phase-to-phase originate from load rejections. A full load rejection in the distribution system itself does not cause substantial high overvoltages. However, a load rejection in the transmission system, to which the distribution system is connected, may have to be considered. In this example it is assumed that the load rejection temporary overvoltage reaches 1,15 times the highest system voltage, which is $1,15 \times U_s = 27,6 \text{ kV}$ or approximately 28 kV. This value is assumed to be the highest possible voltage stress and thus is the representative temporary phase-to-phase overvoltage: $U_{rp} = 28 \text{ kV}$.

G.4.2.2 Slow-front overvoltages

Slow-front overvoltages may originate from earth faults or line energization or re-energization. As distribution transformers usually remain connected during a re-energization of lines, and as the reclosing is not fast, the presence of trapped charges is improbable. The re-

energization overvoltages, therefore, have the same probability distribution as those due to energization. The 2 % values in Table G.3 are selected according to Annex C for the phase-peak method taking into account the usual operation conditions, no closing resistors, complex feeding network and no parallel compensation. The 2 % values are assumed to be $u_{e2} = 2,6$ p.u. (phase-to-earth) and $u_{p2} = 3,86$ p.u. (phase-to-phase).

As the deterministic insulation co-ordination procedure is sufficient for distribution systems and as surge arresters do not usually limit slow-front overvoltages in this voltage range, the representative slow-front overvoltages U_{rp} are considered to correspond to the truncation values U_{et} and U_{pt} of the overvoltage probability distributions. With the equations of Annex C, the truncation values are obtained: $u_{et} = 3,0$ p.u. which leads to $U_{rp} = 59$ kV phase-to-earth and $u_{pt} = 4,4$ p.u. which leads to $U_{pt} = 86$ kV phase-to-phase.

G.4.2.3 Fast-front overvoltages

With the exception of motor switching by some type of circuit-breakers, fast-front overvoltages due to switching operations can be neglected.

Fast-front lightning overvoltages are transmitted on the lines connected to the substation. The simplified method described in Clause E.4 is applied to estimate the return periods of the representative lightning overvoltage amplitudes. No reference value is specified and, therefore, no value can be given in Table G.3.

G.4.3 Step 2: determination of the co-ordination withstand voltages – values of U_{cw}

G.4.3.1 Temporary overvoltages

As the previously defined representative temporary overvoltages correspond to the maximum assumed voltage stresses, the deterministic insulation co-ordination procedure is applicable (see Clause 5). The deterministic co-ordination factor is $K_c = 1$ and the resulting co-ordination power-frequency withstand voltages U_{cw} correspond to the representative overvoltage values U_{rp} ($U_{cw} = K_c U_{rp} = U_{rp}$).

G.4.3.2 Slow-front overvoltages

The co-ordination withstand voltages U_{cw} are obtained as: $U_{cw} = K_{cd} U_{rp}$. The deterministic co-ordination factor is $K_{cd} = 1$ because the insulation co-ordination procedure is applied to the truncation values of the overvoltage distributions (no skewing effect as discussed in 5.3.3.1). Therefore, in this example, values of the co-ordination withstand voltages are the same as those for representative slow-front overvoltages: $U_{cw} = 59$ kV phase-to-earth and $U_{cw} = 86$ kV phase-to-phase.

G.4.3.3 Fast-front overvoltages

For the determination of the co-ordination lightning impulse withstand voltages, the following values are assumed:

- the arrester lightning impulse protection level is $U_{pl} = 80$ kV;
- four wood-pole lines ($n = 4$) are connected to the station. Referring to Table E.2, the corresponding value for the factor A is 2 700;
- the observed overhead line outage rate is $R_{km} = 6/(100 \text{ km} \cdot \text{year})$ or, in the recommended units, $R_{km} = 6 \times 10^{-5}/(\text{m} \cdot \text{year})$;
- the span length is $L_{sp} = 100$ m;
- the acceptable failure rate is $R_a = 1/400$ year.

As it is common practice to install arresters close to the power transformers, the separation distance may be different for internal insulation (example: 3 m) and external insulation (example: 5 m). Therefore, the co-ordination withstand voltages values U_{cw} may be different for different equipment.

With these values, the overhead line section, in which the outage rate will be equal to the acceptable failure rate, will be in accordance with Equation (E.18):

$$L_a = 42 \text{ m}$$

This means that protection is required for lightning strokes to the first span of the overhead line.

The co-ordination lightning impulse withstand voltages are obtained according to Equation (E.19) as $U_{cw} = 94 \text{ kV}$ for internal insulation (power transformer, distance to the arrester = 3 m) and $U_{cw} = 104 \text{ kV}$ for the more distant external insulation.

G.4.4 Step 3: determination of required withstand voltages – values of U_{rw}

G.4.4.1 General

The required withstand voltages are obtained by applying the recommended safety factors (see 6.3.5) and the altitude correction (see 6.2.2). For the example given, it is assumed that substations of the same design shall be used up to altitudes of 1 000 m.

G.4.4.2 Safety factors

The recommended safety factors from 6.3.5 are:

- for internal insulation: $K_s = 1,15$;
- for external insulation: $K_s = 1,05$.

G.4.4.3 Altitude correction factor

The altitude correction factor is defined in 6.2.2. It is applicable to the external insulation only and its value depends on the overvoltage shape (parameter m in Equation (11)).

- For power-frequency (clean insulators), $m = 1,0$.
- For slow-front overvoltages, the value of m depends on the value of U_{cw} . For values of U_{cw} less than 300 kV phase-to-earth or 1 200 kV phase-to-phase, $m = 1,0$.
- For lightning impulse withstand, $m = 1,0$ and $K_a = 1,13$.

G.4.4.4 Temporary overvoltage

The temporary overvoltage values are as follows:

- Phase-to-earth:
 - internal insulation $\Rightarrow U_{rw} = U_{cw} \times 1,15 = 24 \times 1,15 = 28 \text{ kV}$;
 - external insulation $\Rightarrow U_{rw} = U_{cw} \times 1,05 \times 1,13 = 24 \times 1,05 \times 1,13 = 28 \text{ kV}$.
- Phase-to-phase:
 - internal insulation $\Rightarrow U_{rw} = U_{cw} \times 1,15 = 28 \times 1,15 = 32 \text{ kV}$;
 - external insulation $\Rightarrow U_{rw} = U_{cw} \times 1,05 \times 1,13 = 28 \times 1,05 \times 1,13 = 33 \text{ kV}$.

G.4.4.5 Slow-front overvoltage

The slow-front overvoltage values are as follows:

- Phase-to-earth:
 - internal insulation $\Rightarrow U_{rw} = U_{cw} \times 1,15 = 59 \times 1,15 = 68 \text{ kV}$;
 - external insulation $\Rightarrow U_{rw} = U_{cw} \times 1,05 \times 1,13 = 59 \times 1,05 \times 1,13 = 70 \text{ kV}$.
- Phase-to-phase:

- internal insulation $\Rightarrow U_{rw} = U_{cw} \times 1,15 = 86 \times 1,15 = 99 \text{ kV};$
- external insulation $\Rightarrow U_{rw} = U_{cw} \times 1,05 \times 1,13 = 86 \times 1,05 \times 1,13 = 102 \text{ kV}.$

G.4.4.6 Fast-front overvoltage

The fast-front overvoltage values are as follows:

- internal insulation: $\Rightarrow U_{rw} = U_{cw} \times 1,15 = 95 \times 1,15 = 109 \text{ kV};$
- external insulation: $\Rightarrow U_{rw} = U_{cw} \times 1,05 \times 1,13 = 95 \times 1,05 \times 1,13 = 125 \text{ kV}.$

G.4.5 Step 4: conversion to standard short-duration power-frequency and lightning impulse withstand voltages

G.4.5.1 General

For the selection of the standard withstand voltages in Table 2 of IEC 60071-1:2006, the required switching impulse withstand voltages are converted into short-duration power-frequency withstand voltages and into lightning impulse withstand voltages by applying the test conversion factors of Table 2 (for internal insulation, factors corresponding to liquid-immersed insulation are selected).

G.4.5.2 Conversion to short-duration power-frequency withstand voltage (SDWV)

The conversion values to SDWV are as follows:

- Phase-to-earth:
 - internal insulation $\Rightarrow \text{SDWV} = U_{rw} \times 0,5 = 68 \times 0,5 = 34 \text{ kV};$
 - external insulation $\Rightarrow \text{SDWV} = U_{rw} \times 0,6 = 70 \times 0,6 = 42 \text{ kV}.$
- Phase-to-phase:
 - internal insulation $\Rightarrow \text{SDWV} = U_{rw} \times 0,5 = 99 \times 0,5 = 50 \text{ kV};$
 - external insulation $\Rightarrow \text{SDWV} = U_{rw} \times 0,6 = 102 \times 0,6 = 61 \text{ kV}.$

G.4.5.3 Conversion to lightning impulse withstand voltage (LIWV)

The conversion values to LIWV are as follows:

- Phase-to-earth:
 - internal insulation $\Rightarrow \text{LIWV} = U_{rw} \times 1,10 = 68 \times 1,1 = 75 \text{ kV};$
 - external insulation $\Rightarrow \text{LIWV} = U_{rw} \times 1,06 = 70 \times 1,06 = 74 \text{ kV}.$
- Phase-to-phase:
 - internal insulation $\Rightarrow \text{LIWV} = U_{rw} \times 1,10 = 99 \times 1,1 = 109 \text{ kV};$
 - external insulation $\Rightarrow \text{LIWV} = U_{rw} \times 1,06 = 102 \times 1,06 = 108 \text{ kV}.$

G.4.6 Step 5: selection of standard withstand voltages

Table 2 of IEC 60071-1:2006 gives, for $U_m = 24 \text{ kV}$, a standard short-duration power-frequency withstand voltage of 50 kV. This is adequate to cover the requirements for temporary overvoltage and all slow-front overvoltages except the phase-to-phase requirement for external insulation which can be accommodated by adequate air clearances. Table 2 of IEC 60071-1:2006 provides three possible values for the standard lightning impulse withstand voltage for $U_m = 24 \text{ kV}$. Selection of a value of 125 kV covers the lightning impulse requirement as well as the switching impulse withstand voltage for external phase-to-phase insulation.

G.4.7 Summary of insulation co-ordination procedure for the example of Clause G.4

Table G.3 summarizes values obtained while completing the insulation co-ordination procedure for this example, for a considered maximum operating voltage $U_s = 24$ kV.

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Table G.3 – Values related to the insulation co-ordination procedure for the example in G.4

Type of overvoltage		Temporary				Slow-front				Fast-front	
		Phase-to-earth		Phase-to-phase		Phase-to-earth		Phase-to-phase		Phase-to-earth and phase-to-phase	
		Internal	External	Internal	External	Internal	External	Internal	External	Internal	External
Step 1	Representative voltage stresses in service	24 kV	24 kV	28 kV	28 kV	59 kV	59 kV	86 kV	86 kV	—	—
Step 2	Co-ordination withstand voltages	1,0 24 kV	1,0 24 kV	1,0 28 kV	1,0 28 kV	1,0 59 kV	1,0 59 kV	1,0 86 kV	1,0 86 kV	— 95 kV	— 105 kV
Step 3	Required withstand voltages	1,15 — 28 kV	1,05 1,13 28 kV	1,15 — 32 kV	1,05 1,13 33 kV	1,15 — 68 kV	1,05 1,13 70 kV	1,15 — 99 kV	1,05 1,13 102 kV	1,15 — 109 kV	1,05 1,13 125 kV
Step 4	Standard withstand voltages	1) Test conversion factors				To short-duration power-frequency		To lightning impulse			
		2) Resulting required withstand voltages				Short duration power-frequency		Lightning impulse			
Step 5	Selection of standard withstand voltages	Short-duration power-frequency 50 kV				34 kV 75 kV		50 kV 109 kV		Lightning impulse 125 kV	

Annex H (informative)

Atmospheric correction – Altitude correction

H.1 General principles

H.1.1 Atmospheric correction in standard tests

IEC 60060-1 specifies the atmospheric correction factors for testing of air clearances and insulators with the standardized

- short-duration power-frequency voltage,
- switching impulse voltage,
- lightning impulse withstand voltage, and
- direct voltage.

Direct test voltages are disregarded here, because such tests are not required for systems within the scope of IEC 60071-1.

The standard insulation levels of external insulation refer to the standard reference atmosphere as given in IEC 60071-1:2006, 5.9.2, and IEC 60060-1:2010, 4.3.1.

The standard reference atmosphere is:

- ambient air temperature ϑ_0 : 20 °C
- absolute air pressure p_0 : 1 013 hPa (1 013 mbar)
- absolute air humidity h_0 : 11 g/m³

NOTE Deviating from the standards mentioned above, the letter symbol ϑ is used here for ambient air temperature to be in line with the common usage in scientific literature.

Any deviation of air temperature, pressure or humidity from these reference values will affect the dielectric strength of the external insulation. These deviations have to be corrected in the test to verify a certain standard insulation as required in IEC 60060-1:2010, 4.3. In accordance with this document, the atmospheric correction factor is defined as

$$K_t(t) = k_1 \times k_2 \quad (\text{H.1})$$

where

k_1 is the air density correction factor;

k_2 is the humidity correction factor.

$K_t(t)$ is time dependent according to the varying conditions in the considered time period (seasons or years) and corresponds with the correction factor K_t of IEC 60060-1 for the moment of test.

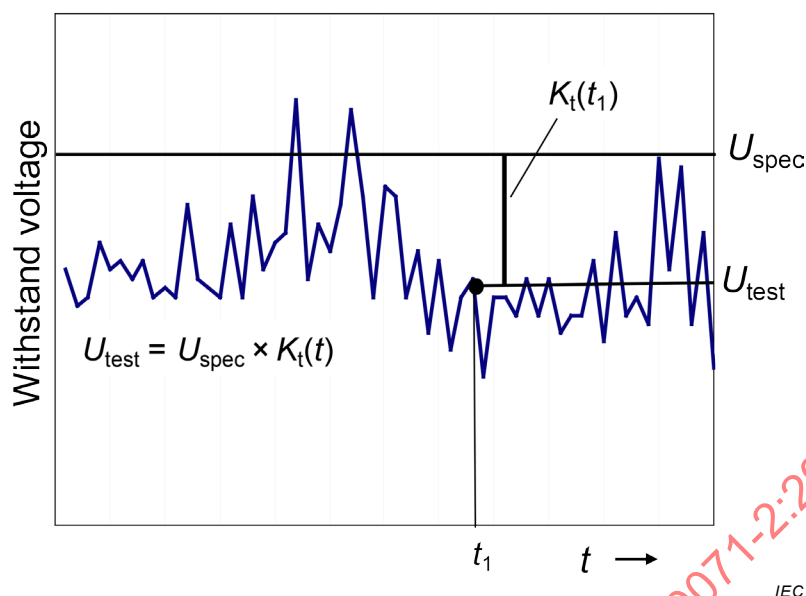


Figure H.1 – Principle of the atmospheric correction during test of a specified insulation level according to the procedure of IEC 60060-1

The principles of the atmospheric correction during tests are outlined in Figure H.1. The atmospheric conditions at the test location vary throughout for example the year. Therefore, the atmospheric correction factor $K_t(t)$ at the time of testing and the voltage U_{test} to be applied to the test object vary accordingly to prove the specified voltage U_{spec} , which is related to the standard reference atmosphere and normally in line with the standard withstand voltages according to IEC 60071-1 and applicable product standards.

$$U_{\text{spec}} = \frac{U_{\text{test}}}{K_t(t)} \quad (\text{H.2})$$

During testing, by considering the atmospheric condition, the altitude of the test location is covered by the atmospheric correction of IEC 60060-1. The altitude correction of standard insulation levels has no relation to testing in a certain location at a certain time.

H.1.2 Task of atmospheric correction in insulation co-ordination

The actual withstand voltage of external insulation of equipment in service $U_{10}(t)$ varies over the year in the same way as during testing according to IEC 60060-1. The atmospheric correction factor and the safety correction factor used in insulation co-ordination have to cover these variations in order to achieve the specified insulation when stressing external insulation with these atmospheric conditions.

The task of insulation co-ordination is to determine one required withstand voltage value that results in an acceptable risk-of-flashover taking into account the varying withstand voltage over the life time of the equipment.

Based on the co-ordination withstand voltage, the correction has to be chosen in the way that the required withstand voltage covers sufficiently the actual withstand voltages in service:

$$U_{\text{rw}} = \frac{K_s \times U_{\text{cw}}}{K_t} \quad (\text{H.3})$$

where

U_{rw} is the required withstand voltage;

U_{cw} is the co-ordination withstand voltage;

K_s is the safety factor;

K_t is the atmospheric correction factor (selected value out of $K_t(t)$).

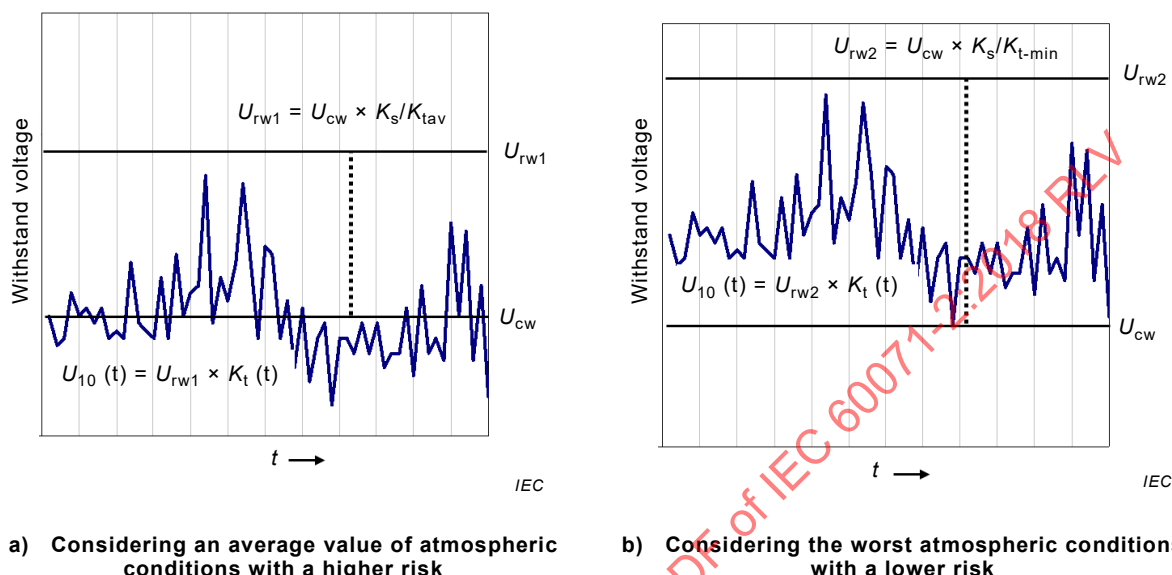


Figure H.2 – Principal task of the atmospheric correction in insulation co-ordination according to IEC 60071-1

Figure H.2 shows this procedure in principle. In Figure H.2 a), the correction is based on an average value of atmospheric correction K_{tav} resulting in a required withstand voltage U_{rw1} , which covers the actual time dependent withstand voltage of equipment $U_{10}(t)$. Considering the worst atmospheric condition with K_{t-min} will lead to a higher required withstand voltage U_{rw2} as shown in Figure H.2 b). This includes a lower risk of failure in comparison to Figure H.2 a).

The safety factor K_s is increasing the required withstand voltage by a constant factor and has to be considered in the process of insulation co-ordination. For convenient reading, it is neglected in the following.

From the required withstand voltage U_{rw} results a standard rated withstand voltage U_w according to IEC 60071-1, which normally is the voltage U_{spec} applied during a withstand test after atmospheric correction with $K_t(t)$ according to IEC 60060-1.

The atmospheric correction according to IEC 60060-1 can only be performed when all necessary data for the atmospheric conditions, the required insulation level of the equipment and the dimensions of the equipment are known. For the specification of the required withstand voltages in the insulation co-ordination process of IEC 60071-1, these data are frequently not fully available, and simplifications have to be adopted to determine the required withstand voltages. The application of atmospheric correction can be simplified in most cases by using an altitude correction factor only. The validation of this simplification and the limits of its application are shown in the following Clauses H.2 to H.4.

H.2 Atmospheric correction in insulation co-ordination

H.2.1 Factors for atmospheric correction

For air clearances and dry insulators, the atmospheric correction factor K_t is given in IEC 60060-1 as

$$K_t = k_1 \times k_2 = \delta^m \times k_h^w \quad (\text{H.4})$$

where

δ is the relative air density;

k_h is the parameter for humidity depending on air density and test voltage;

m, w are the exponents depending on parameter g (each parameter is defined in IEC 60060-1).

For configurations with inhomogeneous electric field distributions under impulse voltages, as they are usually present in the higher voltage ranges, the parameter g is always below 1,2. In this range of g the exponents are equal:

$$m = w \quad (\text{H.5})$$

With this simplification, for $g \leq 1,2$, the atmospheric correction factor to be applied to the voltages stressing the air clearances of equipment is given by

$$K_t = (\delta \times k_h)^m \quad (\text{H.6})$$

With δ and k_h as defined in IEC 60060-1, a detailed equation for the atmospheric correction K_t with the three atmospheric parameters pressure, temperature and humidity and exponent m is given.

H.2.2 General characteristics for moderate climates

To find an overall valid atmospheric correction for the location of installation, the variations of the weather conditions over the year have to be investigated.

Generally, the relative air density δ is high in winter time due to the low temperature and low in summer due to the high temperature. The humidity, described by correction factor k_h , shows the opposite trend. For the overall correction $\delta \times k_h$ the values of relative air density and humidity compensate each other. The variation of the overall correction $\delta \times k_h$ over the year is much smaller than the variation of the air density alone owing to the compensating influence of the humidity.

This situation is valid also for high altitudes. Although the relative air density δ is low due to the high altitude, and humidity correction factor k_h is low due to low temperature, both are following the same trend as at the stations on sea level.

Owing to the strong correlation between temperature and absolute humidity, it is appropriate to separate the atmospheric correction into two parts (Equation (H.7)), which seem to be independent one from each other: One factor being the air pressure related to the reference pressure (p/p_0), the second factor being the inverted relative temperature multiplied by the humidity correction factor ($T_0/T \times k_h$).

$$K_t = [\delta \times k_h]^m = \left[\frac{p}{p_0} \times \frac{T_0}{T} \times k_h \right]^m \quad (\text{H.7})$$

Due to the compensation effect, the term $(T_0/T \times k_h)$ is nearly equal to 1 for all altitudes. The given relation is valid for regions with moderate climate which provide sufficient air humidity at increasing temperature.

The term (p/p_0) fits very well to the average overall atmospheric correction $\delta \times k_h$. Therefore the best estimation for the average atmospheric correction $\delta \times k_h$ is the related average pressure p/p_0 .

With these considerations of the compensating effect and with Equation (H.7) follows that, for insulation co-ordination purpose, the atmospheric correction factor K_t can be simply used by taking only the air pressure p into account:

$$K_t = \left[\frac{p}{p_0} \right]^m \quad (\text{H.8})$$

H.2.3 Special atmospheric conditions

For regions with special atmospheric conditions, different considerations may apply. Figure H.3 shows the summary of data from various weather stations around the world, comparing the overall atmospheric correction $\delta \times k_h$ with the pressure related correction p/p_0 . For most locations, the difference is within the standard deviation of the values justifying the considerations for moderate climates above.

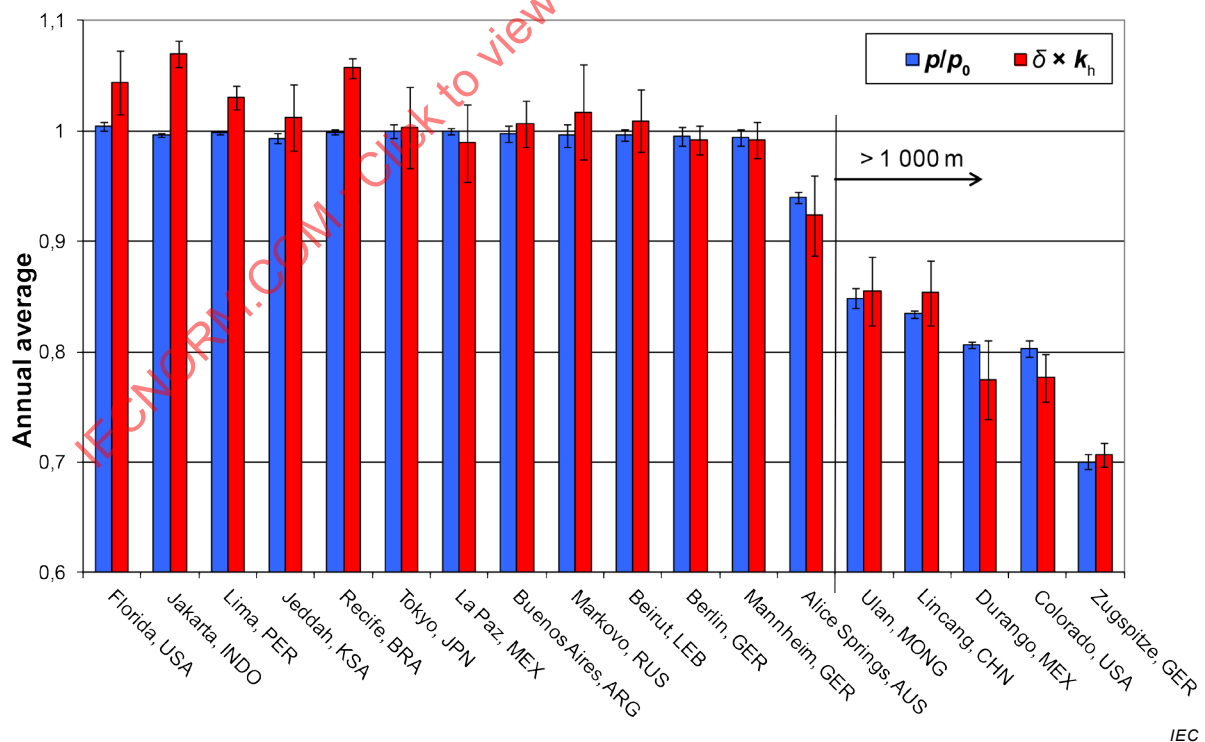


Figure H.3 – Comparison of atmospheric correction $\delta \times k_h$ with relative air pressure p/p_0 for various weather stations around the world

Higher differences show special atmospheric conditions which may need special consideration. There is no compensation and the application of the complete atmospheric correction may become necessary instead of the simplification by taking in account the pressure only. For example, for tropical climate with high temperature and very high humidity (like Jakarta, Indonesia and Recife, Brazil), factor $(T_0/T \times k_h)$ dominates the correction $\delta \times k_h$.

For such special atmospheric conditions at sea level it should be noted that this difference is covered by the insulation co-ordination procedure for normal environmental conditions which includes the altitude of 1 000 m. This leads to a pressure related correction with p/p_0 (correction factor 1,13) covering the overall correction $\delta \times k_h$, and no further consideration is needed.

For areas at high altitude with a large difference it is recommended to consider the complete atmospheric correction $\delta \times k_h$ to cover the effects of pressure, temperature and humidity.

H.2.4 Altitude dependency of air pressure

As shown above, the atmospheric correction can be reduced in most cases to a correction considering the air pressure only. The dependency of air pressure and altitude will be described in the following.

According to ISO 2533:1975, the simultaneous solution of the equations of static atmosphere and the perfect gas law gives a dependency of air pressure p on altitude H (ISO 2533:1975, Equation (12)). A linear reduction of temperature with altitude is included by a temperature gradient. By using a constant average temperature the dependency of p versus H can be simplified to the exponential function:

$$p = p_0 e^{-\frac{H}{8150}} \quad (\text{H.9})$$

The deviation of this simplified way of pressure calculation to the pressure calculation including the temperature gradient of ISO 2533 is shown in Figure H.4. The maximum deviation up to nearly 4 000 m altitude is less than 0,5 %. The difference is small and the simplified equation can be applied with sufficient accuracy.

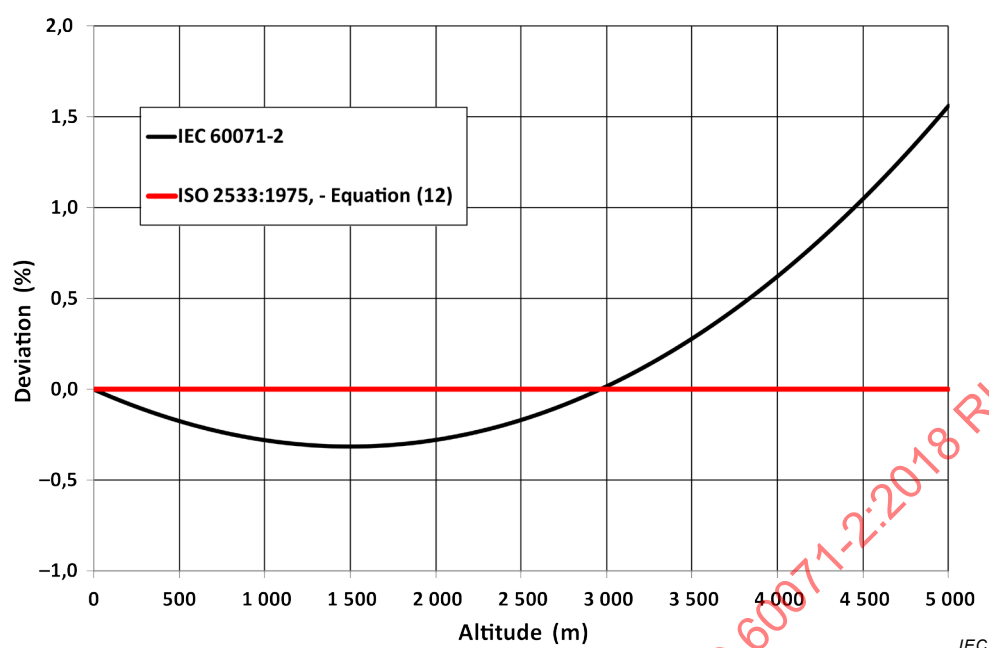


Figure H.4 – Deviation of simplified pressure calculation by exponential function in this document from the temperature dependent pressure calculation of ISO 2533

H.3 Altitude correction

H.3.1 Definition of the altitude correction factor

With the basic idea of atmospheric correction for insulation co-ordination to simplify it to a pure pressure dependent correction the correction factor K_t can be written in exponential form by combining Equations (H.8) and (H.9).

$$K_t = \left(\frac{p}{p_0} \right)^m = e^{-m \frac{H}{8150}} \quad (\text{H.10})$$

It describes the reduction of the withstand voltage at elevated altitude.

The altitude correction factor has to compensate the reduction. It is defined as a factor, by which the rated withstand voltage has to be increased to a higher value at standard reference atmosphere in order to assure a withstand voltage equal to the required value at certain altitude.

The altitude correction factor is given by

$$K_a = \frac{1}{K_t} = e^{m \frac{H}{8150}} \quad (\text{H.11})$$

The altitude correction is a simplification of the atmospheric correction. It implies that the differences in the atmospheric conditions at an elevated altitude can be described by one single parameter, namely the installation altitude H of the equipment.

H.3.2 Principle of altitude correction

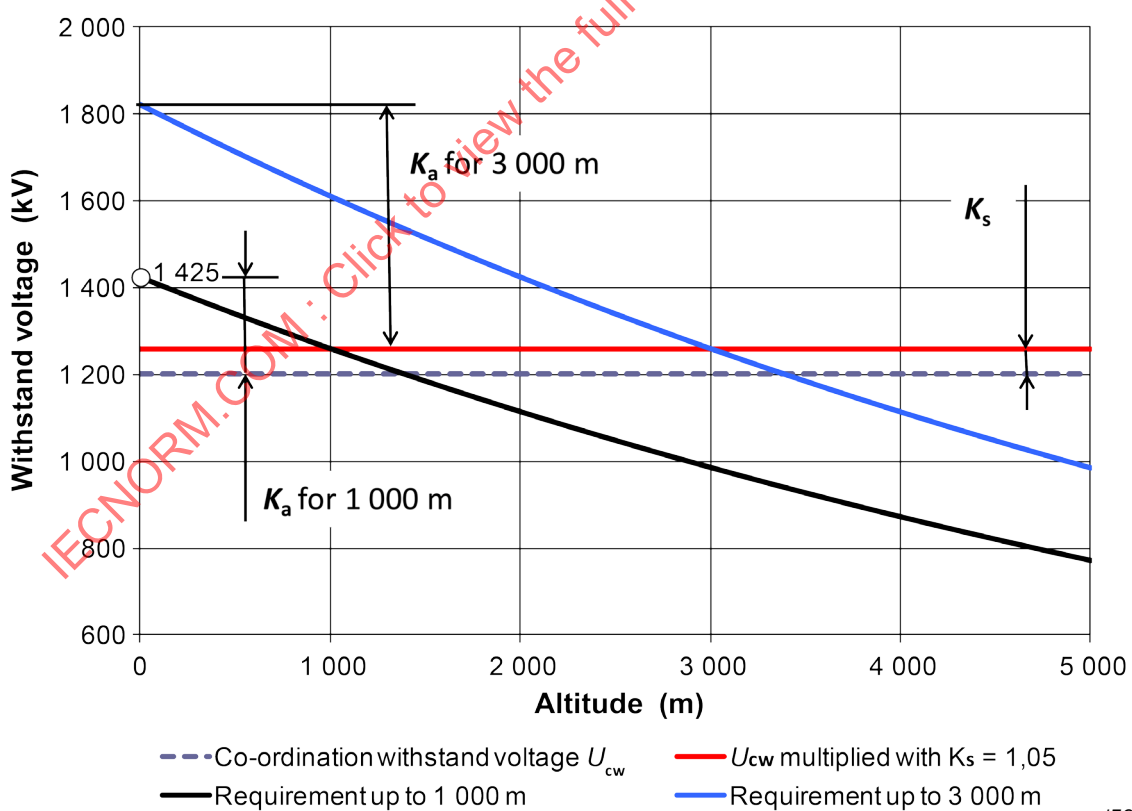
In insulation co-ordination, the co-ordination withstand voltage U_{cw} has to be applied with the safety factor K_s and the altitude correction factor K_a to achieve the required withstand voltage U_{rw} .

$$U_{rw} = K_s \times K_a \times U_{cw} \quad (H.12)$$

Figure H.5 shows the principle of altitude correction for an example of $U_m = 420$ kV and a rated lightning impulse withstand voltage of 1 425 kV. The actual withstand voltage of the equipment decreases from the rated value at sea level with the installation altitude according to the decreasing air pressure.

The value 1 425 kV has been derived from the co-ordination withstand voltage $U_{cw} = 1\,200$ kV multiplied by the safety factor $K_s = 1,05$ recommended in this document for external insulation. As this example relates to a standardized equipment, an altitude correction factor $K_a = 1,13$ (according to the pressure at 1 000 m) has been applied. The design meets the requirements for the withstand voltage to be equal to 1 260 kV ($1,05 U_{cw}$) exactly up to 1 000 m.

In order to meet the design requirement for the external insulation at altitudes above 1 000 m (e.g. 3 000 m in Figure H.5), the withstand voltage of the external insulation at standard reference atmosphere has to be increased by altitude correction according to the altitude of installation. An altitude correction according Equation (H.11) has to be applied to cover the requirements at installation altitude. With $K_a = 1,45$, a withstand voltage of 1 822 kV at sea level is necessary to meet the requirements at 3 000 m.



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**Figure H.5 – Principle of altitude correction:
decreasing withstand voltage U_{10} of equipment with increasing altitude**

H.3.3 Standard equipment operating at altitudes up to 1 000 m

When equipment designed according to an existing IEC standard is used, the equipment shall fulfill all requirements of the relevant standard concerning the environmental conditions. For the external insulation, it means that equipment shall be able to operate in the range of atmospheric conditions specified in the standards. Normal environmental conditions in IEC 60071-1 and in equipment standards (e.g. IEC 62271-1) specify among others an altitude of operation up to 1 000 m.

It is evident that the insulation design shall take into account the variations of the atmospheric conditions within this specified range. Considering the compensating effect of humidity and temperature, the altitude up to 1 000 m can be covered by the pressure related altitude correction factor to meet the requirements of normal environmental conditions. For example, for lightning impulse (with exponent $m = 1,0$), an altitude correction factor of $K_a = 1,13$ according to Equation (H.11) has to be applied to cover the required installation altitude up to 1 000 m.

IEC 60071-1 has standardized a list of rated withstand voltages, which are based on the experience with equipment located in systems that are operated under normal environmental conditions. These conditions include altitudes up to 1 000 m and, consequently, the range of rated withstand voltages is assumed to cover the requirements for all external insulations to be located at altitudes up to 1 000 m.

As a conclusion, the following has to be stated.

- The rated withstand voltage values standardized in IEC 60071-1 are valid for the standard reference atmospheric conditions and only for these conditions. The standard reference atmospheric conditions include the average pressure at sea level altitude.
- For each U_m value, the associated range of rated withstand voltages proposed in the present standard cover the requirements for all equipment operating under normal environmental conditions including those to be installed at altitudes up to 1 000 m.

Following the general practice of insulation co-ordination procedure for standardized equipment an altitude correction factor according to Equation (H.11) has to be applied to cover the required installation altitude up to 1 000 m.

H.3.4 Equipment operating at altitudes above 1 000 m

Besides the normal environmental conditions, further requirements may arise from special environmental conditions among which an altitude exceeding 1 000 m is of special interest for the external insulation. Generally, it has to be considered by altitude correction according to Equation (H.11).

Only equipment which is standardized and approved for altitudes up to 1 000 m needs to be corrected by Equation (H.13) for installations above 1 000 m. The standardized voltage levels have to be increased by:

$$K_{a1000} = e^{m \times \frac{H-1000}{8150}} \quad (\text{H.13})$$

This equation takes into account that rated withstand voltages of standardized equipment already covers the necessary correction up to altitudes of 1 000 m.

H.4 Selection of the exponent m

H.4.1 General

The exponent m in atmospheric and altitude correction takes into account the discharge behavior of the considered air gap.

For the following voltage and overvoltage classes, the exponent m may be applied.

1) Co-ordination long-duration power-frequency withstand voltages

As long as specific values of exponent m to determine the pollution withstand voltage are not specified by IEC TC 36, the following value may be applied:

$m = 0,5$ for overhead line insulators;

$m = 0,8$ for station insulators, bushings and housings.

2) Co-ordination short-duration power-frequency withstand voltages

A conservative estimate may be used:

$m = 1$.

3) Co-ordination lightning impulse withstand voltages

For lightning impulses, the exponent m is equal to 1, which has to be expected for a streamer discharge where the flashover voltage is linearly dependent on the gap clearance:

$m = 1$.

This is valid also for the combined lightning impulse/power-frequency voltage of longitudinal insulations. Reason is that lightning impulses are so short in time duration that the flashover will be a streamer discharge. The flashover voltage, therefore, increases linearly with distance.

4) Co-ordination switching impulse withstand voltages

For switching impulses, the exponent m is obtained for each co-ordination withstand voltage U_{cw} . An according dependency is given in Figure 9.

The derivation of exponent m for standard switching impulse voltage shapes is shown in H.4.2. It shows in detail that the exponent m is, beside U_{cw} , depending on altitude H and gap factor K . Figure H.6 or Figure H.7 should be used for selection of exponent m to determine the altitude correction factor K_a when dealing with standard impulse shapes.

The derivation of exponent m for critical switching impulse voltage shapes is shown in H.4.3 in the same way with the results in Figure H.8 and Figure H.9.

H.4.2 Derivation of exponent m for switching impulse voltage

The exponent m can be derived from a set of well-known and approved relations:

- 1) flashover characteristic based on rod-plane gaps (Equation (F.4)) for standard switching impulse voltage;
- 2) parameter g providing the exponent m (IEC 60060-1);
- 3) atmospheric correction;
- 4) normalized conventional standard deviation $z = 0,06$ for switching impulse;
- 5) pressure related exponential function of altitude correction.

With this set of relations a dependency of exponent m on the co-ordination withstand voltage U_{cw} with the parameters K and H can be derived as described in the following.

Basically, exponent m is derived from the equation of parameter g and the equation of the flashover characteristic of phase-to-earth configuration. In both equations, the air gap clearance L is used and will be set equal.

For both equations, the 50 % flashover voltages are needed. Taking Equation (7) and considering that

U_{cw} is the 10% flashover voltage U_{10} , and

U_{c50} is the 50% flashover voltage U_{50} ,

U_{c50} can be calculated as follows:

$$U_{c50} = \frac{U_{cw}}{1 - 1,3 \times z} \quad (\text{H.14})$$

The normalized value of conventional standard deviation is 6 % for switching impulse voltage referred to U_{50} .

Air gap clearance d from parameter g

The minimum air clearance d of equipment is not known and has to be determined.

Based on the equation for the parameter g of IEC 60060-1 the applicable minimum clearance d at the location of installation is given by

$$d = \frac{U_{c50}}{500 \times g \times \delta \times k_h} \quad (\text{H.15})$$

Air gap clearance d from flashover characteristic based on rod-plane gaps

To determine the air clearances necessary for a required 50 % flashover voltage, a voltage based on the characteristic of a rod-plane configuration has been used (Equation (F.4)).

$$U_{r50} = K \times 500 \times d^{0,6} \quad (\text{H.16})$$

The required 50 % flashover voltage U_{r50} valid for reference conditions can be converted to the co-ordination flashover voltage U_{c50} by atmospheric correction (disregarding the safety factor K_s in this respect):

$$U_{r50} = \frac{U_{c50}}{K_t} = \frac{U_{c50}}{(\delta \times k_h)^m} \quad (\text{H.17})$$

The air gap clearance is given now by:

$$d = \left[\frac{U_{c50}}{500 \times K \times (\delta \times k_h)^m} \right]^{1/0,6} \quad (\text{H.18})$$

Setting equal Equations (H.15) and (H.18) leads to:

$$\frac{U_{c50}}{500 \times g \times \delta \times k_h} = \left[\frac{U_{c50}}{500 \times K \times (\delta \times k_h)^m} \right]^{1/0,6} \quad (\text{H.19})$$

Replace g by (from IEC 60060-1):

$$g = 0,1 + \sqrt{0,8 \times m + 0,01} \quad (\text{H.20})$$

The term of the atmospheric correction $\delta \times k_h$ is known from the designated installation and can be replaced by

$$\delta \times k_h = \frac{-H}{e^{8/150}} \quad (\text{H.21})$$

Including Equations (H.14), (H.20) and (H.21) into (H.19) leads to the dependency of exponent m on U_{cw} with the parameters H and K . Equation (H.19) can only be solved iteratively.

The dependency of exponent m on the co-ordination withstand voltage U_{cw} is plotted in Figure H.6 for selected gap factors K and selected altitudes H up to 4 000 m. Typical values of the gap factor K are indicated in Table G.1 and Table G.2.

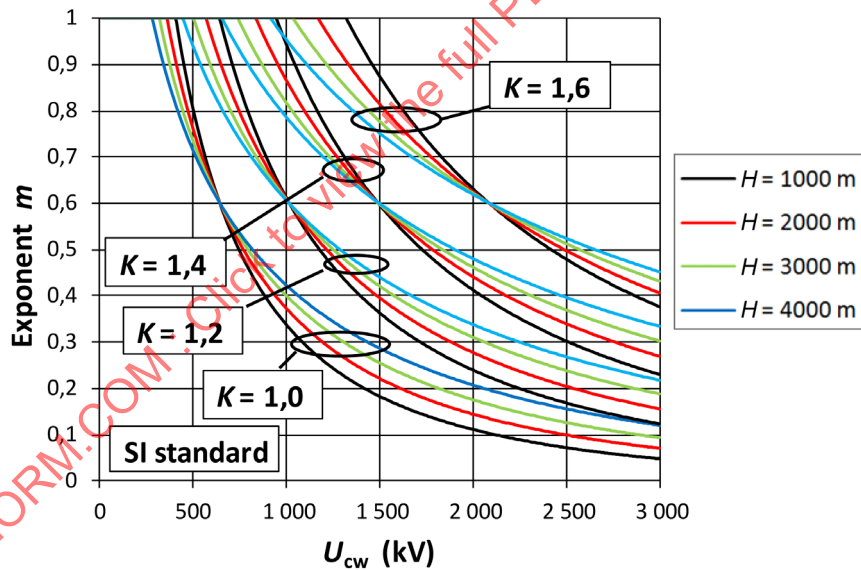


Figure H.6 – Sets of m -curves for standard switching impulse voltage including the variations in altitude for each gap factor

The exponent m varies in a wide range considering the two parameters altitude and gap factor. By examining the effect of exponent m on altitude correction factor K_a it can be stated that the sensitivity of K_a on variations in m is low. Due to the fact that the sensitivity is decreasing with altitude the m curves for the highest altitude can be used in a first approach for the lower altitudes by accepting a maximum failure within engineering tolerance of $\pm 3 \%$ (Figure H.7).

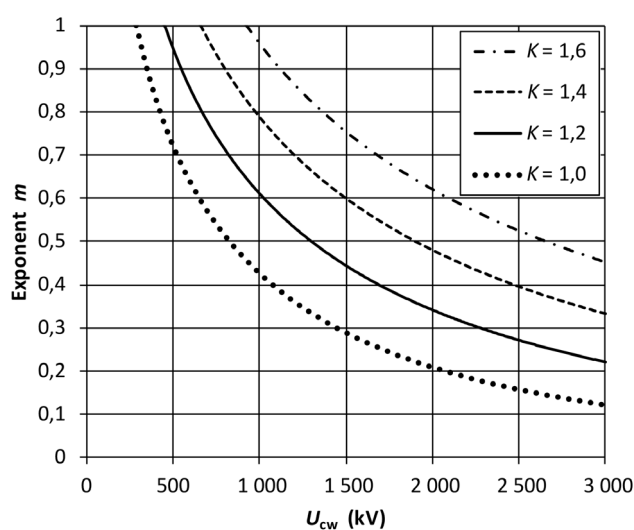


Figure H.7 – Exponent m for standard switching impulse voltage for selected gap factors covering altitudes up to 4 000 m

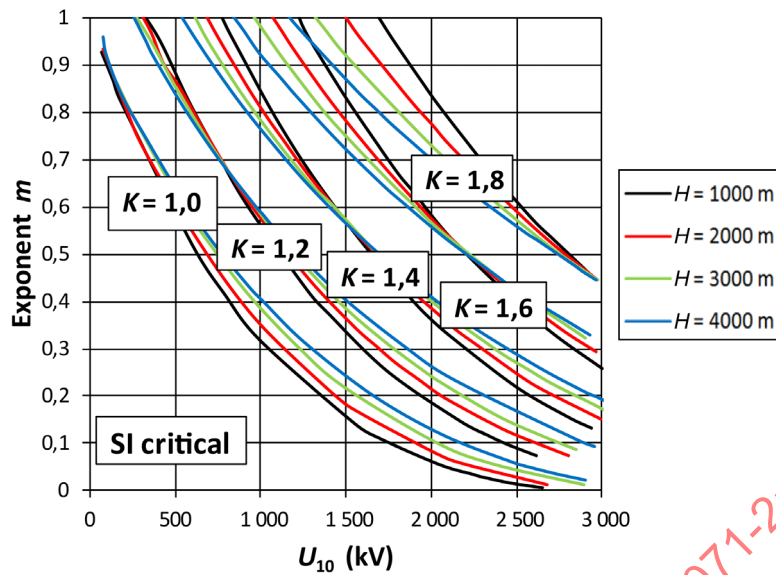
H.4.3 Derivation of exponent m for critical switching impulse voltage

If the critical switching impulse voltage is used for determination of exponent m the derivation can be done in the same way as for standard switching impulse (described in H.4.2) by just replacing the equation for the flashover characteristics. The characteristic based on rod-plane gaps (based on Equation (F.3)) for switching impulse voltage with critical front time strength has to be used.

$$U_{r50} = K \times 1\,080 \times \ln(0,46 \times d + 1) \quad (\text{H.22})$$

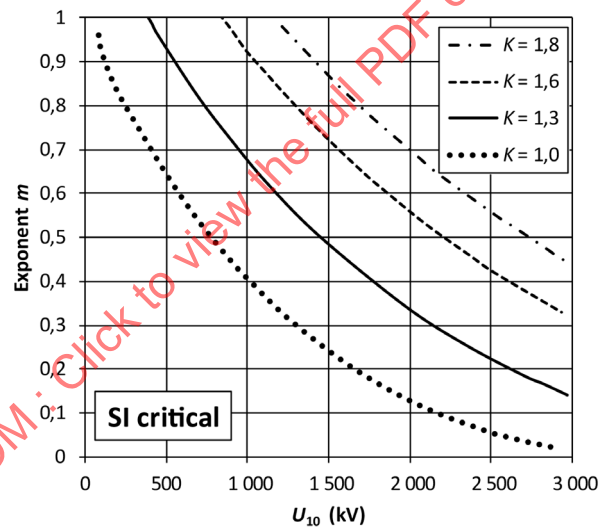
All other relations remain unchanged.

The outcome is also a set of curves for each gap factor covering the selected altitudes 1 000 m up to 4 000 m (Figure H.8) and the reduced diagram for all altitudes up to 4 000 m (Figure H.9).



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Figure H.8 – Sets of m -curves for critical switching impulse voltage including the variations in altitude for each gap factor



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Figure H.9 – Exponent m for critical switching impulse voltage for selected gap factors covering altitudes up to 4 000 m

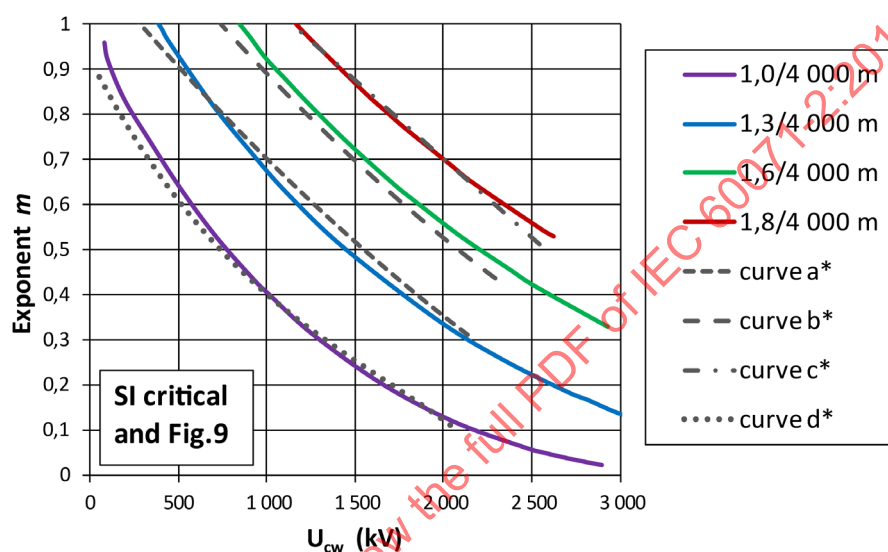
The curves are more flat than the curves determined by the equation for the standard switching impulse. They have a similar gradient in comparison with the m -curves of Figure 9.

After selection of appropriate parameters for gap factor K and altitude H , it can be shown that some curves are in good accordance with the curves of Figure 9. The conformity is visualized in Figure H.10, and a comparison of the functional expressions of Figure 9 to the selected parameters is listed in Table H.1.

Table H.1 – Comparison of functional expressions of Figure 9 with the selected parameters from the derivation of m -curves with critical switching impulse

Insulation according Figure 9		Determination by critical SI Equation (F.3) Parameter: gap factor/altitude
Phase-to-earth	curve a*	1,3/4 000
Longitudinal	curve b*	1,6/4 000
Phase-to-phase	curve c*	1,8/4 000
Rod-plane gap	curve d*	1,0/4 000

NOTE The asterisks defining the curves refer to Figure H.10.



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Figure H.10 – Accordance of m -curves from Figure 9 with determination of exponent m by means of critical switching impulse voltage for selected gap factors and altitudes

Figure 9 has been used for several years. To avoid changes in actual practical designs by replacing the curves of Figure 9 with the determined curves described above they can be used further on. It is recommended to investigate the validity of the new curves according Figure H.6 and Figure H.7 as well when dealing with standard impulse shapes only.

Annex I (informative)

Evaluation method of non-standard lightning overvoltage shape for representative voltages and overvoltages

I.1 General remarks

In the insulation co-ordination stage of "representative overvoltage", overvoltage shapes are supposed to be the standard voltage shapes, which is especially significant for a lightning impulse. Recent researches have analysed field surges, clarified insulating characteristics for field real surges in comparison with those for the standard voltage shape in the lightning surge time region, and proposed the shape evaluation method for GIS (Gas insulated switchgear) [14] and transformer [15]. These techniques have been discussed in CIGRE working groups, and adopted in the technical brochures [11], [16], [17]. According to the aforementioned documents, the decay of the field overvoltage is generally large, making the insulation requirements not as severe as those of the standard overvoltage shape. Consequently, it could be possible in some cases to use lower withstand voltages.

I.2 Lightning overvoltage shape

From the results of the analyses of lightning overvoltage, disconnector switching overvoltage, and measurements at UHV and 550 kV substations, representative overvoltage shapes were extracted as the following five types, "Shape A" to "Shape E". The rise time of the shape crest varies, as a whole, in the range of 0,1 μ s to 1,0 μ s for GIS and 0,5 μ s to 1,5 μ s for transformer.

- Shape A: pulse-shape.
- Shape B: the shape front has a steep pulse-shaped part, and the shape tail is flat (ratio between peak and flat part: 0,7/0,9 both for GIS and transformer).
- Shape C: a damped oscillatory shape whose first peak is maximum (frequency: 0,5 MHz to 5,0 MHz for GIS, 0,4 MHz to 1,0 MHz for transformer).
- Shape D: a damped oscillatory shape whose second peak has the crest value (frequency: 0,5 MHz to 5,0 MHz for GIS, 0,4 MHz to 1,0 MHz for transformer).
- Shape E: double-frequency oscillatory shape (lower frequency: approx. 1,0 MHz, upper frequency: approx. 5,0 MHz for GIS).

Shape B appears depending upon the positional relationships with protected points when the lightning arrester operates. Shapes C and D occur as a result of a negative and/or positive reflection inside and/or outside the substation. Shape A corresponds to the one when the decay of the DC component and/or oscillatory components of shapes B, C and D are large. Also, shape E occurs during a re-striking inside a substation as a disconnector surge, when there exist two oscillation routes within a substation. Thus, in general, it can be said that these shapes are representative shapes in view of the mechanism under which they occur. Figure I.1 a) to e) show examples of shapes A, B, C, D, and E.

I.3 Evaluation method for GIS

I.3.1 Experiments

The SF₆ gas gap and partly the insulating spacer surface were used as the insulating elements of GIS. The electrodes used in the tests generated quasi-equal electric fields whose utilization factors (η) were 0,60 and 0,45. The gas pressure was basically an absolute pressure of 0,50 MPa. With changing shape parameters, such as the frequency and the decay time, more than 200 cases were examined. Moreover, effects of other factors were

investigated, like the scale, the gas pressure, the voltage polarity, superposition with DC, electrode material, and roughness.

As an example of the results, Figure I.2 shows the characteristics with respect to the shape E. The minimum value of the insulation breakdown V-t characteristics is 259 kV, which is 1,19 times that of the case of a standard lightning impulse. In other words, this means that it is possible to evaluate the overvoltage into the standard voltage with dividing the crest value by 1,19. This interpretation applies to the other experimental results as well.

The insulation characteristics are arranged according to the duration time of the 80 % level of the peak value. Figure I.3 presents how to calculate the duration time t_d : the sum of $t_{d1} + t_{d2}$. All of the characteristics for shape A, the pulse parts of shape B, and shapes C and D, and the double-frequency oscillatory shape E, lie roughly along one characteristic line. This characteristic corresponds to equations in the "Calculation of evaluation factor K_{ev} " box in Figure I.4 later discussed.

I.3.2 Evaluation of overvoltage shape

The overvoltage shape is resolved into elements including each oscillatory shape, the flat part, and so on. It is then evaluated based on the characteristics as described above, and finally the crest value that is evaluated into an equivalent standard voltage shape. Figure I.4 exhibits the whole evaluation flow for GIS together with for transformer referred to in I.4.2.

Figure I.5 shows an example of the lightning overvoltage applied to GIS in a UHV substation. This overvoltage is classified to the shape B whose tail level is approximately 60% of the peak, after the steep oscillatory surge has decayed. Table I.1 shows the results of analyzing and evaluating this overvoltage shape using the flow of Figure I.4. In this case, the shape crest is severer than the shape tail, and the representative overvoltage is equivalent to a 2 094 kV (25 % lower).

I.4 Evaluation method for transformer

I.4.1 Experiments

The oil gap, section-to-section insulation and turn-to-turn insulation were used as the insulating elements of a transformer. About 100 cases were examined with changing shape parameters, such as the frequency and the decay time.

As an example of the results, Figure I.6 exhibits the characteristics with respect to shape C of the turn-to-turn insulation. The average value of the insulation breakdown V-t characteristics is 185 kV, which is 1,26 times that of the case of a standard lightning impulse. In a similar manner to GIS, this means that it is possible to evaluate the overvoltage into the standard voltage with dividing the crest value by 1,26. This interpretation applies to the other experimental results as well.

Concerning the oil gap and section-to-section insulation, when the insulation characteristics are arranged according to the duration time of the 80 % level of the peak value, all of the characteristics for shape A, the pulse parts of shape B, and shapes C and D, lie roughly along one characteristic line. Meanwhile, regarding the turn-to-turn insulation, when the insulation characteristics are arranged according to the duration time of the 90 % level of the peak value, all of the characteristics for shape A, the pulse parts of shape B, and shapes C and D, lie roughly along one characteristic line. However, in contrast to the other models, the duration time for 90 % and higher in the case of an oscillatory shape is not a total value, but is calculated separately for each shape as shape A.

I.4.2 Evaluation of overvoltage shape

The shape is resolved into elements V_{pij} including each oscillatory shape, the flat part, and so on. It is then evaluated based on the characteristics as described above, and finally the crest

value is evaluated as the equivalent standard voltage V_{sj} . The whole overvoltage shape evaluation flow for an oil-filled transformer is presented in Figure I.4 together with for GIS.

Figure I.7 is an example of a lightning overvoltage applied to a transformer in a 550 kV substation. In this case, the shape tail maintains a level of about 70 % with respect to the peak after the steep oscillatory surge has decayed. Table I.2 summarizes the results of analyzing and evaluating this shape using the flow of Figure I.4. The severest part of the overvoltage is the pulse-shaped one "No. 2" with respect to the turn-to-turn insulation. The crest value of equivalent standard voltage is 934 kV (24 % lower).

To think of the principle of construction, these methods both for GIS and transformer can be generally applicable to lower voltage systems as well as 550 kV and above.

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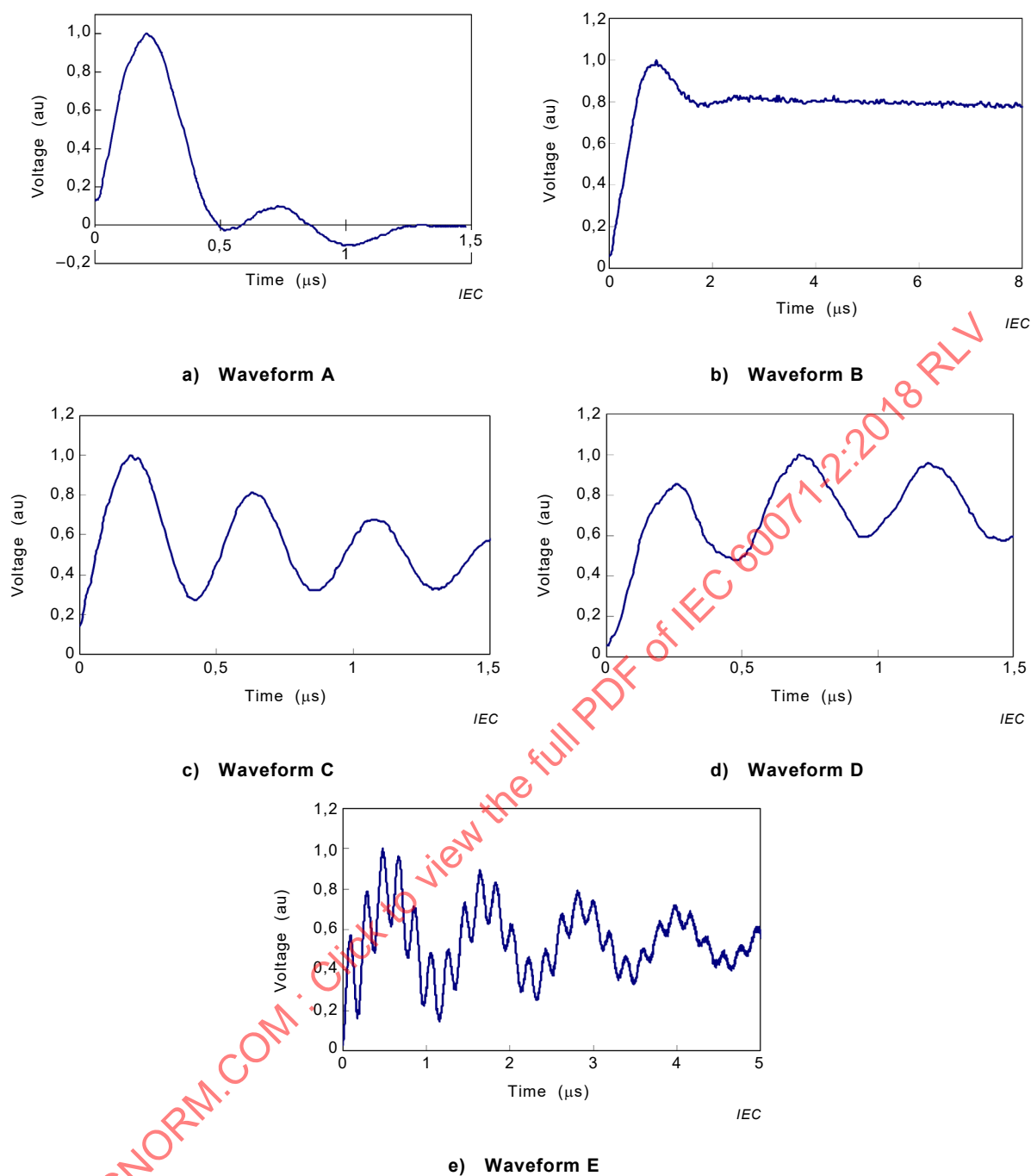


Figure I.1 – Examples of lightning overvoltage shapes

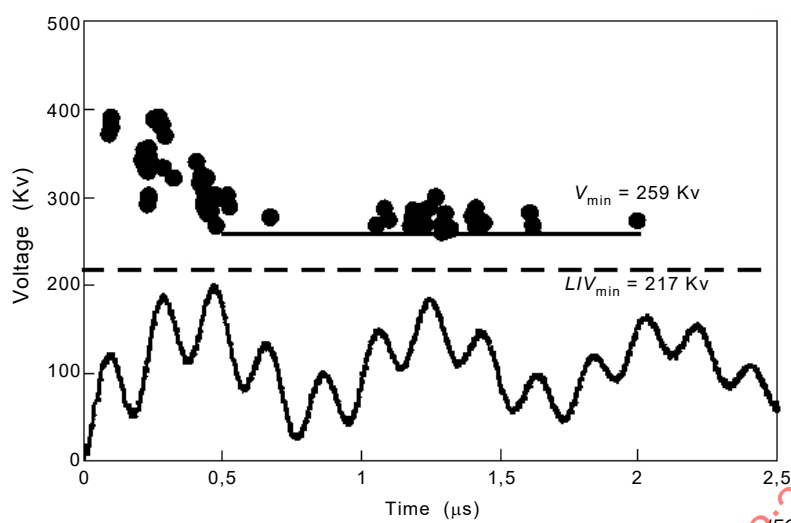


Figure I.2 – Example of insulation characteristics with respect to lightning overvoltages of the SF₆ gas gap (Shape E)

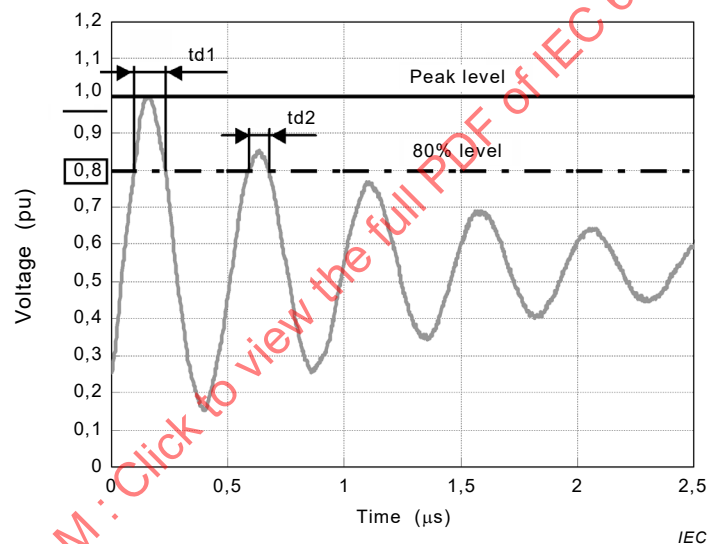


Figure I.3 – Calculation of duration time T_d

Table I.1 – Evaluation of the lightning overvoltage in the GIS of UHV system

Shape element	80 % duration time	Peak voltage	Evaluation ratio	Equivalent standard LI Vol.
B (shape crest)	0,16 μs	2 617 kV	1,25 (1,30)	2 094 kV [$\eta = 0,60$] (2 016 kV [$\eta = 0,45$])
B (shape tail)	-	1 517 kV	0,90	1 686 kV

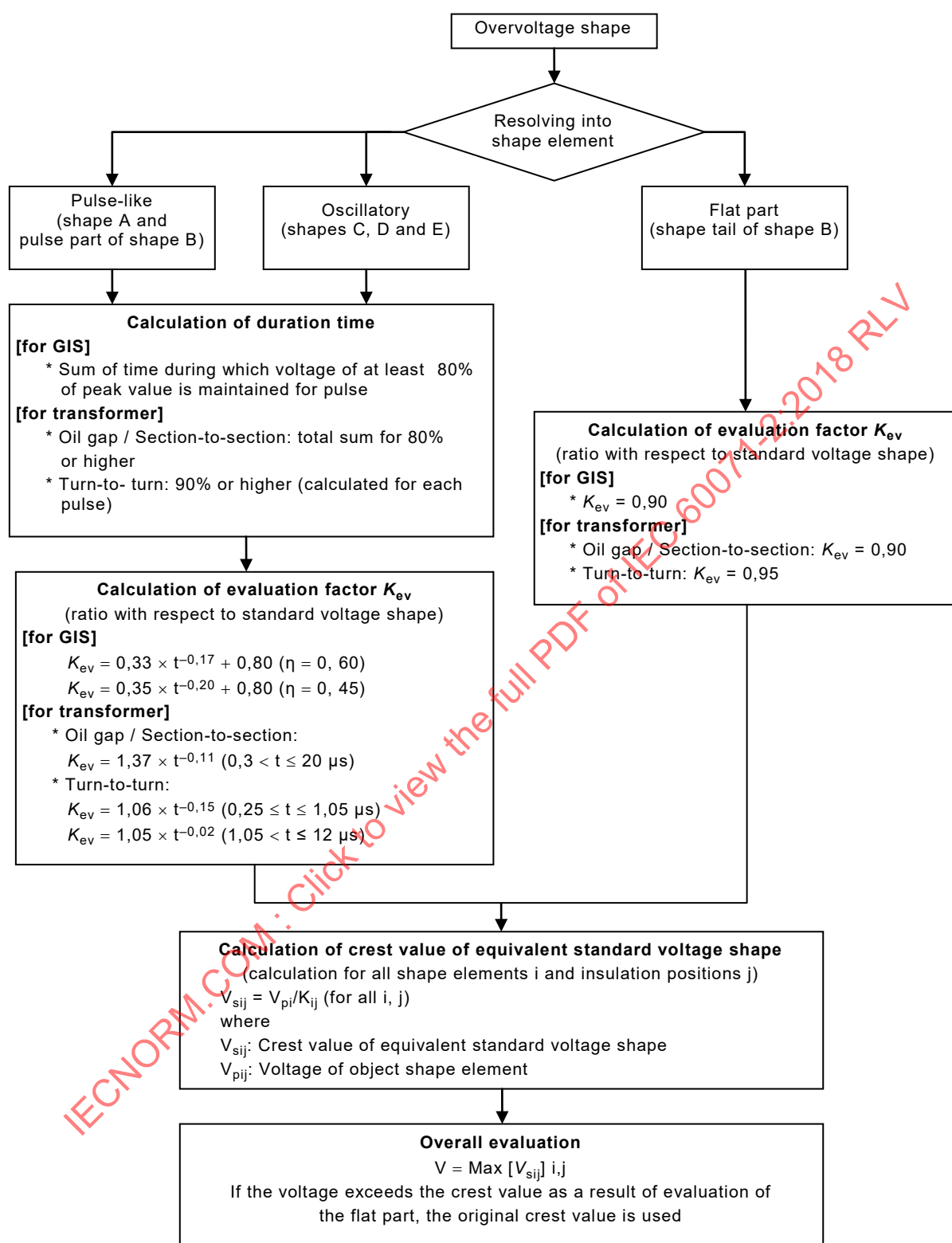


Figure I.4 – Shape evaluation flow for GIS and transformer

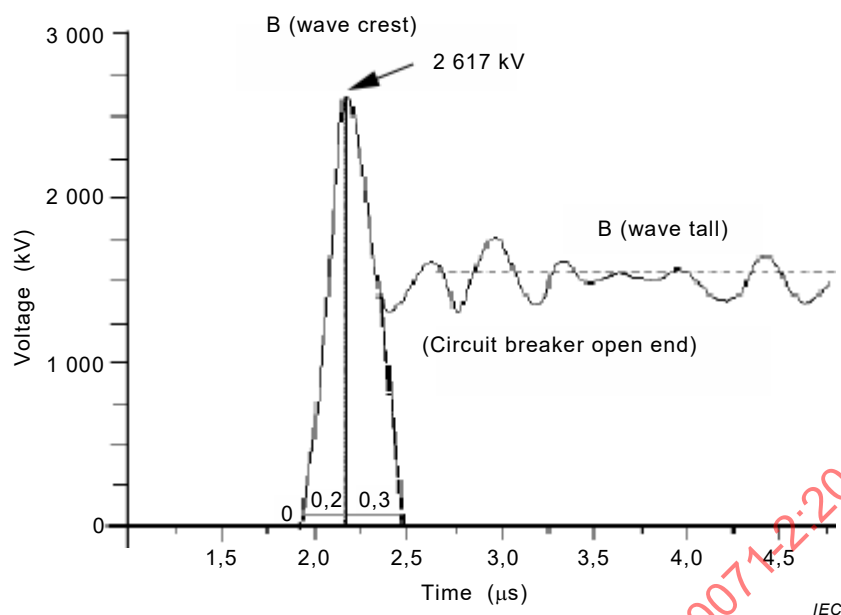


Figure I.5 – Application to GIS lightning overvoltage

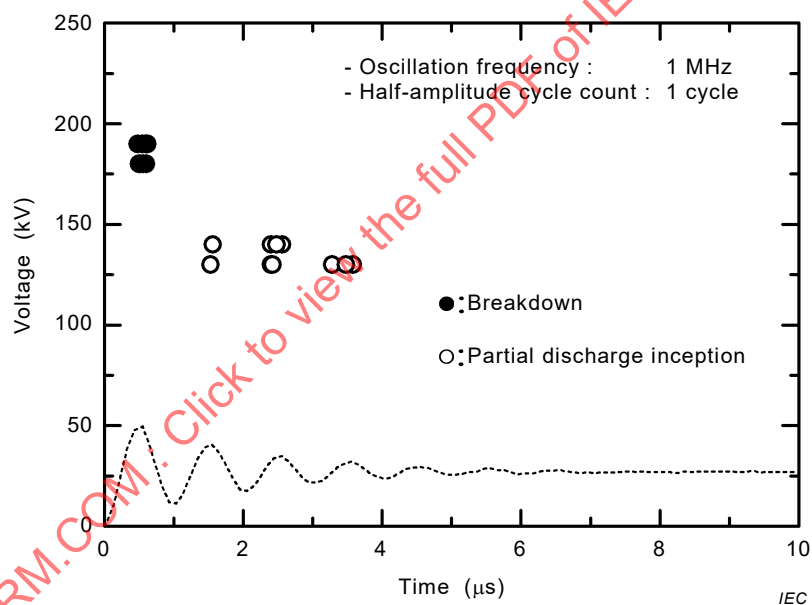


Figure I.6 – Example of insulation characteristics with respect to lightning overvoltage of the turn-to-turn insulation (Shape C)

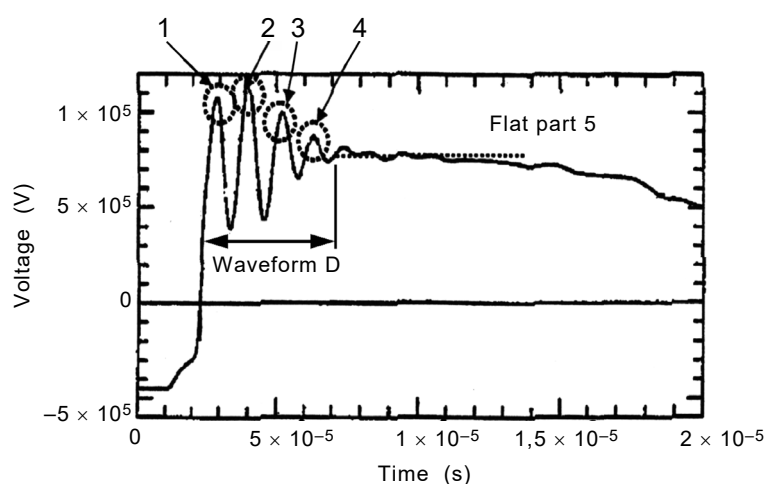


Figure I.7 – Application to transformer lightning overvoltage

Table I.2 – Evaluation of lightning overvoltage in the transformer of 500 kV system

Insulation element	Shape element	Duration time	Peak voltage	Evaluation ratio	Equivalent standard LI Vol.
Oil gap / Section-to-section	Oscillatory parts (1~4): C or D	0,84 μ s	1 158 kV	1,40	827kV
	Flat part (5)	-	784 kV	0,90	871kV
Turn-to-turn	Max pulse (2)	0,35 μ s	1 158 kV	1,24	934kV
	Other pulses (1)	0,35 μ s	1 084 kV	1,24	874kV
	Flat part (5)	-	784 kV	0,95	825kV

Annex J (informative)

Insulation co-ordination for very-fast-front overvoltages in UHV substations

J.1 General

VFFO in GIS have been studied by various CIGRÉ working groups and a common CIGRÉ technical brochure TB 519 [13] was published.

VFFO were considered to be more important for insulation co-ordination in UHV AC substations, than in HV substations. VFFO in GIS are of greater concern at UHV, because the ratio of the lightning impulse withstand voltage to the rated voltage is comparably low. VFFO can become the limiting dielectric stress.

Especially in the UHV range, the knowledge of the VFFO level is necessary as basis for the insulation co-ordination and the evaluation of potential risks and countermeasures. Because the VFFO are determined by superposition of traveling waves, they depend strongly on the specific configuration and it is not possible to give generally valid voltage values. It is necessary to perform a system analysis by accurate simulation for each substation to assess the VFFO.

As an indication, the required withstand voltage depends on the dielectric behavior of the equipment and the trapped charge behavior of the disconnector. As a result, the withstand voltages could vary for different equipment (transformer, SF₆ insulation, air insulation) and different disconnector design.

A three step procedure is recommended for VFFO insulation co-ordination. This procedure is outlined in Figure J.1, and its steps are described in Clause J.3.

A more detailed description of the procedure can be found in TB 519 [13]. The general approach is based on the insulation co-ordination procedure for the determination of rated or standard insulation level according to IEC 60071-1.

J.2 Influence of disconnector design

The value of the VFFO depends on the voltage drop at the disconnector just before striking. The voltage drop is dependent on the charge remaining on the load side of the disconnector from the preceding striking. The "trapped charge" is the charge remaining after the last striking of an opening operation, and the trapped charge voltage (TCV) is the voltage resulting from this charge.

This TCV is specific for each disconnector design and depends mainly on the contact speed and the field homogeneity of the contact system.

For slow acting disconnectors (contact speed < 1 m/s) the maximum trapped charge voltage lies well below 1 p.u. The resulting VFFO is in the range of 1,7 p.u. and reaches 2,0 p.u. for very specific cases.

Fast acting disconnectors (contact speed > 1 m/s) exhibit trapped charge levels up to 1 p.u. Consequently generally higher VFFO are produced compared to the slow acting disconnector. The integration of a damping resistor into the disconnector is a proven mitigation measure, VFFO amplitudes in the range around 1,3 p.u. can be reached.

J.3 Insulation co-ordination for VFFO

1) Step 1: Calculation of peak value and rise time of VFFO

- System analysis (using a travelling wave computer simulation program).
- Calculation of the maximum peak value $U_{\max-VFFO}$ and rise time for the GIS and the connected equipment.
- If known, the real trapped charge behavior of the disconnecter should be used, i.e.
 - the 99 % probability value determined by simulation, or
 - maximum values measured during testing.
- Otherwise, the worst case assumption of a trapped charge voltage of -1 p.u. should be used for the simulation.
- The accuracy of the simulation model shall be verified.

In the context of insulation co-ordination process, travelling wave simulation is a well-established instrument. However, the accuracy of a VFFO simulation depends on the quality of the model of each individual GIS component. In order to achieve reasonable results, even for time periods of some micro-seconds or for very complex GIS structures, accurate models for all components, internal and external, connected to the GIS, are necessary. This allows for calculating VFFO which differ less than 5 % from measured voltage curves. The accuracy of a simulation is usually verified by VFFO measurement on a GIS test pole or the actual gas-insulated substation arrangement and the comparison of simulated and measured VFFO.

2) Step 2: Calculation of required VFFO withstand voltage ($U_{rw-VFFO}$) and comparison to LIWV

The required VFFO withstand voltage $U_{rw-VFFO}$ shall be calculated for the different equipment by multiplication of $U_{\max-VFFO}$ with K-factors:

- Co-ordination factor K_c : K_c covers the statistical distribution and frequency of occurrence of VFFO and the inaccuracy of simulation. In case of a proved simulation tool a co-ordination factor K_c of 1,05 is recommended. $U_{\max-VFFO}$ multiplied with K_c gives the VFFO co-ordination voltage $U_{cw-VFFO}$.
- Safety factor K_s and atmospheric correction factor K_t : K_s covers the aging behavior in service, quality of installation and other unknown influences. For external insulation a safety factor K_s of 1,05, for internal insulation (applicable for any equipment) a safety factor K_s of 1,15 is recommended. In case of external insulation the atmospheric correction factor K_t shall be applied. $U_{cw-VFFO}$ multiplied with K_s and K_t gives the required VFFO withstand voltage $U_{rw-VFFO}$.

3) Step 3: Definition of measures according to the insulation co-ordination

The required VFFO withstand voltage $U_{rw-VFFO}$ is compared to the LIWV in order to determine a risk of insulation failure. For this purpose, the required VFFO withstand voltage $U_{rw-VFFO}$ has to be multiplied with a test conversion factor K_{tc} :

- K_{tc} describes the different withstand behavior under VFFO and standard LI voltage stress. For SF₆ insulated systems the recommended K_{tc} is 0,95. The recommended test conversion factor K_{tc} for oil or oil/solid insulated systems is 1,0.

Based on the result of the comparison

- if $K_{tc} \times U_{rw-VFFO} < \text{LIWV}$, no measures are required;
- otherwise, measures to mitigate the risk of failure should be considered.

Mitigation may be achieved for instance by applying a disconnecter with low(er) TCV or a disconnecter with integrated damping resistor. Other measures may also be appropriate, for instance increasing of the LIWV.

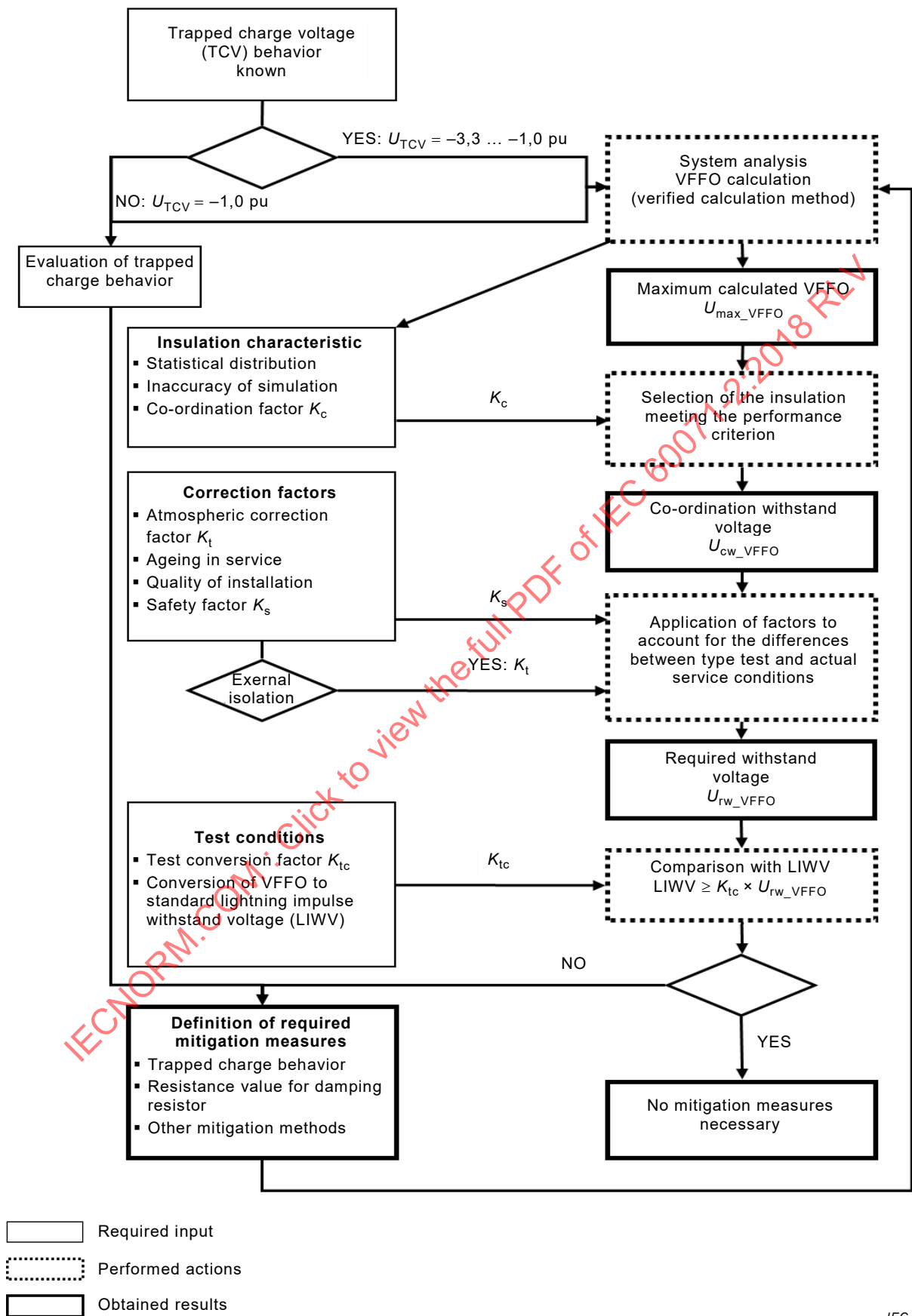


Figure J.1 – Insulation co-ordination for very-fast-front overvoltages

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COMMISSION ÉLECTROTECHNIQUE INTERNATIONALE

COORDINATION DE L'ISOLEMENT –

Partie 2: Lignes directrices en matière d'application

AVANT-PROPOS

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La Norme internationale IEC 60071-2 a été établie par le Comité d'études 28 de l'IEC: Coordination de l'isolement.

Cette quatrième édition annule et remplace la troisième édition parue en 1996. Cette édition constitue une révision technique.

Cette édition inclut les modifications techniques majeures suivantes par rapport à l'édition précédente:

- a) l'annexe relative à la distance d'isolement dans l'air pour installation garantissant une tension de tenue aux chocs spécifiée est supprimée car cette annexe est déjà présente dans l'IEC 60071-1;
- b) 4.2 et 4.3 relatifs aux parafoudres ont été mis à jour;

- c) 4.3.5 relatif aux surtensions à front très rapide a été révisé. L'Annexe J relative à la coordination de l'isolement pour les surtensions à front très rapide dans les postes UHT a été ajoutée;
- d) l'Annexe H relative à la correction atmosphérique – correction de l'altitude a été ajoutée;
- e) l'Annexe I relative à la méthode d'évaluation de la forme de la surtension de foudre non normalisée a été ajoutée.

Le texte de cette Norme internationale est issu des documents suivants:

FDIS	Rapport de vote
28/255/FDIS	28/256/RVD

Le rapport de vote indiqué dans le tableau ci-dessus donne toute information sur le vote ayant abouti à l'approbation de cette Norme internationale.

Le présent document a été rédigé selon les Directives ISO/IEC, Partie 2.

Il a le statut d'une norme horizontale conformément au Guide 108 de l'IEC.

Le comité a décidé que le contenu du présent document ne sera pas modifié avant la date de stabilité indiquée sur le site web de l'IEC sous "<http://webstore.iec.ch>" dans les données relatives au document recherché. À cette date, le document sera

- reconduit,
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IMPORTANT – Le logo "*colour inside*" qui se trouve sur la page de couverture de cette publication indique qu'elle contient des couleurs qui sont considérées comme utiles à une bonne compréhension de son contenu. Les utilisateurs devraient, par conséquent, imprimer cette publication en utilisant une imprimante couleur.

COORDINATION DE L'ISOLEMENT –

Partie 2: Lignes directrices en matière d'application

1 Domaine d'application

La présente partie de l'IEC 60071 constitue des lignes directrices en matière d'application et concerne le choix des niveaux d'isolement des matériels ou des installations pour les réseaux triphasés. Elle a pour objet de donner des recommandations pour la détermination des tensions de tenue assignées pour les plages I et II de l'IEC 60071-1 et de justifier l'association de ces valeurs assignées avec les valeurs normalisées des tensions les plus élevées pour le matériel.

Cette association ne couvre que les besoins de la coordination de l'isolement. Les exigences relatives à la sécurité des personnes ne sont pas traitées dans le présent document.

Le présent document traite des réseaux triphasés de tension nominale supérieure à 1 kV. Les valeurs déduites ou qui y sont proposées ne sont généralement applicables qu'à ces seuls réseaux. Cependant, les principes présentés sont également valables pour les réseaux biphasés ou monophasés.

Le présent document traite de l'isolement phase-terre, entre phases et longitudinal.

Le présent document n'est pas destiné à détailler les essais individuels de série, qui doivent être spécifiés par les comités de produits concernés.

Le contenu du présent document suit strictement l'organigramme de la procédure de coordination de l'isolement présenté à la Figure 1 de l'IEC 60071-1:2006. Les Articles 4 à 7 correspondent à chacun des rectangles de l'organigramme et donnent des informations détaillées sur les principes de la procédure de coordination de l'isolement qui conduit à déterminer les niveaux de tenue spécifiés.

Ce document insiste sur la nécessité de prendre en considération, dès le départ, toutes les origines, toutes les classes et tous les types de contraintes de tension en service quelle que soit la plage de la tension la plus élevée pour le matériel. Ce n'est qu'à la fin de la procédure, au moment de sélectionner les tensions de tenue normalisées, que le principe de couvrir une contrainte de tension particulière en service par une tension de tenue normalisée est appliqué. De même, le document fait référence, à cette étape finale, aux corrélations établies dans l'IEC 60071-1 entre les niveaux d'isolement normalisés et la tension la plus élevée pour le matériel.

Les annexes contiennent des exemples et des informations détaillées qui expliquent ou corroborent les principes décrits dans le texte principal, et les techniques analytiques de base qui sont utilisées.

2 Références normatives

Les documents suivants cités dans le texte constituent, pour tout ou partie de leur contenu, des exigences du présent document. Pour les références datées, seule l'édition citée s'applique. Pour les références non datées, la dernière édition du document de référence s'applique (y compris les éventuels amendements).

IEC 60060-1:2010, *Techniques des essais à haute tension – Partie 1: Définitions et exigences générales*

IEC 60071-1:2006, *Coordination de l'isolement – Partie 1: Définitions, principes et règles*
IEC 60071-1:2006/AMD1:2010

IEC 60505:2011, *Évaluation et qualification des systèmes d'isolation électrique*

IEC TS 60815-1, *Selection and dimensioning of high-voltage insulators intended for use in polluted conditions– Part 1: Definitions, information and general principles (disponible en anglais seulement)*

ISO 2533:1975, *Atmosphère type*

3 Termes, définitions, termes abrégés et symboles

3.1 Termes et définitions

Aucun terme n'est défini dans le présent document.

L'ISO et l'IEC tiennent à jour des bases de données terminologiques destinées à être utilisées en normalisation, consultables aux adresses suivantes:

- IEC Electropedia: disponible à l'adresse <http://www.electropedia.org/>
- ISO Online browsing platform: disponible à l'adresse <http://www.iso.org/obp>

3.2 Termes abrégés

MOSA	metal-oxide surge arrester (parafoudre à oxyde métallique)
SFO	slow-front overvoltage (surtension à front lent)
FFO	fast-front overvoltage (surtension à front rapide)
VFFO	very-fast-front overvoltage (surtension à front très rapide)
LSA	line surge arrester (parafoudre de ligne)
EGLA	externally gapped line arrester (parafoudre de ligne avec éclateur extérieur)
NGLA	non-gapped line arrester (parafoudre de ligne sans éclateur)
LIWV	lightning impulse withstand voltage (tension de tenue au choc de foudre)
SIWV	switching impulse withstand voltage (tension de tenue au choc de manœuvre)
SDWV	short-duration power-frequency withstand voltage (tension de tenue de courte durée à fréquence industrielle)
LIPL	lightning impulse protection level (niveau de protection au choc de foudre)
SIPL	switching impulse protection level (niveau de protection au choc de manœuvre)
GIS	gas-insulated switchgear (poste (sous enveloppe métallique) à isolation gazeuse)
UHT	ultra haute tension
TOV	temporary power-frequency overvoltages (surtensions à fréquence industrielle temporaires)
SVU	series varistor unit (bloc de varistances en série)
ESDD	equivalent salt deposit density (densité équivalente de dépôt salin)
TCV	trapped charge voltage (tension de charge piégée)

3.3 Symboles

Pour les besoins du présent document, les symboles et définitions suivants s'appliquent. Le symbole est suivi de l'unité normalement utilisée. Les grandeurs sans dimension sont indiquées comme suit: (-).

Certaines grandeurs sont données en p.u. Une grandeur par unité est le rapport entre la valeur réelle d'un paramètre électrique (tension, courant, fréquence, puissance, impédance, etc.) et une valeur de référence donnée du même paramètre.

A	(kV)	paramètre caractérisant l'influence de la sévérité de la foudre pour le matériel dépendant du type de ligne aérienne à laquelle il est raccordé
a_1	(m)	longueur de la liaison reliant le parafoudre à la ligne
a_2	(m)	longueur de la liaison reliant le parafoudre à la terre
a_3	(m)	longueur du conducteur de phase entre le parafoudre et le matériel protégé
a_4	(m)	longueur de la partie active du parafoudre
B	(-)	facteur utilisé pour décrire la caractéristique d'amorçage entre phases
C_e	(nF)	capacité des enroulements primaires d'un transformateur par rapport à la terre
C_s	(nF)	capacité série des enroulements primaires d'un transformateur
C_2	(nF)	capacité phase-terre de l'enroulement secondaire d'un transformateur
C_{12}	(nF)	capacité entre les enroulements primaire et secondaire d'un transformateur
C_{1in}	(nF)	capacité d'entrée équivalente des bornes des transformateurs triphasés
C_{2in}	(nF)	capacité d'entrée équivalente des bornes des transformateurs triphasés
C_{3in}	(nF)	capacité d'entrée équivalente des bornes des transformateurs triphasés
c	(m/μs)	vitesse de la lumière
c_f	(p.u.)	facteur de couplage des tensions entre câble de garde et conducteur de phase d'une ligne aérienne
E_0	(kV/m)	gradient d'ionisation du sol
F		fonction de répartition des amplitudes des surtensions, où $F(U) = 1 - P(U)$; voir l'Article B.3
f		fonction décrivant la densité de probabilité des amplitudes de surtension
d_r	(-)	taux de transmission capacitive des ondes de tension
H	(m)	altitude au-dessus du niveau de la mer
h	(-)	facteur de tension à fréquence industrielle pour les ondes transmises dans les transformateurs
H_t	(m)	hauteur au-dessus du sol
I	(kA)	amplitude du courant de foudre
I_g	(kA)	valeur limite du courant de foudre dans le calcul de la prise de terre des pylônes
I_n	(kA)	courant de décharge nominal d'un parafoudre
J	(-)	facteur d'enroulement pour les ondes transmises par induction dans les transformateurs
K	(-)	facteur d'intervalle prenant en compte l'influence de la configuration de l'intervalle sur la tenue
K_a	(-)	facteur de correction de l'altitude
K_c	(-)	facteur de coordination
K_s	(-)	facteur de sécurité

K_{cd}	(-)	facteur de coordination déterministe
K_{co}	($\mu s/(kVm)$)	constante d'atténuation par effet couronne
K_{cs}	(-)	facteur de coordination statistique
K_{f+}	(-)	facteur d'intervalle pour les impulsions à front rapide de polarité positive
K_{f-}	(-)	facteur d'intervalle pour les impulsions à front rapide de polarité négative
K_{ev}	(-)	facteur d'évaluation du rapport de surtension de foudre sur la forme de tension normalisée
k	(-)	facteur de défaut à la terre
k_h	(-)	paramètre de correction d'humidité
d	(m)	distance de séparation entre le parafoudre et le matériel protégé
L_a	(m)	longueur de ligne aérienne correspondant à un taux de coupures égal au taux admissible (lié à R_a)
L_t	(m)	longueur de ligne aérienne pour laquelle le taux de coupures dues à la foudre est égal au taux de retour retenu (lié à R_t)
L_{sp}	(m)	longueur de portée
M	(-)	nombre d'isolations en parallèle considérées comme étant simultanément contraintes par une surtension
m	(-)	exposant de la formule du facteur de correction atmosphérique de la tenue de l'isolation externe
N	(-)	nombre d'écarts-types entre U_{50} et U_{spec} pour une isolation autorégénératrice
n	(-)	nombre de lignes aériennes considérées comme étant raccordées au poste pour l'évaluation de l'amplitude de l'onde incidente
P	(%)	probabilité de décharge d'une isolation autorégénératrice
P_w	(%)	probabilité de tenue d'une isolation autorégénératrice
q	(-)	facteur de réponse des enroulements de transformateur pour les ondes transmises par induction
Q_{rs}	(C)	caractéristiques assignées de transfert de charges répétitives d'un parafoudre
Q_{th}	(C)	caractéristiques assignées de transfert de charges thermiques d'un parafoudre
R	(-)	risque de défaillance (défaillances par événement)
R_a	(1/a)	taux de défaillance admissible d'un appareil; pour les lignes de transport, ce paramètre est généralement exprimé en (1/a)/100 km
R_{hc}	(Ω)	valeur à courant fort de la résistance de prise de terre d'un pylône
R_{km}	(1/(m.a))	taux de coupures annuel d'une ligne aérienne d'une conception correspondant au premier kilomètre après le poste
R_{lc}	(Ω)	valeur à courant faible de la résistance de prise de terre d'un pylône
R_p	(1/a)	taux de défaut d'écran des lignes aériennes
R_{sf}	(1/a)	taux d'amorçage par défaut d'écran des lignes aériennes
R_t	(1/a)	taux de retour de surtension retenu (valeur de référence)
R_u	(kV)	rayon d'un cercle dans le plan d'axes U^+/U^- décrivant les surtensions à front lent entre phases et phase-terre
R_0	(Ω)	résistance homopolaire
R_1	(Ω)	résistance directe

R_2	(Ω)	résistance inverse
S	(kV/ μ s)	raideur d'une onde de foudre arrivant sur un poste
S_e	(kV)	écart type de la distribution des surtensions phase-terre
S_p	(kV)	écart type de la distribution des surtensions entre phases
S_{rp}	(kV/ μ s)	raideur représentative d'une onde de foudre incidente
s_e	(-)	valeur normalisée de l'écart type S_e (S_e appelé U_{e50})
s_p	(-)	valeur normalisée de l'écart type S_p (S_p appelé U_{p50})
t_s	(μ s)	temps de propagation d'une onde de foudre
U	(kV)	amplitude d'une surtension (ou d'une tension)
U^+	(kV)	composante positive dans un essai d'isolement au choc de manœuvre entre phases
U^-	(kV)	composante négative dans un essai d'isolement au choc de manœuvre entre phases
U_{spec}	(kV)	valeur de troncature de la fonction de probabilité d'amorçage $P(U)$ d'une isolation autorégénératrice: $P(U \leq U_{spec}) = 0$
U_0^+	(kV)	composante positive équivalente phase-terre utilisée pour représenter la surtension entre phases la plus contraignante
U_{1e}	(kV)	surtension temporaire entre la terre et le neutre de l'enroulement primaire d'un transformateur
U_{2e}	(kV)	surtension temporaire entre la terre et le neutre de l'enroulement secondaire d'un transformateur
U_{2N}	(kV)	tension assignée de l'enroulement secondaire du transformateur
U_{10}	(kV)	valeur de la tension de décharge 10 % d'une isolation autorégénératrice; cette valeur est la tension de tenue statistique de l'isolation définie en 3.23 b) de l'IEC 60071-1:2006
U_{16}	(kV)	valeur de la tension de décharge 16 % d'une isolation autorégénératrice
U_{50}	(kV)	valeur de la tension de décharge 50 % d'une isolation autorégénératrice
U_{50M}	(kV)	valeur de la tension de décharge 50 % de M isolations autorégénératrices en parallèle
U_{50RP}	(kV)	valeur de la tension de décharge 50 % d'un intervalle pointe-plan
U_c	(kV)	tension de régime permanent d'un parafoudre
U_c^+	(kV)	composante positive définissant le centre d'un cercle qui décrit les surtensions à front lent entre phases et phase-terre
U_c^-	(kV)	composante négative définissant le centre d'un cercle qui décrit les surtensions à front lent entre phases et phase-terre
U_{cw}	(kV)	tension de tenue de coordination du matériel.
U_e	(kV)	amplitude d'une surtension phase-terre
U_{et}	(kV)	valeur de troncature de la fonction de répartition $F(U_e)$ des surtensions phase-terre: $F(U_e \geq U_{et}) = 0$ (voir l'Article B.3)
U_{e2}	(kV)	valeur de la surtension phase-terre ayant une probabilité de 2 % d'être dépassée: $F(U_e \geq U_{e2}) = 0,02$ (voir l'Article B.3)
U_{e50}	(kV)	valeur à 50 % de la fonction de répartition $F(U_e)$ des surtensions phase-terre (voir l'Article B.3)
U_l	(kV)	amplitude de l'onde de surtension de foudre incidente
U_m	(kV)	tension la plus élevée pour le matériel.

U_p	(kV)	amplitude d'une surtension entre phases
U_{p2}	(kV)	valeur de la surtension entre phases ayant une probabilité de 2 % d'être dépassée: $F(U_p \geq U_{p2}) = 0,02$ (voir l'Article B.3)
U_{p50}	(kV)	valeur à 50 % de la fonction de répartition $F(U_p)$ des surtensions entre phases (voir l'Article B.3)
U_r	(kV)	tension assignée d'un parafoudre en fonction des surtensions temporaires
U_s	(kV)	tension la plus élevée d'un réseau
U_w	(kV)	tension de tenue normalisée
U_{pl}	(kV)	niveau de protection au choc de foudre d'un parafoudre
U_{ps}	(kV)	niveau de protection au choc de manœuvre d'un parafoudre
U_{pt}	(kV)	valeur de troncature de la fonction de répartition $F(U_p)$ des surtensions entre phases: $F(U_p \geq U_{pt}) = 0$ (voir l'Article B.3)
U_{rp}	(kV)	amplitude de la surtension représentative
U_{rw}	(kV)	tension de tenue exigée
U_{T1}	(kV)	surtension appliquée à l'enroulement primaire d'un transformateur produisant (par transfert) une surtension sur l'enroulement secondaire
U_{T2}	(kV)	surtension sur l'enroulement secondaire d'un transformateur produite (par transfert) par une surtension appliquée à l'enroulement primaire
UHV	(-)	ultra haute tension: tension la plus élevée du réseau de transport dépassant 800 kV
u	(p.u.)	amplitude d'une surtension (ou d'une tension) par unité, par rapport à $U_s \sqrt{2/\sqrt{3}}$.
w_{21}	(-)	rapport de transformation d'un transformateur: tension entre phases du secondaire divisée par la tension entre phases du primaire
W	(kJ)	absorption d'énergie exigée d'un parafoudre
W_{th}	(kJ/kV)	caractéristiques assignées d'énergie thermique d'un parafoudre
X	(m)	distance entre le point d'impact de la foudre et le poste
X_p	(km)	distance limite sur une ligne aérienne sur laquelle les événements de foudre doivent être pris en considération
X_T	(km)	longueur de ligne aérienne à utiliser dans les calculs simplifiés de surtension de foudre
X_0	(Ω)	réactance homopolaire d'un réseau
X_1	(Ω)	réactance directe d'un réseau
X_2	(Ω)	réactance inverse d'un réseau
x	(-)	variable normalisée dans une fonction de probabilité de décharge $P(U)$ d'une isolation autorégénératrice
x_M	(-)	variable normalisée dans une fonction de probabilité de décharge $P(U)$ de M isolations autorégénératrices en parallèle
Z	(kV)	écart type de la fonction de probabilité de décharge $P(U)$ d'une isolation autorégénératrice
Z_0	(Ω)	impédance homopolaire
Z_1	(Ω)	impédance directe
Z_2	(Ω)	impédance inverse
Z_e	(Ω)	impédance d'onde du câble de garde d'une ligne aérienne
Z_L	(Ω)	impédance d'onde d'une ligne aérienne

Z_M	(kV)	écart type de la fonction de probabilité de décharge $P(U)$ de M isolations autorégénératrices en parallèle
Z_s	(Ω)	impédance d'onde du conducteur de phase d'un poste
z	(-)	valeur normalisée de l'écart type Z par rapport à U_{50} .
α	(-)	rapport entre la composante négative d'une onde de manœuvre et la somme des deux composantes (positive + négative) d'une surtension entre phases
β	(kV)	paramètre d'échelle d'une fonction cumulative de Weibull
U_0	(kV)	valeur de troncature d'une fonction cumulative de Weibull
η	(-)	facteur d'utilisation du champ électrique
Φ		fonction intégrale de Gauss
ϕ	(-)	angle d'inclinaison de la caractéristique d'un isolement entre phases
γ	(-)	paramètre de forme d'une fonction cumulative de Weibull-3
σ	(p.u.)	valeur par unité de l'écart type (S_e ou S_p) d'une distribution de surtensions
ρ	(Ωm)	résistivité du sol
τ	(μs)	constante de temps de queue d'une surtension de foudre due aux amorçages en retour sur les lignes aériennes

4 Contraintes de tension représentatives en service

4.1 Origine et classification des contraintes de tension

L'IEC 60071-1 classe les contraintes de tension en fonction de paramètres appropriés, tels que la durée de la tension à la fréquence industrielle ou la forme d'une surtension, en fonction de leur effet sur l'isolation ou sur le dispositif de protection. Au sein de ce classement, les contraintes de tension ont plusieurs origines:

- les tensions permanentes (à la fréquence industrielle): elles trouvent leur origine dans l'exploitation des réseaux en conditions normales;
- les surtensions temporaires: elles peuvent être dues à des défauts, des manœuvres telles qu'une perte de charge, des conditions de résonance, des non-linéarités (ferro-résonances) ou à une combinaison de ces causes;
- les surtensions à front lent: elles peuvent être dues à des défauts, des manœuvres ou des coups de foudre directs sur les conducteurs de lignes aériennes;
- les surtensions à front rapide: elles peuvent être dues à des manœuvres, des coups de foudre ou des défauts;
- les surtensions à front très rapide: elles peuvent être dues à des défauts ou des manœuvres dans des postes (sous enveloppe métallique) à isolation gazeuse (GIS);
- les surtensions combinées: elles peuvent être dues à toutes les causes mentionnées ci-dessus. Elles se produisent entre les phases d'un réseau (phase-phase) ou sur la même phase, entre deux parties séparées d'un réseau (longitudinale).

Toutes les contraintes de surtension précédentes, excepté les surtensions combinées, sont détaillées séparément en 4.3. Les surtensions combinées sont présentées à l'endroit approprié, dans un ou plusieurs des paragraphes de 4.3.

Pour chaque type de contrainte de tension, il convient de tenir compte du transfert à travers les transformateurs (voir l'Annexe D).

En règle générale, toutes les classes de surtensions peuvent se rencontrer dans les deux plages de tensions I et II (voir l'IEC 60071-1). Cependant, l'expérience a montré que certains types de tension sont plus d'importance dans une plage de tensions donnée, ce point étant

traité dans le présent document. Dans tous les cas, il convient de noter que ce sont les études détaillées, s'appuyant sur les modèles adéquats pour représenter le réseau et les caractéristiques des dispositifs de limitation des surtensions, qui permettent d'obtenir la connaissance des contraintes la meilleure (valeurs de crête et formes).

Dans le cadre de l'analyse d'un système d'alimentation électrique, des outils de simulation numériques (l'outil de simulation des transitoires électromagnétiques, par exemple) ont été utilisés dans de nombreux pays. Certains pays comparent également les résultats d'analyse et les valeurs mesurées. La validité a été confirmée jusqu'aux réseaux UHT. Par exemple, dans le cas des lignes UHT au Japon et en Chine, l'erreur maximale entre les mesurages et la simulation des surtensions de manœuvre est d'environ 5 %, ce qui est convenable dans la conception des lignes de transport. Pour de plus amples informations, il peut être fait référence aux activités du CIGRE [1]¹.

4.2 Caractéristiques des dispositifs de protection contre les surtensions

4.2.1 Remarques générales

Pour assurer une conception et un fonctionnement sûrs, fiables et économiques des réseaux haute tension, des postes et du matériel, il est indispensable d'utiliser des dispositifs de protection contre les surtensions.

La conception et l'installation des dispositifs de protection contre les surtensions doivent permettre de limiter les amplitudes de surtensions au niveau des bornes du matériel à protéger. En règle générale, une protection efficace est assurée contre les surtensions à front lent (SFO) et les surtensions à front rapide (FFO).

Il ne faut pas oublier que les surtensions aux bornes du dispositif de protection contre les surtensions et du matériel à protéger sont en général différentes, plus particulièrement dans les conditions de surtensions à front rapide. Les chutes de tension inductives sur les câbles de liaison et, bien plus encore, les processus d'ondes progressives en sont largement responsables.

Les parafoudres à oxyde métallique (MOSA) sans éclateurs sont des parafoudres "normalisés" qui doivent être installés dans tous les postes ou directement sur les transformateurs montés sur poteau et les extrémités de câble des lignes de distribution. La distance de protection des parafoudres étant limitée (de quelques mètres à plusieurs dizaines de mètres, selon le niveau de tension du réseau), ils doivent être installés aussi proche que possible du matériel à protéger. Il peut s'avérer nécessaire d'installer des parafoudres supplémentaires aux entrées de ligne des postes.

Dans certains pays sont utilisés des MOSA avec éclateurs intérieurs, lesquels sont appliqués aux réseaux d'alimentation électrique de U_s jusqu'à 52 kV et sont couverts par leur propre norme d'essai (IEC 60099-6).

Outre cette application générale des MOSA comme dispositif de protection, des parafoudres de ligne (LSA) sont souvent utilisés pour les lignes aériennes de transmission et de distribution. Ils empêchent les contournements d'isolateur dus aux coups de foudre directs sur le conducteur d'une ligne non blindée, par un défaut d'écran d'une ligne blindée ou en raison d'amorçages en retour. À cet effet, des parafoudres de ligne avec éclateur extérieur en série (EGLA) et des parafoudres de ligne sans éclateur (NGLA) sont utilisés.

En outre, les éclateurs sont encore parfois considérés comme un autre dispositif de limitation des surtensions, bien qu'aucune norme IEC ne leur soit consacrée. Toutefois, il convient en règle générale de préférer les parafoudres, les éclateurs produisant des montées de tension

¹ Les chiffres entre crochets se réfèrent à la Bibliographie.

importantes directement au niveau du matériel à protéger, leurs caractéristiques d'amorçage sous FFO étant parfois critiques. Étant donné qu'il n'existe aucune norme, il convient de demander ces caractéristiques de tension d'amorçage en fonction du temps au fabricant ou qu'elles soient établies par l'exploitant sur la base de ses propres spécifications.

4.2.2 Parafoudres à oxyde métallique (MOSA) sans éclateur

4.2.2.1 Généralités

Les caractéristiques de protection et l'application des MOSA sont spécifiées dans l'IEC 60099-4 et l'IEC 60099-5.

La procédure générale de sélection des parafoudres est recommandée dans l'IEC 60099-5:

- détermination de la tension de régime permanent U_c ;
- détermination de la tension assignée U_r en fonction des surtensions temporaires;
- détermination de l'absorption d'énergie exigée W et choix d'un courant de décharge nominal I_n ;
- détermination du niveau de protection au choc de foudre U_{pl} et du niveau de protection au choc de manœuvre U_{ps} .

Les niveaux de protection peuvent être utilisés pour les surtensions à front lent et à front rapide représentatives. La tension de coordination de tenue au choc de foudre est déterminée en tenant compte des performances des lignes aériennes vis-à-vis de la foudre, du taux de défaillance acceptable du matériel et de la zone de protection du parafoudre.

La procédure est itérative. Après avoir choisi la procédure, si les niveaux de protection du MOSA sont trop élevés, il convient d'étudier la possibilité d'utiliser une tension permanente inférieure, un courant de décharge nominal plus élevé, une capacité d'absorption d'énergie plus importante ou de réduire la distance entre le parafoudre et le matériel protégé. Ces mesures se traduiront soit par des tensions résiduelles du MOSA inférieures à une amplitude de courant de choc imposé, soit par des niveaux de surtension réduits au niveau du matériel protégé pour une tension résiduelle du MOSA donnée.

L'évaluation des niveaux de protection donne une valeur approximative globalement acceptable. L'IEC 60099-5 donne des informations détaillées relatives aux performances de protection des parafoudres.

4.2.2.2 Caractéristiques de la protection relatives aux surtensions à front rapide

Les tensions suivantes caractérisent le niveau de protection à front rapide d'un MOSA:

- niveau de protection au choc de foudre U_{pl} (également appelé LIPL);
- tension résiduelle maximale au choc de courant à front raide.

Le niveau de protection au choc de foudre est la tension résiduelle maximale au niveau du courant de décharge nominal pendant une durée de 8 μ s à 20 μ s (IEC 60099-4). S'agissant de la coordination de l'isolement des réseaux UHT, les parafoudres présentant de faibles niveaux de protection sont d'une importance particulière. Le courant de décharge nominal des parafoudres UHT est en général de 20 kA.

La tension de protection au choc de courant à front raide obtenue (avec une durée du front de 1 μ s) doit être prise en considération en cas de chutes de tension inductive dans les liaisons et la longueur du parafoudre. Le contexte est décrit dans l'IEC 60099-5.

4.2.2.3 Caractéristiques de la protection relatives aux surtensions à front lent

Le niveau de protection à front lent d'un MOSA se caractérise par le niveau de protection au choc de manœuvre U_{ps} (également appelé SIPL), qui est la tension résiduelle maximale au

courant de décharge de choc de manœuvre spécifié (voir l'IEC 60099-4) ou à d'autres amplitudes de courant définies dans le cadre d'un accord entre le fabricant et l'utilisateur de parafoudre. Les chutes de tension inductive et les phénomènes d'ondes progressives (distance de protection) ne doivent pas être pris en considération.

S'agissant des parafoudres de distribution, les niveaux de protection au choc de manœuvre ne sont pas spécifiés, n'étant en général pas un problème pour les réseaux de distribution.

Plus particulièrement pour les parafoudres UHT, d'autres courants de choc de manœuvre peuvent être utilisés compte tenu de la possible suppression des surtensions à front lent dans les réseaux UHT par suite de l'adoption des mesures suivantes:

- manœuvre commandée;
- disjoncteurs avec résistances d'ouverture ou résistances d'ouverture/de fermeture;
- toutes les combinaisons des mesures ci-dessus.

4.2.2.4 Capacité de gestion de l'énergie

La capacité de gestion de l'énergie d'un MOSA est définie par deux caractéristiques.

- a) Pour les parafoudres de distribution ("D"), qui comprennent les sous-catégories DH, DM, DL (les lettres "H", "M" et "L" indiquant "high" (haut), "medium" (moyen) et "low" ("bas"), respectivement):
 - caractéristiques assignées de transfert de charges répétitives, Q_{rs} ;
 - caractéristiques assignées de transfert de charges thermiques, Q_{th} .
- b) Pour les parafoudres de poste ("S"), qui comprennent les sous-catégories SH, SM, SL:
 - caractéristiques assignées de transfert de charges répétitives, Q_{rs} ;
 - caractéristiques assignées d'énergie thermique, W_{th} .

NOTE Le dernier système de classe de décharge de ligne des parafoudres de poste n'existe plus depuis l'IEC 60099-4:2014.

4.2.3 Parafoudres de ligne (LSA) pour les lignes aériennes de transmission et de distribution

L'objet et les caractéristiques des parafoudres de ligne sont décrits dans l'IEC 60099-5. Les parafoudres de ligne sans éclateur (NGLA) sont des MOSA normalisés, soumis à l'essai conformément à l'IEC 60099-4, alors que les parafoudres de ligne avec éclateur extérieur en série (EGLA) sont soumis à l'essai selon l'IEC 60099-8.

La capacité de gestion de l'énergie des NGLA est définie, outre les caractéristiques du MOSA, par leur capacité de décharge au choc de foudre assignée.

Les EGLA protègent les ensembles d'isolateurs uniquement des contournements provoqués par la foudre. Par conséquent, il est important de déterminer les caractéristiques de protection au choc de foudre du parafoudre composant la tension d'amorçage pour le choc à front rapide et le choc de foudre normalisé, et les tensions résiduelles pour le courant de décharge nominal. De plus, la tenue diélectrique de l'EGLA par rapport aux surtensions à front lent maximales sur le réseau doit être déterminée.

La coordination correcte entre les caractéristiques de contournement de l'ensemble d'isolateurs et la tension d'amorçage de l'EGLA doit être démontrée avec la tension de tenue normalisée et les tensions résiduelles. Toutes les opérations d'amorçage sous tension de choc de foudre doivent avoir lieu dans l'éclateur extérieur en série de l'EGLA sans générer de contournement de l'ensemble d'isolateurs à protéger.

Les EGLA n'exécutent aucune tâche d'exploitation pour les surtensions à front lent et les surtensions à fréquence industrielle temporaires (TOV).

Les EGLA ne doivent pas fonctionner à la tension de tenue spécifiée au choc de manœuvre et au niveau de TOV maximal du réseau, que les blocs de varistances en série (SVU) soient en bon état de fonctionnement ou défaillants (surchargés).

La tension assignée d'un EGLA est la valeur efficace maximale admissible de la tension à fréquence industrielle entre ses bornes, à laquelle il est conçu pour fonctionner correctement. Elle doit donc être supérieure ou égale à la surtension temporaire à fréquence industrielle prévue dans l'installation concernée. La tension assignée fait également office de paramètre de référence pour la spécification des caractéristiques de fonctionnement et d'interruption de courant.

Les EGLA sont classés en fonction de leurs courants de décharge nominaux et de leurs capacités de tenue au courant de choc. Deux autres systèmes de classification sont disponibles ("Série X" et "Série Y". Pour plus de détails, voir l'IEC 60099-8).

4.3 Tensions et surtensions représentatives

4.3.1 Tension permanente (à la fréquence industrielle)

Dans les conditions d'exploitation normales, la tension à la fréquence industrielle peut varier dans le temps et être différente d'un point à l'autre du réseau. Cependant, pour les besoins de la conception et de la coordination de l'isolement, la tension permanente à fréquence industrielle représentative doit être considérée comme constante et égale à la tension la plus élevée du réseau. En pratique, jusqu'à 72,5 kV, la tension la plus élevée du réseau U_s peut être nettement inférieure à la tension la plus élevée pour le matériel U_m , alors que pour des niveaux de tension supérieurs, ces tensions tendent à être égales.

4.3.2 Surtensions temporaires

4.3.2.1 Généralités

Les surtensions temporaires se caractérisent par leur amplitude, leur forme et leur durée. Tous ces paramètres dépendent de l'origine des surtensions, et leurs amplitudes et leurs formes peuvent varier pendant la durée même de la surtension.

Pour les besoins de la coordination de l'isolement, il est admis que la forme de la surtension temporaire représentative soit celle de la tension normalisée de courte durée (1 min) à fréquence industrielle. Son amplitude peut être définie par une valeur (le maximum présumé), un ensemble de valeurs de crête ou une distribution statistique complète de valeurs de crête. L'amplitude retenue pour la surtension temporaire représentative doit prendre en considération

- l'amplitude et la durée de la surtension réelle en service, et
- la caractéristique amplitude/durée de la tenue à la fréquence industrielle de l'isolation considérée.

Si cette dernière caractéristique n'est pas connue, à titre de simplification, une amplitude égale à l'amplitude maximale ayant en service une durée réelle inférieure à 1 min peut être retenue, et pour la durée, une durée égale à 1 min.

Dans certains cas particuliers, une procédure de coordination statistique peut être utilisée, décrivant la surtension représentative par une distribution statistique amplitude/durée des surtensions temporaires prévisibles en service (voir 5.3.2).

4.3.2.2 Défauts à la terre

Un défaut entre une phase et la terre peut entraîner des surtensions phase-terre sur les deux autres phases. Il ne se produit normalement pas de surtension temporaire entre phases ni sur une isolation longitudinale. La forme de la surtension est celle d'une tension à fréquence industrielle.

Les amplitudes de surtension dépendent du régime du neutre du réseau et de l'emplacement du défaut. L'Annexe A donne des recommandations pour leur détermination. Sur les configurations normales de réseaux, il convient par hypothèse que l'amplitude de surtension représentative soit égale à sa valeur maximale. Il convient d'envisager les configurations de réseaux anormales (des parties de réseau dont le neutre n'est pas relié à la terre dans un réseau à neutre normalement relié à la terre, par exemple) séparément, en tenant compte de leur probabilité d'occurrence simultanément avec des défauts à la terre.

La durée de la surtension est égale à la durée du défaut (jusqu'à son élimination). Sur les réseaux avec neutre à la terre, cette durée est généralement inférieure à 1 s. Sur les réseaux à neutre compensé par bobine d'extinction avec élimination de défaut, elle est généralement inférieure à 10 s. Sur les réseaux exploités à défaut maintenu, cette durée peut atteindre plusieurs heures. Dans de tels cas, il peut être nécessaire de définir la tension permanente à fréquence industrielle comme étant la valeur de la surtension temporaire pendant un défaut à la terre.

NOTE L'attention est attirée sur le fait que la tension la plus élevée à la fréquence industrielle qui peut apparaître sur une phase saine pendant un défaut à la terre ne dépend pas seulement du facteur de défaut à la terre, mais également de la valeur de la tension de service au moment du défaut qui peut généralement être considérée comme égale à la tension la plus élevée du réseau U_s .

4.3.2.3 Perte de charge

Les surtensions temporaires phase-terre ou longitudinales dues à une perte de charge dépendent de la charge perdue, de la configuration du réseau après la déconnexion et des caractéristiques des sources d'énergie (puissance de court-circuit au niveau du poste, régulation de vitesse et de tension des alternateurs, etc.).

Les élévations des trois tensions phase-terre sont identiques, et en conséquence, les mêmes surtensions relatives se manifestent entre phase et terre et entre phases. Ces élévations de tension peuvent être particulièrement importantes en cas de perte de charge à l'extrémité éloignée d'une longue ligne (effet Ferranti) et affectent principalement le matériel de poste relié au côté source du disjoncteur ouvert éloigné.

Les surtensions temporaires longitudinales dépendent du degré de déphasage après la séparation des réseaux, l'opposition de phases étant la situation possible la plus défavorable.

Du point de vue des surtensions, il convient de distinguer différentes configurations de réseau. Par exemple, les deux cas extrêmes suivants peuvent être envisagés:

- les réseaux comprenant des lignes relativement courtes avec des puissances de court-circuit relativement élevées aux postes d'extrémité, où se produisent de faibles surtensions;
- les réseaux comprenant des lignes longues avec de faibles valeurs de puissance de court-circuit au niveau du site de production, ce qui est courant sur un réseau à très haute tension à son état initial, et sur lesquels des surtensions très élevées peuvent se produire en cas de perte brutale d'une charge importante.

Lors de l'analyse des surtensions temporaires, il est recommandé de prendre en considération les points suivants (avec la tension de référence de 1,0 p.u. égale à $U_s \sqrt{2}/\sqrt{3}$).

- Sur des réseaux d'ampleur moyenne, la perte d'une pleine charge peut donner lieu à des surtensions phase-terre d'amplitude généralement inférieure à 1,2 p.u. La durée de surtension dépend du fonctionnement du matériel de contrôle de la tension et peut être de plusieurs minutes;
- Sur les réseaux étendus, en cas de perte de pleine charge, les surtensions phase-terre peuvent atteindre 1,5 p.u., voire davantage lorsque se produisent des effets Ferranti ou des phénomènes de résonance. Leur durée peut être de l'ordre de quelques secondes;
- S'il n'y a ni moteur ni générateur sur la partie déconnectée, la surtension temporaire longitudinale est en principe égale à la surtension phase-terre. Sur les réseaux

comportant des moteurs ou des générateurs sur la partie déconnectée, une séparation de réseaux peut entraîner une surtension temporaire longitudinale composée de deux surtensions phase-terre en opposition de phase dont l'amplitude maximale est normalement inférieure à 2,5 p.u. (des valeurs plus importantes peuvent être observées dans des cas exceptionnels, tels que les réseaux à très haute tension étendus).

4.3.2.4 Résonance et ferrorésonance

Les surtensions temporaires dues aux résonances et ferrorésonances se produisent généralement soit lorsque sont mis sous tension des circuits comportant d'importants éléments capacitifs (lignes, câbles, lignes compensées en série) et inductifs (transformateurs, bobines d'inductance shunt) présentant des caractéristiques d'aimantation non linéaires, soit par suite de pertes de charge.

Les surtensions temporaires dues à des phénomènes de résonance peuvent atteindre des valeurs extrêmement élevées. Elles doivent être évitées ou limitées par les mesures recommandées en 4.3.2.7. Par conséquent, elles ne doivent en principe pas être considérées comme servant de base au choix de la tension assignée du parafoudre, ni à la conception d'isolations, sauf si ces moyens ne sont pas suffisants (voir 4.3.2.8).

4.3.2.5 Surtensions longitudinales pendant une opération de synchronisation

Les surtensions temporaires longitudinales représentatives sont déduites de la surtension prévisible en exploitation dont l'amplitude est égale au double de la tension de service phase-terre et qui peut durer de plusieurs secondes à quelques minutes.

En outre, si les opérations de synchronisation sont fréquentes, la probabilité d'occurrence d'un défaut à la terre et de la surtension qu'il entraîne doit être prise en considération. Dans ces conditions, les amplitudes de surtension représentatives sont égales à la somme de la surtension maximale prévue due au défaut à la terre sur une borne et de la tension de service permanente en opposition de phase sur l'autre borne.

4.3.2.6 Combinaisons de plusieurs causes de surtension temporaire

4.3.2.6.1 Généralités

Avant de combiner des surtensions temporaires d'origines différentes, leur probabilité d'occurrence simultanée doit être soigneusement examinée. Ces combinaisons peuvent se traduire par des caractéristiques assignées plus élevées pour les parafoudres, ayant pour conséquence des niveaux de protection et d'isolement plus élevés. Or, ceux-ci ne se justifient techniquement et économiquement que si la probabilité d'occurrence simultanée est suffisamment élevée.

4.3.2.6.2 Défaut à la terre avec perte de charge

La combinaison défaut à la terre/perte de charge peut se produire quand, lors d'un défaut sur la ligne, le disjoncteur côté charge s'ouvre en premier et que la charge déconnectée cause une surtension de perte de charge dans la partie du réseau toujours en défaut, jusqu'à l'ouverture du disjoncteur côté alimentation.

La combinaison défaut à la terre/perte de charge peut également se produire lorsqu'une charge importante est déconnectée et que la surtension temporaire qui s'ensuit entraîne un défaut à la terre sur le reste du réseau. Cependant, la probabilité d'un tel événement est faible lorsque les surtensions dues à la variation de la charge sont elles-mêmes limitées, et un défaut consécutif à une perte de charge n'est susceptible de se produire que dans des conditions extrêmes (en cas de pollution majeure, par exemple).

Enfin, une telle combinaison peut résulter d'un défaut sur une ligne, suivi de l'ouverture avortée d'un disjoncteur. Même si elle est faible, la probabilité d'une telle combinaison n'est pas négligeable dans la mesure où il s'agit d'événements qui ne sont pas indépendants d'un

point de vue statistique. Une telle suite d'événements, qui fait qu'un alternateur se trouve relié, via un transformateur, à une longue ligne en défaut, peut entraîner une surtension importante sur les phases saines. La surtension est composée d'un transitoire à front lent et d'une surtension temporaire variable et prolongée, qui dépend elle-même des caractéristiques de l'alternateur et des actions du régulateur de tension de l'alternateur.

Il est recommandé d'étudier le réseau si de telles combinaisons sont considérées comme probables. Sans ces études, il pourrait s'avérer nécessaire de combiner ces surtensions, ce qui est considéré comme trop pessimiste pour les raisons suivantes:

- le facteur de défaut à la terre change lorsqu'il est lié à la surtension de perte de charge;
- la configuration du réseau n'est plus la même après variation de charge –par exemple, le facteur de défaut à la terre au niveau des transformateurs principaux avec neutre à la terre est inférieur à 1 après leur déconnexion du réseau;
- la perte de la totalité de la charge assignée n'est pas un phénomène habituel sur les transformateurs de réseau.

4.3.2.6.3 Autres combinaisons

Étant donné qu'il convient d'éviter les phénomènes de résonance, il convient de ne considérer leur combinaison avec des phénomènes d'origine différente que comme une conséquence supplémentaire de ces résonances. Cependant, sur certains réseaux, il n'est pas facile d'éviter les phénomènes de résonance. Il importe alors de procéder à des études détaillées.

4.3.2.7 Limitation des surtensions temporaires

4.3.2.7.1 Surtensions de défaut à la terre

Les surtensions dues à un défaut à la terre dépendent des paramètres du réseau et ne peuvent être maîtrisées que par un choix approprié de ces paramètres lors de la conception du réseau. Les amplitudes de surtension sont généralement moins importantes dans les réseaux avec neutre à la terre. Il existe toutefois une exception pour ces réseaux dont le neutre est mis à la terre lorsque, dans des conditions exceptionnelles, une partie de ces réseaux peut se trouver séparée avec les neutres des transformateurs n'étant pas reliés à la terre. Dans une telle situation, la durée des surtensions importantes dues à des défauts à la terre dans la partie séparée peut être contrôlée par une mise à la terre rapide de ces neutres avec des commutateurs ou des parafoudres spécialement choisis sur le neutre qui le mettent en court-circuit après un défaut.

4.3.2.7.2 Modifications rapides de la charge

Ces surtensions peuvent être contrôlées par des bobines d'inductance shunt, des condensateurs-série ou des compensateurs statiques.

4.3.2.7.3 Résonance et ferrorésonance

Il convient de limiter les surtensions dues à ces phénomènes en désaccordant le réseau pour la fréquence de résonance, par une modification de la configuration du réseau ou par des résistances d'amortissement.

4.3.2.8 Protection fournie par le parafoudre contre les surtensions temporaires

En règle générale, le choix de la tension assignée du parafoudre repose sur l'enveloppe des surtensions temporaires prévisibles, en prenant en compte l'aptitude du parafoudre à dissiper l'énergie. En général, l'ajustement des caractéristiques assignées du parafoudre aux contraintes de surtension temporaire est plus critique en plage II, pour laquelle les marges sont plus faibles, qu'en plage I. Habituellement, la productibilité du parafoudre soumis à une contrainte de surtension temporaire est exprimée par une caractéristique amplitude/durée fournie par le fabricant.

En pratique, les parafoudres ne limitent pas les surtensions temporaires. Il existe une exception pour les surtensions temporaires dues à des phénomènes de résonance et pour lesquels les parafoudres peuvent être utilisés pour limiter, voire empêcher, de telles surtensions. Pour ce type d'application, il convient d'étudier avec soin les contraintes thermiques dont les parafoudres font l'objet, de façon à éviter leur surcharge.

4.3.3 Surtensions à front lent

4.3.3.1 Généralités

Les surtensions à front lent ont des durées de front comprises entre quelques dizaines et quelques milliers de microsecondes, des temps de queue du même ordre de grandeur, et sont de nature oscillatoire. Elles sont généralement dues aux phénomènes suivants:

- enclenchement et réenclenchement d'une ligne;
- défauts et élimination de défauts;
- pertes de charge;
- coupure de courants capacitifs ou inductifs;
- coups de foudre éloignés sur un conducteur de ligne aérienne.

La contrainte de tension représentative est caractérisée par

- une forme de tension représentative, et
- une amplitude représentative qui peut être soit une surtension maximale prise par hypothèse, soit une fonction de répartition des amplitudes de surtension.

La forme de tension représentative est la tension normalisée de choc de manœuvre (durée jusqu'à la crête 250 μ s et durée de décroissance jusqu'à mi-valeur 2 500 μ s). L'amplitude représentative est l'amplitude de la surtension considérée indépendamment de la durée réelle jusqu'à la crête. Cependant, sur certains réseaux de la plage II, des surtensions ayant des fronts très longs peuvent se produire, et leur amplitude représentative peut être déduite en prenant en compte l'influence du temps de front sur la tenue diélectrique de l'isolation.

La fonction de répartition des surtensions sans fonctionnement de parafoudre se caractérise par sa valeur à 2 %, son écart type et sa valeur de troncature. Même si cette méthode n'est pas parfaitement valide, la fonction de répartition peut être représentée approximativement par une loi de Gauss entre la valeur à 50 % et la valeur de troncature, au-delà de laquelle aucune valeur n'est censée exister. Une loi de Weibull modifiée peut d'autre part être utilisée (voir l'Annexe B).

Par hypothèse, la valeur maximale de la surtension représentative est égale à la valeur de troncature des surtensions (voir 4.3.3.2 à 4.3.3.7) ou au niveau de protection au choc de manœuvre du parafoudre (voir 4.3.3.8), selon la valeur la plus basse.

4.3.3.2 Surtensions dues à l'enclenchement et au réenclenchement d'une ligne

4.3.3.2.1 Généralités

L'enclenchement ou le réenclenchement d'une ligne triphasée produit des surtensions de manœuvre sur les trois phases d'une ligne. En conséquence, chaque manœuvre engendre trois surtensions phase-terre et trois surtensions entre phases correspondantes [1].

Pour les applications pratiques, plusieurs simplifications ont été introduites dans l'évaluation des surtensions. En ce qui concerne le nombre de surtensions par manœuvre, deux méthodes sont utilisées.

- Méthode valeur de crête par phase: pour chaque manœuvre, la valeur de crête la plus élevée de la surtension, entre chaque phase et la terre ou entre chaque combinaison de phases, est introduite dans la fonction de répartition de surtension. Cela signifie que

chaque manœuvre contribue avec trois valeurs de crête à la fonction de répartition de surtension représentative. Cette distribution doit ensuite être par hypothèse identique pour les trois isolations impliquées dans chaque partie de l'isolement, phase-terre, phase-phase ou longitudinale.

- Méthode valeur crête par cas: pour chaque manœuvre, la valeur de crête la plus élevée des surtensions entre les trois phases et la terre, ou entre les trois phases elles-mêmes, est introduite dans la fonction de répartition de surtension. Cela signifie que chaque manœuvre contribue avec une valeur à la distribution de surtension représentative. Cette distribution est ensuite appliquée à une isolation dans chaque catégorie.

Les amplitudes de surtension dues à l'enclenchement de ligne dépendent de plusieurs facteurs dont le type de disjoncteur (avec résistance de fermeture ou non), la nature et la puissance de court-circuit du jeu de barres à partir duquel la ligne est enclenchée, la nature du moyen de compensation utilisé et la longueur de la ligne enclenchée, la façon dont se termine la ligne (ouverte, sur un transformateur, avec parafoudre), etc.

Les réenclenchements triphasés peuvent générer d'importantes surtensions à front lent dues aux charges piégées sur la ligne réenclenchée. Au moment du réenclenchement, l'amplitude de la surtension résiduelle sur la ligne (due aux charges piégées) peut être aussi élevée que la crête de surtension temporaire. L'écoulement de ces charges piégées dépend des matériels restant connectés à la ligne, de la conductivité superficielle des isolateurs, des conditions d'effet couronne sur les conducteurs et de l'instant de refermeture.

Dans les réseaux habituels, le réenclenchement monophasé (refermeture) ne génère pas de surtensions plus importantes que celles dues au simple enclenchement. Pour les lignes dans lesquelles peuvent apparaître des effets de résonance ou Ferranti, une refermeture monophasée peut toutefois entraîner des surtensions plus importantes qu'un enclenchement triphasé.

Une fonction de répartition correcte des amplitudes de surtension ne peut être déterminée qu'à partir d'une simulation soignée des manœuvres obtenue par calcul informatique, analyseur de transitoires, etc., et il convient de considérer les valeurs classiques (celles données à la Figure 1, par exemple) à titre purement indicatif. Toutes les considérations concernent les surtensions à l'extrémité ouverte (côté aval) de la ligne. Les surtensions à l'entrée peuvent être sensiblement plus faibles. Pour les raisons données à l'Annexe C, la Figure 1 peut être utilisée à la fois pour la méthode valeur crête par phase et la méthode valeur crête par cas.

4.3.3.2.2 Surtensions phase-terre

Une méthode d'estimation de la fonction de répartition de surtensions représentatives est donnée à l'Annexe C.

À titre indicatif, la Figure 1 donne la plage des valeurs de surtension à 2 % (en p.u. de $U_s \sqrt{2}/\sqrt{3}$) qui peut être prévue entre phase et terre, sans la limitation provenant de parafoudres [5]. Les données de la Figure 1 s'appuient sur de nombreux retours d'expérience et études. Elles incluent les effets de la plupart des facteurs déterminant les surtensions.

Il convient d'utiliser la Figure 1 comme une indication pour déterminer si, dans une situation donnée, les surtensions peuvent être suffisamment élevées pour poser problème. Si c'est le cas, la plage de valeurs indique dans quelle mesure les surtensions peuvent être limitées. À cet effet, il serait nécessaire de réaliser des études détaillées.

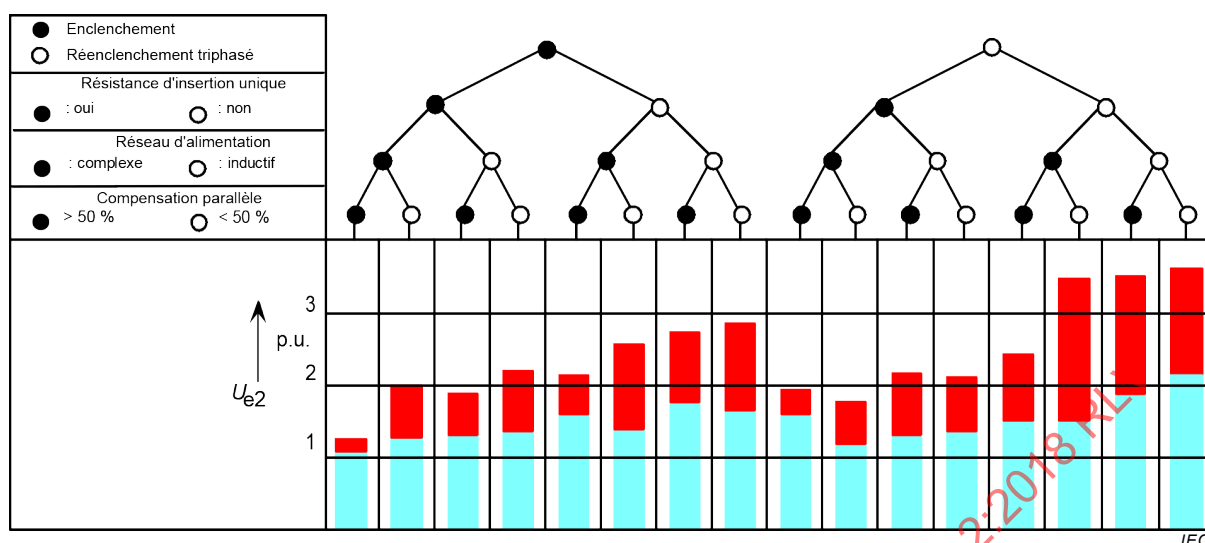


Figure 1 – Plages de valeurs à 2 % des surtensions à front lent côté aval dues à l'enclenchement ou au réenclenchement de ligne

4.3.3.2.3 Surtensions entre phases

L'évaluation des surtensions entre phases nécessite de tenir compte d'un paramètre supplémentaire. Étant donné que l'isolement est sensible à la répartition d'une valeur donnée de surtension entre phases en deux composantes phase-terre, le choix d'un instant spécifique doit tenir compte des caractéristiques de l'isolement. Deux instants ont été sélectionnés [1]:

- l'instant de la crête de surtension entre phases: il s'agit de l'instant auquel la valeur de la surtension entre phases est la plus élevée. Il représente la contrainte la plus importante pour toutes les configurations d'isolation dont la rigidité diélectrique entre phases n'est pas sensible à la répartition en composantes. L'isolation entre enroulements ou des faibles distances dans l'air sont des exemples types de cette situation;
- la surtension entre phases à l'instant de la crête de surtension phase-terre: même si cet instant donne habituellement des valeurs de surtension inférieures à celles existant lors de la crête de surtension entre phases, les valeurs en question peuvent être plus critiques pour toutes les configurations d'isolation dont la rigidité diélectrique entre phases est influencée par la répartition en composantes. Des distances dans l'air importantes, pour lesquelles l'instant de la crête positive phase-terre est le plus critique, ou des postes (sous enveloppe métallique) à isolation gazeuse (sous enveloppe triphasée), pour lesquels la crête négative est la plus critique, constituent des exemples types de cette situation.

Les caractéristiques statistiques des surtensions entre phases et les relations entre les valeurs relevant de ces deux instants sont décrites à l'Annexe C. Il en est déduit que la surtension représentative entre phases est égale à la crête de surtension entre phases pour tous les types d'isolations, sauf pour les distances dans l'air relevant de la plage II. Pour ces dernières, et plus particulièrement pour les réseaux dont la tension est supérieure ou égale à 500 kV, il convient de déterminer la surtension représentative entre phases à partir des crêtes de surtension phase-terre et entre phases (voir l'Annexe C).

La valeur de surtension entre phases à 2 % peut être approximativement déterminée à partir de la surtension phase-terre. La Figure 2 donne la plage de valeurs possibles des rapports entre les valeurs à 2 % entre phases et phase-terre. La limite haute de cette plage correspond aux surtensions de réenclenchement triphasé rapide, la limite basse correspondant aux surtensions d'enclenchement triphasé.

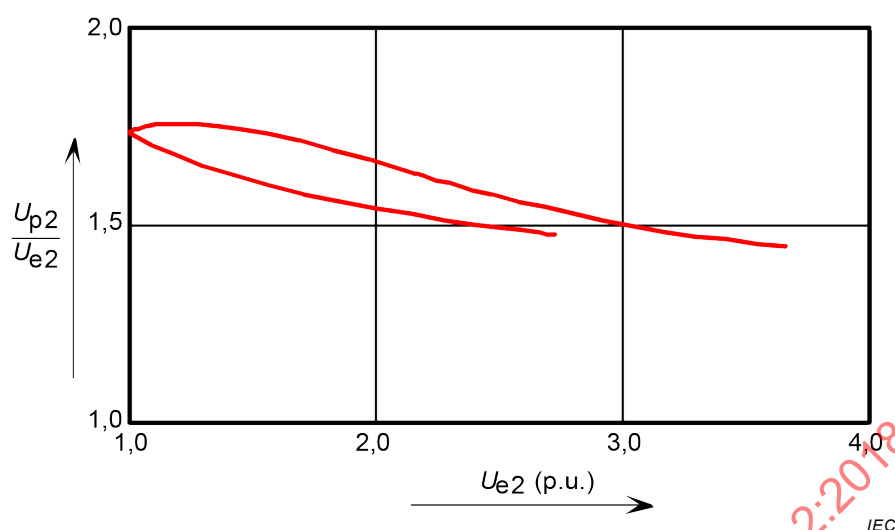


Figure 2 – Rapport entre les valeurs à 2 % des surtensions à front lent entre phases et phase-terre

4.3.3.2.4 Surtensions longitudinales

Les surtensions longitudinales entre bornes lors d'un enclenchement ou d'un réenclenchement se composent de la tension de régime permanent sur une borne et de la surtension de manœuvre sur l'autre. Sur les réseaux synchronisés, la crête de surtension de manœuvre la plus élevée et la tension de service ont la même polarité, et la surtension de l'isolation longitudinale est inférieure à celle de l'isolation phase-terre.

En revanche, une isolation longitudinale entre deux réseaux non synchronisés peut être soumise à des surtensions d'enclenchement sur une borne et à une crête de tension de service normale de polarité opposée sur l'autre.

Pour la composante de surtension à front lent, les mêmes principes que pour l'isolation phase-terre sont applicables.

4.3.3.2.5 Surtensions maximales présumées

Si aucune protection par des parafoudres n'est fournie, la surtension maximale présumée en cas d'enclenchement ou de réenclenchement est la suivante:

- pour la surtension phase-terre, la valeur de troncature U_{et} ;
- pour la surtension entre phases, la valeur de troncature U_{pt} ou, pour une isolation externe dans la plage II, la valeur déterminée selon l'Annexe C. Ces deux valeurs se décomposent en deux composantes égales, de polarités opposées;
- pour la surtension longitudinale, il s'agit de la valeur de troncature U_{et} de la surtension phase-terre due à la mise sous tension sur une borne et la crête de polarité opposée de la tension de service normale (de polarité opposée) sur l'autre borne.

Cette définition de la surtension longitudinale maximale part du principe que les fréquences industrielles sont synchronisées (via une liaison parallèle) sur les deux bornes, de façon à ne pas avoir à examiner séparément les surtensions dues au réenclenchement (l'effet d'une charge piégée étant pris en considération par cette hypothèse).

4.3.3.3 Surtensions survenant lors d'un défaut et de son élimination

Lors de l'apparition et de l'élimination d'un défaut, des surtensions à front lent apparaissent lorsque la tension passe de la tension de service à une surtension temporaire sur les phases saines, et au retour, depuis une valeur proche de zéro à la tension de service sur la phase

défaillante. Dans les deux cas, il n'y a surtensions qu'entre phase et terre. Les surtensions entre phases peuvent être ignorées. Calculée au plus juste, l'estimation de la valeur maximale présumée de la surtension représentative U_{et} est la suivante:

– apparition du défaut $U_{et} = (2k - 1) U_s \sqrt{2/\sqrt{3}}$ (kV crête)

où k est le facteur de défaut à la terre.

– élimination du défaut $U_{et} = 2,0 U_s \sqrt{2/\sqrt{3}}$ (kV crête)

Dans la plage I, les surtensions causées par des défauts à la terre doivent être prises en considération sur les réseaux dans lesquels le neutre des transformateurs est isolé ou compensé par bobine d'extinction. Le facteur de défaut à la terre est alors approximativement égal à $\sqrt{3}$. Sur ces réseaux, la coordination de l'isolement peut se fonder sur la surtension maximale présumée, et il n'est pas nécessaire de tenir compte de la probabilité d'occurrence des amplitudes de surtension.

Dans la plage II, lorsque les surtensions dues à un enclenchement ou à un réenclenchement sont limitées à des valeurs inférieures à 2 p.u., les surtensions survenant lors de défauts et de leur élimination doivent être examinées avec soin si elles ne sont pas contrôlées au même point.

4.3.3.4 Surtensions dues à une perte de charge

Les surtensions à front lent dues à une perte de charge n'ont d'importance que dans les réseaux de la plage II, sur lesquels les surtensions dues à un enclenchement ou à un réenclenchement sont limitées à des valeurs inférieures à 2 p.u. Dans ces cas, il faut examiner la question, en particulier en présence de transformateurs principaux ou de longues lignes de transport.

4.3.3.5 Surtensions dues à la coupure de courants inductifs et capacitifs

La coupure de courants capacitifs et inductifs peut donner lieu à des surtensions qui méritent attention. Il convient en particulier de tenir compte des manœuvres suivantes:

- coupure de courants de démarrage des moteurs;
- coupure de courants inductifs, par exemple lors de la coupure du courant magnétisant d'un transformateur ou d'une inductance shunt [6];
- manœuvre et fonctionnement de fours à arc et de leurs transformateurs, ces manœuvres pouvant entraîner un arrachement du courant;
- manœuvre de câbles à vide et de batteries de condensateurs;
- coupure de courants par des fusibles haute tension.

Le réamorçage des disjoncteurs lors de la coupure de courants capacitifs (manœuvre de lignes ou de câbles à vide ou de batteries de condensateurs) peut entraîner des surtensions particulièrement dangereuses, aussi l'utilisation des disjoncteurs sans réamorçage est nécessaire. De plus, au moment de mettre sous tension des batteries de condensateurs, en particulier si elles ne sont pas reliées à la terre, il convient d'évaluer avec soin les surtensions entre phases (voir aussi 4.3.4.3).

4.3.3.6 Surtensions de foudre à front lent

Sur les réseaux comportant de longues lignes (supérieures à 100 km), les coups de foudre tombant à distance sur les conducteurs de phase entraînent des surtensions de foudre à front lent, lorsque le courant de foudre est suffisamment faible pour ne pas entraîner de contournement de l'isolation de la ligne, et lorsque la distance est suffisamment importante pour donner lieu à un front lent.

Étant donné que la durée jusqu'à la mi-valeur des courants de foudre dépasse rarement 200 μ s, il ne se produit pas de surtension de forte amplitude et présentant des durées jusqu'à la crête critique pour l'isolation. Les surtensions de foudre à front lent jouent donc un rôle mineur dans la coordination de l'isolement et sont généralement négligées.

4.3.3.7 Limitation des surtensions à front lent

La méthode la plus couramment utilisée pour limiter les surtensions de manœuvre sur les lignes consiste à utiliser des résistances de fermeture sur les coupeurs de lignes. D'autres moyens (le contrôle électronique de la fermeture et les varistances en parallèle sur les chambres de coupure, par exemple) peuvent aussi être utilisés pour limiter les surtensions à l'enclenchement d'une ligne et à la coupure de courants inductifs ou capacitifs.

Les transformateurs de tension inductifs raccordés aux bornes de lignes réduisent efficacement les charges piégées sur les phases d'une ligne après l'ouverture. Les surtensions à front lent dues à un réenclenchement triphasé ultérieur sont ainsi limitées au niveau d'un simple enclenchement de ligne.

L'effet de saturation de la tenue aux chocs de manœuvre a un impact important sur les distances dans l'air. Les résistances de fermeture et d'ouverture, les parafoudres et/ou la manœuvre commandée peuvent réduire les surtensions de manœuvre.

4.3.3.8 Protection contre les surtensions à front lent au moyen de parafoudres

Les parafoudres à oxyde métallique sans éclateurs et les parafoudres à éclateurs spécialement conçus fournissent une protection appropriée contre les surtensions à front lent sur les réseaux présentant des surtensions temporaires modérées, alors que les parafoudres à résistance variable ne fonctionnent que dans les cas extrêmes de surtensions à front lent, du fait des caractéristiques d'amorçage des éclateurs en série.

NOTE Lorsque les parafoudres sont installés aux extrémités de longues lignes de transport dans le but de limiter les surtensions à front lent, les surtensions au milieu de ces lignes peuvent être nettement supérieures à celles rencontrées aux extrémités.

En règle générale, il peut être estimé que les parafoudres à oxyde métallique limitent l'amplitude des surtensions phase-terre (kV crête) à environ deux fois la tension assignée du parafoudre (kV en valeur efficace). En d'autres termes, les parafoudres à oxyde métallique sont appropriés pour limiter les surtensions à front lent dues à l'enclenchement et au réenclenchement de ligne et à la coupure de courants inductifs et capacitifs. En revanche, ils ne permettent généralement pas de limiter les surtensions causées par des défauts à la terre et leur élimination, dans la mesure où les amplitudes présumées de ces dernières sont trop faibles (à l'exception éventuelle du cas de défauts sur les lignes compensées série).

Les surtensions dues aux enclenchements et réenclenchements de lignes produisent des courants circulant à travers les parafoudres inférieurs à environ 0,5 kA à 2 kA (voir IEC 60099-4). Dans cette plage de courant, il n'est pas essentiel de connaître l'amplitude exacte du courant, du fait de l'extrême variabilité du matériau à oxyde métallique. Le comportement des parafoudres à oxyde métallique dépend peu des durées de front du courant pour les surtensions à front lent et ce point peut également être négligé. En outre, il n'est pas nécessaire de tenir compte de l'effet de séparation à l'intérieur des postes. Cependant, certaines surtensions nettement supérieures au niveau de protection peuvent venir contraindre l'isolation des lignes aériennes en des points éloignés.

Les parafoudres sont généralement installés entre phase et terre et il convient d'observer que, si des parafoudres à oxyde métallique sont utilisés pour limiter des surtensions à front lent à un niveau inférieur à 70 % de la valeur à 2 % de la surtension phase-terre présumée, les surtensions entre phases peuvent atteindre une valeur égale à environ deux fois le niveau de protection du parafoudre entre phase et terre. La surtension entre phases sera alors constituée de deux composantes phase-terre le plus souvent également réparties [7]. Voir également 5.3.4.1.

La valeur maximale présumée de la surtension représentative phase-terre est égale au niveau de protection du parafoudre: $U_{rp} = U_{ps}$.

Pour les surtensions entre phases, elle est égale à deux fois le niveau de protection ou deux fois la valeur de troncature des surtensions entre phases déterminées à l'Annexe C, selon la valeur la plus faible. Si des surtensions entre phases inférieures sont exigées, il convient d'installer des parafoudres supplémentaires entre phases.

Dans tous les cas, l'utilisation de parafoudres pour limiter les surtensions à front lent doit prendre en considération, pour le choix de la classe du parafoudre appropriée, le cycle de service exigé et les exigences de dissipation d'énergie.

4.3.4 Surtensions à front rapide

4.3.4.1 Surtensions de foudre sur les lignes aériennes

Les surtensions de foudre sont provoquées par des coups de foudre directs sur les conducteurs de phase, par des amorçages en retour ou sont induites par des coups de foudre au sol tombant à proximité de la ligne. Les ondes de foudre induites sont généralement à l'origine de surtensions inférieures à 400 kV sur une ligne aérienne et ne présentent donc d'importance que pour les réseaux de la plage de tensions la plus faible. Du fait de la tenue élevée de l'isolation, les amorçages en retour sont moins fréquents dans la plage II que dans la plage I et sont rares sur les réseaux de 500 kV ou plus.

La forme représentative de la surtension de foudre est la tension normalisée de choc de foudre (1,2/50 μ s). L'amplitude représentative est donnée soit sous la forme d'une valeur maximale présumée soit sous la forme d'une fonction de répartition de valeurs de crête, souvent présentée comme étant la valeur de crête dépendante du taux de retour des surtensions.

4.3.4.2 Surtensions de foudre dans les postes

4.3.4.2.1 Généralités

Les surtensions de foudre dans un poste et leur fréquence d'apparition dépendent de

- la performance vis-à-vis de la foudre des lignes aériennes qui y sont raccordées,
- la disposition du poste, sa taille et en particulier le nombre de lignes qui y sont raccordées, et
- la valeur instantanée de la tension de service (au moment du coup de foudre).

L'importance des surtensions de foudre sur les équipements du poste est déterminée par la combinaison de ces trois facteurs, et il est nécessaire de passer par différentes étapes pour s'assurer que la protection est adaptée. L'amplitude des surtensions (sans limitation par un parafoudre) est généralement trop élevée pour établir la coordination de l'isolement sur ces valeurs. Cependant, dans certains cas, et en particulier avec les postes avec câble raccordé, l'effet d'autoprotection dû à la faible impédance d'onde des câbles peut réduire les amplitudes des surtensions de foudre à des valeurs suffisamment basses (voir l'Annexe E).

Pour l'isolement entre phases et l'isolement longitudinal, la valeur instantanée de la tension à la fréquence industrielle sur les bornes opposées doit être prise en considération. Pour l'isolement entre phases, il peut être pris pour hypothèse que les effets de la tension à fréquence industrielle et le couplage entre les conducteurs de la ligne aérienne s'annulent, et il peut être considéré que les bornes opposées sont mises à la terre. Cependant, pour l'isolement longitudinal, ces effets ne s'annulent pas et la tension à fréquence industrielle doit être prise en considération.

4.3.4.2.2 Coups de foudre directs

Les défauts d'écran peuvent intervenir de façon aléatoire en un point quelconque de la courbe de tension à la fréquence industrielle. L'effet de la fréquence industrielle à la borne opposée d'une isolation longitudinale doit être prise en considération en

- calculant les taux de retour des surtensions de foudre pour différentes valeurs instantanées de la tension de service,
- évaluant la probabilité de défaut d'isolement pour les différentes décompositions en composantes – en général, le paramètre déterminant est la somme des deux composantes,
- déterminant le taux de défaut d'isolement en fonction de la somme de la surtension de foudre et de la valeur instantanée de la fréquence industrielle, et
- appliquant le critère de performance à ce taux de défaillance prévisible pour obtenir la somme nécessaire des deux composantes.

Si cette somme se décompose en une composante de choc de foudre égale à la surtension de foudre représentative phase-terre et une composante à fréquence industrielle, la composante de la tension à fréquence industrielle sera inférieure à la crête de la tension de service phase-terre. Il a été déterminé qu'un facteur 0,7 pouvait être adéquat. Cela signifie que, pour les défauts d'écran, il convient que la surtension longitudinale représentative soit composée de la surtension de foudre représentative à la terre sur une borne et 0,7 fois la valeur de crête de la tension de service phase-terre avec la polarité opposée sur l'autre borne.

4.3.4.2.3 Amorçages en retour

Les amorçages en retour se produisent de préférence sur la phase dont la valeur de la tension à fréquence industrielle instantanée est la plus élevée, en polarité opposée. Cela signifie que, pour les postes, la surtension de foudre longitudinale représentative doit être égale à la somme de la surtension de foudre représentative à la terre sur une borne et de la valeur de crête de la tension de service sur l'autre borne (polarité opposée).

4.3.4.3 Surtensions dues à des manœuvres et à des défauts

Les surtensions de manœuvre à front rapide se produisent lorsque le matériel est connecté au réseau ou déconnecté par l'intermédiaire des connexions courtes principalement à l'intérieur de postes. Des surtensions à front rapide peuvent également se produire en cas de contournement d'une isolation externe. Ces cas peuvent provoquer des contraintes particulièrement sévères sur des isolations internes proches (des enroulements, par exemple).

Même s'il s'agit en général de phénomènes oscillatoires, pour les besoins de la coordination de l'isolement, il peut être considéré que la forme représentative de la surtension correspond à la tension normalisée de choc de foudre (1,2/50 μ s). Cependant, il convient d'accorder une attention particulière aux matériels équipés d'enroulements à cause des contraintes importantes entre spires.

Les valeurs de crête maximales des surtensions dépendent de la nature et du comportement du matériel de connexion. Les valeurs de crête des surtensions étant habituellement inférieures à celles provoquées par la foudre, elles n'ont d'importance que dans des circonstances particulières. Il est donc techniquement justifié de caractériser l'amplitude de la surtension représentative par les valeurs maximales suivantes (en p.u. de $U_s \sqrt{2/\sqrt{3}}$):

- manœuvre de disjoncteur sans réamorçage: 2 p.u.;
- manœuvre de disjoncteur avec réamorçage: 3 p.u.;

NOTE Lors de la manœuvre de charges réactives, certaines catégories de disjoncteurs moyenne tension ont tendance à produire plusieurs coupures de courant transitoires, qui entraînent des surtensions jusqu'à 6 p.u. en l'absence de protections appropriées.

- manœuvre de sectionneurs: 3 p.u.

Sachant que l'apparition simultanée de surtensions de manœuvre à front rapide sur plusieurs phases est très improbable, l'absence de surtensions entre phases supérieures aux surtensions phase-terre peut être admise. Pour ce qui est de ces dernières, les valeurs maximales présumées indiquées ci-dessus peuvent être utilisées pour contrôler l'importance de ces surtensions. Si la valeur obtenue est déterminante pour la tension de tenue au choc de foudre, il est recommandé d'étudier plus précisément la question.

4.3.4.4 Limitation du nombre de surtensions à front rapide

Le nombre de surtensions de foudre peut être limité par une conception appropriée de la ligne aérienne. Selon l'origine de ces surtensions, les moyens suivants sont utilisés:

- pour les coups de foudre directs sur des conducteurs: un blindage approprié du câble de garde;
- pour les amorçages en retour: la réduction de l'impédance de mise à la terre du pylône ou le renforcement de l'isolation;
- l'utilisation des parafoudres de ligne.

Dans certains cas, à proximité des postes, des consoles mises à la terre ou des éclateurs ont été utilisés pour limiter l'amplitude des surtensions de foudre incidentes. Cependant, de telles mesures tendent à augmenter le risque d'amorçage près du poste, ce qui génère par conséquent des ondes à front rapide. Par ailleurs, il convient de porter un soin particulier au blindage et à la mise à la terre des pylônes près du poste pour limiter la probabilité d'amorçage en retour à cet endroit.

Les pylônes de la plage II étant plus hauts et leurs distances interphases étant plus longues que celles des pylônes de la plage I, il convient que les coups de foudre directs sur les conducteurs de phase soit un sujet de préoccupation dans la plage II, même en présence d'un câble de garde, et plus particulièrement sur les réseaux de plus de 550 kV.

La sévérité des surtensions à front rapide dues aux manœuvres peut être limitée grâce au choix d'un matériel de connexion approprié (interrupteurs ou disjoncteurs sans réamorçage, caractéristiques de faible arrachement du courant, utilisation de résistance d'ouverture ou de fermeture, maîtrise de l'instant de manœuvre, etc.).

4.3.4.5 Protection contre les surtensions à front rapide au moyen de parafoudres

La protection fournie par les parafoudres contre les surtensions à front rapide dépend

- de l'amplitude et de la forme de la surtension,
- de la caractéristique de protection du parafoudre,
- de l'amplitude et de la forme du courant dans le parafoudre,
- de l'impédance et/ou de la capacité du matériel protégé,
- de la distance entre le parafoudre et le matériel protégé, y compris les connexions de mise à la terre (voir la Figure 3), et
- du nombre et de l'impédance d'onde des lignes raccordées.

Pour la protection contre les surtensions de foudre, des parafoudres présentant les courants de décharge suivants sont généralement utilisés:

- pour les réseaux dont U_m est dans la plage I: 5 kA ou 10 kA;
- pour les réseaux dont U_m est dans la plage II: 10 kA ou 20 kA.

Si le parafoudre est censé être traversé par des courants supérieurs au courant de décharge nominal, il faut s'assurer que les tensions résiduelles correspondantes permettent encore de limiter les surtensions de manière appropriée.

Pour déterminer l'absorption d'énergie (due à la foudre) des parafoudres installés dans le poste, il est généralement suffisant de partir du principe que l'amplitude représentative de la surtension de foudre prévisible est égale à la tension de tenue au choc de foudre 50 % négative de la ligne aérienne. Cependant, pour l'absorption d'énergie totale, il convient de considérer qu'un éclair peut être composé de plusieurs coups.

Les caractéristiques de protection d'un parafoudre ne sont valables que pour l'emplacement où il est situé. Il convient donc que la limitation de surtension correspondante à l'emplacement du matériel à protéger dépende de la distance entre ces deux points. Plus la distance est grande entre le parafoudre et le matériel protégé, moins la protection de ce matériel est efficace, et, en fait, la surtension dont fait l'objet un matériel augmente au-dessus du niveau de protection du parafoudre lorsque cette distance de séparation s'allonge. En outre, si l'effet dû à la longueur du parafoudre est négligé pour déterminer ses caractéristiques de protection, cette longueur doit être ajoutée à celle des connexions pour évaluer la limitation de surtension effective. Pour les parafoudres à oxyde métallique sans éclateurs, le temps de réaction du matériau lui-même peut être ignoré et la longueur du parafoudre ajoutée à celle des connexions.

Pour une estimation simplifiée de la surtension représentative au niveau de l'objet protégé, l'Équation (1) peut être utilisée. Cependant, pour la protection des transformateurs, il convient d'utiliser l'Équation (1) avec précaution car une capacité supérieure à quelques centaines de picofarads peut provoquer des surtensions supérieures.

$$U_{rp} = U_{pl} + 2St_s \quad \text{pour } U_{pl} \geq 2St_s \quad (1)$$

$$U_{rp} = 2 U_{pl} \quad \text{pour } U_{pl} < 2St_s \quad (2)$$

où

U_{pl} est le niveau de protection en onde de foudre du parafoudre (kV);

S est la pente de l'onde incidente (kV/ μ s);

t_s est le temps de parcours de l'onde de foudre déterminé comme suit:

$$t_s = L / c \quad (3)$$

où

c est la vitesse de la lumière (300 m/ μ s);

L est la somme de a_1 , a_2 , a_3 et a_4 (distances de la Figure 3 [m]).

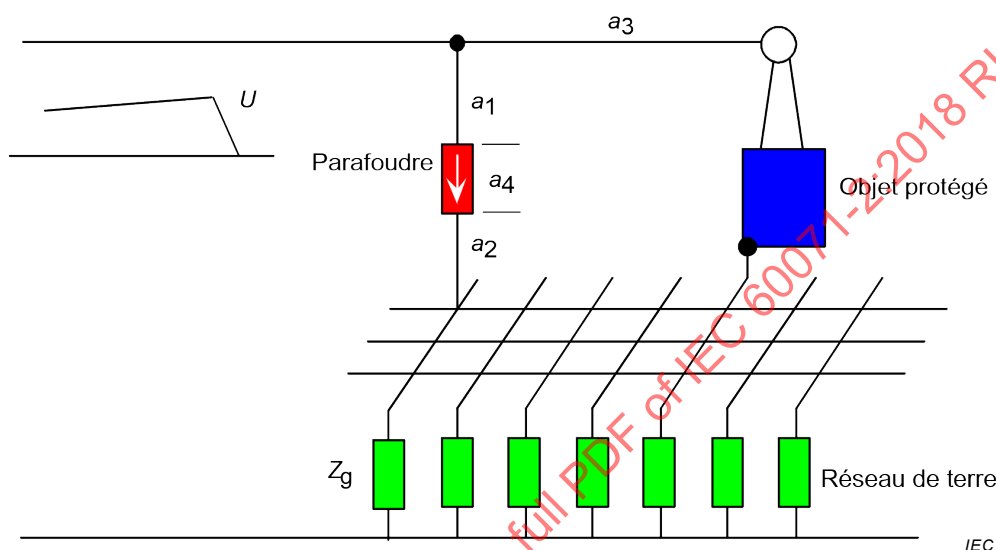
La valeur de la pente doit être choisie en fonction de la performance vis-à-vis de la foudre de la ligne aérienne raccordée au poste et du risque de défaillance retenu pour le poste. Un développement complet est donné dans l'Annexe E.

La fonction de répartition de l'amplitude de surtension de foudre représentative dans le poste peut être déterminée par des calculs de surtensions transitoires prenant en compte la performance vis-à-vis de la foudre des lignes de transport, du comportement des ondes progressives sur les lignes aériennes et dans le poste et la performance de l'isolation du matériel et des parafoudres en fonction de l'amplitude et de la forme d'onde de la surtension. Des références sont fournies à l'Annexe E.

À titre d'indication d'ordre général, pour déterminer les amplitudes représentatives, il convient également de prendre en considération la corrélation entre la tenue de l'isolation et la forme de la surtension. Cela concerne particulièrement les isolations externes et les isolations huile-papier, pour lesquelles la courbe tension-temps de l'isolation peut conduire à des amplitudes représentatives sensiblement plus basses que la valeur de crête des surtensions. Pour les GIS ou les isolations solides, cette différence est négligeable et l'amplitude de la surtension représentative est égale à la crête de surtension.

Une méthode simplifiée pour estimer la fonction de répartition d'amplitude de la surtension de foudre représentative est donnée à l'Annexe E. La valeur maximale présumée de l'amplitude de surtension de foudre représentative est soit la valeur de troncature de la fonction de répartition, soit une valeur résultant de l'expérience sur des réseaux existants. L'Annexe E présente également des méthodes pour estimer ces valeurs.

En général, une simulation numérique est utilisée. La modélisation numérique des installations et matériels électriques est devenue extrêmement précise, ce qui permet de calculer exactement les surtensions de foudre. Des recommandations techniques sont données dans l'IEC TR 60071-4.



Légende

- a_1 longueur de la liaison reliant le parafoudre à la ligne
- a_2 longueur de la liaison reliant le parafoudre à la terre
- a_3 longueur du conducteur de phase entre le parafoudre et le matériel protégé
- a_4 longueur de la partie active du parafoudre
- Z_g impédance de terre
- U surtension incidente

Figure 3 – Schéma du raccordement d'un parafoudre à l'objet protégé

4.3.4.6 Méthode d'évaluation de la forme de surtension de foudre non normalisée

Le stade relatif à la "surtension représentative" de la procédure de coordination de l'isolement est censé présenter une forme de tension normalisée, ce qui est particulièrement significatif pour un choc de foudre dans le cas d'une analyse détaillée par calcul informatique. À ce sujet, de récentes recherches ont permis d'analyser les surtensions de champ, de préciser les caractéristiques d'isolement des surtensions de champ réelles comparées à celles de la forme de tension normalisée dans la région temporelle du coup de foudre, et de proposer une méthode d'évaluation de surtension pour les GIS [14] et les transformateurs [15]. Ces techniques ont été développées par les groupes de travail du CIGRE et adoptées dans les brochures techniques [11], [16], [17].

La dégradation de la surtension de champ est en général importante, les exigences en matière d'isolation devenant alors moins strictes que celles relatives à la forme de tension normalisée. Par conséquent, dans certains cas, il pourrait être possible d'utiliser des tensions de tenue plus faibles (voir l'Annexe I).

4.3.5 Surtensions à front très rapide [13]

Les surtensions à front très rapide (VFFO) surviennent par suite du fonctionnement de sectionneurs ou par suite de défauts à l'intérieur de GIS en raison de l'amorçage rapide de l'isolation gazeuse et de la propagation de l'onde qui ne s'atténue pratiquement pas à l'intérieur des GIS. Leurs amplitudes sont rapidement amorties à la sortie du GIS (au niveau d'une traversée, par exemple) et leur durée de front augmente généralement jusqu'à atteindre celle des surtensions à front rapide.

La forme de surtension présente une augmentation rapide de la tension, atteignant presque sa valeur de crête, avec une durée de front inférieure à 0,1 μ s. Ce front est généralement suivi d'une oscillation avec des fréquences supérieures à 1 MHz. Les composantes de fréquence dominantes peuvent atteindre quelques dizaines de MHz.

En cas de manœuvre d'un sectionneur, l'amplitude de la surtension à front très rapide dépend de la conception du sectionneur et de la configuration du poste. Dans le cas le moins favorable, l'amplitude maximale de la surtension à front très rapide peut atteindre 2,8 p.u.

Une surtension à front très rapide due à des défauts dans le GIS peut présenter des amplitudes atteignant 1,6 fois les tensions d'amorçage.

Une surtension à front très rapide dans des réseaux UHT peut s'avérer dangereuse pour l'isolation du GIS, des transformateurs et des transformateurs de tension. La forme et l'amplitude de la surtension dépendent de la nature de la connexion du matériel au GIS.

Une surtension représentative ne peut être déterminée en l'absence de méthodes normalisées acceptables. L'expérience a montré que les surtensions à front très rapide n'ont aucune influence sur le choix des tensions de tenue assignées jusqu'à des tensions de réseau de 800 kV.

Il faut particulièrement veiller aux transitoires très rapides dans le GIS ou les réseaux UHT. En raison de la diminution du rapport de la tension de tenue au choc de foudre sur la tension du réseau, la surtension à front très rapide peut devenir la contrainte diélectrique de limitation définissant les dimensions du GIS. La manière de gérer cette situation et les mesures d'atténuation en matière de coordination de l'isolement sont décrites à l'Annexe J.

5 Tension de tenue de coordination

5.1 Caractéristiques de résistance d'isolement

5.1.1 Généralités

Dans tous les matériaux, la conductivité est due à la migration de particules chargées. Les conducteurs contiennent un grand nombre d'électrons relativement libres qui sont entraînés lorsqu'un champ électrique est appliqué, alors que les isolants n'ont qu'un très petit nombre d'électrons libres. Si la contrainte électrique dans un milieu isolant augmente à un niveau suffisamment élevé, la résistivité dans ce milieu passe d'une valeur élevée à une valeur comparable à celle des conducteurs. Ce changement est appelé amorçage.

L'amorçage se décompose en trois principales étapes:

- l'ionisation initiale en un ou plusieurs points;
- l'extension d'un canal ionisé à travers l'intervalle;
- le franchissement de l'intervalle et le passage à une décharge autoentretenue.

Un certain nombre de facteurs influent sur la tenue diélectrique de l'isolation. Ces facteurs sont les suivants:

- l'amplitude, la forme, la durée et la polarité de la tension appliquée;
- la répartition du champ dans l'isolant: champ électrique uniforme ou non, électrodes adjacentes à l'intervalle considéré et leur potentiel;
- le type d'isolant: gazeux et/ou liquide et/ou solide; les impuretés et les irrégularités locales;
- l'état physique de l'isolation: température, pression et autres conditions ambiantes, contraintes mécaniques. L'histoire de l'isolant peut aussi avoir une importance;
- la déformation de l'isolation sous contrainte, les effets chimiques, les effets de surface des conducteurs, etc.

L'amorçage dans l'air dépend pour une large mesure de la configuration de l'intervalle, de la polarité et de la forme d'onde de la contrainte de tension appliquée. De plus, les conditions atmosphériques relatives ont un impact sur l'amorçage, quelles que soient la forme et la polarité de la contrainte appliquée. Les caractéristiques concernant la tenue dans l'air issues de mesures en laboratoire sont appelées conditions atmosphériques de référence normalisées (voir l'IEC 60060-1):

- température : 20 °C;
- pression : 1 013 hPa (1 013 mbar);
- humidité absolue : 11 g/m³.

Des mesurages en laboratoire ont également été réalisés en conditions non normalisées: faible densité de l'air, humidité relative importante, pollution, glace et neige, températures élevées et présence de particules de combustion.

Pour l'isolation extérieure, les effets de la densité de l'air, de l'humidité, de la pluie et de la pollution de surface deviennent particulièrement importants. L'IEC 60060-1 définit les procédures d'essai en atmosphère sèche et humide. Pour l'isolation gazeuse interne (poste (sous enveloppe métallique) à isolation gazeuse, par exemple), la pression et la température internes, ainsi que les irrégularités et impuretés locales jouent un rôle important.

Dans les isolations liquides, les impuretés solides, les bulles provoquées par des réactions chimiques ou physiques ou par des décharges locales peuvent réduire sévèrement la résistance d'isolement. Il est également important de noter que la dégradation chimique de l'isolation peut avoir tendance à s'aggraver avec le temps. Il en va de même pour les isolations solides. Leur rigidité diélectrique peut être affectée par des contraintes mécaniques.

Il convient de tenir compte de la nature statistique du processus d'amorçage. En raison de la caractéristique de restauration de l'isolation autorégénératrice, le comportement statistique de sa tenue peut être déterminé par des essais appropriés. C'est pourquoi les isolations autorégénératrices sont caractérisées par la tension de tenue statistique correspondant à une probabilité de tenue de 90 %. Pour les isolations non autorégénératrices, il n'est généralement pas possible au moyen d'essais de déterminer la nature statistique de la rigidité diélectrique. Alors, la tension de tenue présumée est réputée correspondre à une probabilité de tenue de 100 % (voir définition 3.23 de l'IEC 60071-1:2006).

Le vent exerce une influence sur la conception des isolations, notamment dans le cas des lignes aériennes équipées de chaînes de suspension. Généralement, cette influence n'est prise en considération que pour déterminer la longueur des intervalles d'air sur la base de la tenue à la fréquence industrielle et aux chocs de manœuvre.

Les paragraphes 5.1.2 à 5.1.5 donnent des informations sur les différents facteurs qui influent sur le comportement d'une isolation. Pour de plus amples informations, la brochure technique CIGRE [4] peut être consultée.

5.1.2 Influence de la polarité et des formes de surtension

5.1.2.1 Influence de la polarité de la surtension

Avec la géométrie des électrodes généralement rencontrées dans les applications à haute tension, la contrainte est dans la plupart des cas plus grande sur un conducteur sous tension que sur un conducteur mis à la terre. Pour l'isolation par l'air, si l'électrode la plus contrainte est positive, la tension d'amorçage de l'intervalle sera plus basse que si l'électrode la plus contrainte est négative. Cela tient au fait que le phénomène d'ionisation se développe plus facilement sous contrainte positive que négative.

Si la contrainte est équivalente sur les deux électrodes, les deux processus de décharge sont en jeu, avec à la fois les caractéristiques propres aux polarités positives et celles aux polarités négatives. S'il est évident qu'une polarité est plus sévère pour un système d'isolation ou une configuration d'électrodes donné(e), la conception s'appuiera sur cette polarité. Sinon, les deux polarités doivent être prises en considération.

5.1.2.2 Influence de la forme de surtension

Sous contrainte impulsionnelle, la tension d'amorçage dépend aussi en général de la forme de l'impulsion.

Pour les chocs à front lent, la tenue diélectrique de l'isolation externe dépend davantage du front du choc que de sa queue. Cette dernière ne devient vraiment importante qu'en cas de pollution sur la surface de l'isolation externe. La tenue diélectrique d'une isolation interne est censée ne dépendre que de la valeur de crête.

Dans le cas de l'isolation externe, il est courant de considérer qu'à chaque longueur d'intervalle correspond une durée jusqu'à la crête de choc pour laquelle la tension d'amorçage a une valeur minimale (durée de front critique). Généralement, le minimum se situe dans la plage des durées de front qui est typique des surtensions à front lent. Plus la longueur de l'intervalle est grande, plus le minimum est prononcé. Pour les distances de la plage I, l'effet est négligeable et peut être ignoré. Pour les distances dans l'air de la plage II, cette tension d'amorçage minimale est à peu près égale à la tension de claquage pour la durée normalisée jusqu'à la crête de 250 μ s. Cela signifie que l'emploi de la tension de tenue de l'isolation à la forme de tension normalisée 250/2 500 μ s aboutit à une conception prudente de l'isolement pour les surtensions à front lent. Pour certains réseaux, sur lesquels les surtensions à front lent ont des fronts beaucoup plus longs que la valeur normalisée, il peut être avantageux d'utiliser la résistance d'isolement plus élevée à ces valeurs de front.

La tension de claquage de l'isolation externe à la contrainte de choc de foudre diminue au fur et à mesure de l'augmentation du temps de queue. Pour les tensions de tenue, cette diminution est négligée, et la tension d'amorçage est censée être la même que celle de la tension normalisée de choc de foudre à 1,2/50 μ s. Cependant, une réduction notable de l'isolation peut être obtenue (dans les postes à l'air libre protégés par des parafoudres, par exemple) lorsque la forme de la surtension de foudre et ses effets sur la résistance d'isolement sont pris en considération.

Les formes de surtension de foudre sont analysées et les caractéristiques d'isolement du gaz SF₆ et des éléments de transformateur à huile pour ces chocs réels sont clarifiées de manière à les transformer en forme de tension normalisée (voir 4.3.4.6).

5.1.3 Isolation entre phases et isolation longitudinale

La rigidité diélectrique de l'isolation entre phases et de l'isolation longitudinale dépend de la relation entre les deux composantes de tension aux deux bornes. Cette dépendance est très importante pour l'isolation externe dans la plage II ou dans les postes triphasés (sous enveloppe métallique) à isolation gazeuse.

Pour l'isolation externe dans la plage II, la réponse de l'isolation aux surtensions de manœuvre entre phases dépend de la valeur du coefficient α qui relie les composantes positive et négative de la contrainte de tension (voir l'Annexe C). Les essais destinés à vérifier la tension de tenue exigée doivent donc permettre de tenir compte de ce phénomène. La forme de surtension représentative normalisée dans l'IEC 60071-1 est une surtension constituée de deux composantes synchrones de polarité opposées, la composante positive étant un choc de manœuvre normalisé, et la composante négative étant un choc avec une durée jusqu'à la crête et une durée jusqu'à mi-valeur au moins aussi longue que celles de la composante positive. En conséquence, pour une isolation sensible à la valeur relative de ces deux composantes, l'amplitude réelle de la surtension doit être convertie en une amplitude représentative tenant compte des caractéristiques de l'isolation (voir 4.3.3.2 et l'Annexe C qui donne un exemple).

Pour l'isolation longitudinale, les composantes de tension sont déterminées par les surtensions représentatives (voir l'Article 4).

Les valeurs de l'écart type pour la résistance d'isolement phase-terre données en 5.1.5 peuvent également s'appliquer à la résistance de l'isolation externe entre phases ou de l'isolation longitudinale, lorsque la tension de contournement à 50 % est prise comme la somme des composantes appliquées aux deux bornes.

5.1.4 Influence des conditions climatiques sur l'isolation externe

Les tensions de contournement des entrefers dépendent de la teneur en humidité et de la densité de l'air. La résistance d'isolement augmente avec l'humidité absolue jusqu'à former une condensation à la surface des isolateurs. Elle diminue à mesure que la densité de l'air diminue. Une description détaillée des effets de la densité de l'air et de l'humidité absolue est donnée dans l'IEC 60060-1.

Pour déterminer la tension de tenue de coordination, il convient de garder à l'esprit que les conditions les plus sévères du point de vue de la rigidité diélectrique (c'est-à-dire une humidité absolue basse, une pression atmosphérique faible et une température élevée) ne sont généralement pas concomitantes. De plus, sur un site donné, les corrections applicables pour tenir compte des variations d'humidité et de température ambiante s'annulent. Par conséquent, l'estimation de la tenue diélectrique peut en général être fonction des conditions ambiantes moyennes du site. Les conditions atmosphériques extrêmes sur site nécessitent une prise en considération particulière.

Pour les isolateurs, il convient de tenir compte de la réduction éventuelle de la tension de tenue due à la présence de neige, de glace, de rosée ou de brouillard.

5.1.5 Probabilité de décharge disruptive de l'isolation

À l'heure actuelle, aucune méthode ne permet de déterminer la probabilité de décharge disruptive d'un élément unique d'isolation non autorégénératrice. Par conséquent, la probabilité de tenue est censée passer de 0 % à 100 % à la valeur définissant la tension de tenue.

Pour l'isolation autorégénératrice, la capacité de tenue aux contraintes diélectriques provoquées par l'application d'un choc de forme donnée peut en revanche être décrite en termes statistiques. Les méthodes qu'il faut appliquer pour déterminer la courbe de probabilité de tenue sont données dans l'IEC 60060-1. Pour une isolation donnée et pour des chocs de forme donnée et de valeurs de crête U différentes, une probabilité d'amorçage P peut être associée à chaque valeur possible U , établissant ainsi une relation $P = P(U)$. En général, P est une fonction monotone croissante de U . La courbe qui en résulte peut être définie par les trois paramètres suivants:

- a) U_{50} : correspondant à la tension à laquelle l'isolation a une probabilité de 50 % d'amorcer ou de résister;

- b) Z : écart type qui représente la dispersion des tensions de contournement. Il est défini comme étant la différence entre les tensions correspondant aux probabilités de contournement 50 % et 16 %, comme l'indique l'Équation (4):

$$Z = U_{50} - U_{16} \quad (4)$$

- c) U_{spec} : valeur de troncature. La tension maximale en dessous de laquelle une décharge disruptive n'est plus possible. Il n'est cependant pas possible de déterminer cette valeur à partir d'essais.

Généralement, la fonction P est donnée par une fonction mathématique (fonction de répartition) qui est entièrement décrite par les paramètres U_{50} , Z et U_{spec} . Dans la loi de Gauss, traditionnellement utilisée, la valeur U_{50} représente également la moyenne, et l'écart type est obtenu directement à partir de l'Équation (4). Le point de troncature est rarement pris en considération par souci de simplification.

Pour l'application de la méthode statistique à la coordination de l'isolement pour les surtensions à front lent, l'utilisation de la fonction de répartition modifiée de Weibull donnée par l'Équation (5) présente des avantages par rapport à la fonction gaussienne (avantages exposés à l'Annexe B). L'Équation (5) représente une fonction de répartition de Weibull dont les paramètres sont déterminés de façon à correspondre à une fonction de répartition gaussienne pour les probabilités de contournement 50 % et 16 % et pour réaliser la troncature de la répartition à $U_{50} - NZ$ (voir l'Annexe B).

$$P(U) = 1 - 0,5^{\left(1 + \frac{x}{N}\right)^{\gamma}} \quad (5)$$

où

x est le nombre d'écarts types correspondant à U ;

N est le nombre d'écarts types correspondant à la tension de troncature U_{spec} pour laquelle $P(U_{\text{spec}}) = 0$.

Et

$$x = (U - U_{50}) / Z$$

Pour un écart type sur la fonction de répartition gaussienne (pour $x = -1$), $P(U) = 0,16$ dans l'Équation (5). Si $N = 4$ est choisi, la valeur exacte de γ doit être 4,83 dans l'Équation (5). Arrondir cette valeur à $\gamma = 5$ n'entraîne pas d'erreur notable, ce qui permet de définir dans le présent document la fonction modifiée de Weibull par l'Équation (6).

$$P(U) = 1 - 0,5^{\left(1 + \frac{x}{4}\right)^5} \quad (6)$$

La Figure 4 représente cette fonction de Weibull modifiée avec la fonction de répartition gaussienne à laquelle elle correspond. La Figure 5 représente les mêmes fonctions de répartition avec des échelles gaussiennes.

Pour le calcul statistique des performances prévues en exploitation, il convient d'utiliser des données détaillées obtenues sur le terrain ou provenant d'essais en laboratoire. En l'absence de telles données, il est recommandé d'utiliser dans les calculs statistiques les écarts types suivants qui résultent d'un grand nombre d'essais:

- pour les chocs de foudre: $Z = 0,03 U_{50}$ (kV), et
- pour les chocs de manœuvre: $Z = 0,06 U_{50}$ (kV)

L'influence des conditions climatiques (voir 5.1.4) est prise en considération dans les valeurs des écarts types ci-dessus.

Dans l'IEC 60071-1, le paramètre U_{10} (obtenu à partir de l'Équation (5)) correspondant à la probabilité de tenue de 90 % est utilisé pour décrire la fonction de répartition de probabilité de tenue ainsi que l'écart type:

$$U_{10} = U_{50} - 1,3 Z \quad (7)$$

L'Annexe B contient des informations détaillées sur les équations statistiques à appliquer dans le cas où un grand nombre d'isolations identiques en parallèle subissent simultanément une contrainte.

L'Annexe F donne des recommandations sur la détermination de la résistance au claquage de l'isolation dans l'air pour les différentes catégories de surtensions.

5.2 Critère de performance

Selon la définition 3.22 de l'IEC 60071-1:2006, le critère de performance d'une isolation en service est le taux de défaillance admissible (R_a).

La performance de l'isolement d'un réseau est jugée sur la base du nombre de défauts d'isolement en service. Les défauts peuvent avoir des conséquences différentes selon l'endroit du réseau où ils se produisent. Par exemple, dans un réseau maillé, un défaut en ligne permanent ou la refermeture non réussie en raison de surtensions à front lent ne sont pas aussi graves qu'un défaut sur un jeu de barre ou que des défauts équivalents sur un réseau radial. Par conséquent, le taux de défaillance admissible dans un réseau peut varier d'un point à un autre selon les conséquences d'un défaut en chacun de ces points.

Les statistiques de défaut concernant les réseaux en service et les projets de conception tenant compte de ces statistiques fournissent des exemples de taux de défaillance admissibles. Pour le matériel, les taux de défaillance admissibles R_a dues à des surtensions se situent entre 0,001/an et 0,004/an en fonction du temps de réparation. Pour les lignes aériennes, les taux de défaillances admissibles dues à la foudre varient entre 0,1/100 km/an et 20/100 km/an (la valeur haute correspondant aux lignes de distribution). Les chiffres correspondants pour les taux de défaillances admissibles dues aux surtensions de manœuvre se situent entre 0,01 et 0,001 par manœuvre. Il convient que les valeurs pour des taux de défaillances admissibles se situent dans ces ordres de grandeur.

5.3 Procédures de coordination de l'isolement

5.3.1 Généralités

5.3.1.1 Aperçu

La détermination des tensions de tenue de coordination consiste à déterminer les plus faibles valeurs des tensions de tenue de l'isolation, qui satisfont au critère de performance, lorsque ces isolations sont soumises aux surtensions représentatives dans les conditions de service.

Il existe deux méthodes de coordination de l'isolement vis-à-vis des surtensions transitoires: l'une est déterministe et l'autre est statistique. Cependant, de nombreuses procédures appliquées résultent d'une combinaison des deux méthodes. Par exemple, certains facteurs utilisés dans la méthode déterministe ont été établis à partir de considérations statistiques et certaines variations statistiques ont été négligées dans les méthodes statistiques.

5.3.1.2 Méthode déterministe

La méthode déterministe est en principe utilisée en l'absence d'informations statistiques provenant d'essais concernant le taux de défaillances éventuel du matériel en exploitation.

Dans la méthode déterministe,

- quand l'isolation est caractérisée par sa tension de tenue conventionnelle présumée ($P_W = 100\%$), celle-ci est choisie égale à la tension de tenue de coordination, obtenue en multipliant la surtension représentative (maximum présumé) par un facteur de coordination K_C , prenant en compte les incertitudes liées aux hypothèses pour les deux valeurs (la tension de tenue présumée et la tension représentative), et
- quand l'isolation est caractérisée par la tension de tenue statistique ($P_W = 90\%$), comme pour une isolation externe, il convient que K_C tienne compte également de la différence entre cette tension et la tension de tenue présumée.

Avec cette méthode, il n'est fait référence à aucun taux de défaillance éventuel du matériel en service.

Exemples types:

- coordination de l'isolement des isolations internes contre les surtensions à front lent, en cas de protection par parafoudres;
- protection par parafoudres contre les surtensions de foudre pour les matériels connectés à des lignes aériennes, pour lesquels une expérience avec un matériel analogue est disponible.

5.3.1.3 Méthode statistique

La méthode statistique repose sur la fréquence d'occurrence d'une cause donnée, la fonction de répartition de surtension relative à cette cause et la probabilité d'amorçage de l'isolation. Le risque de défaillance peut également être déterminé en combinant, au coup par coup, les calculs de probabilité de décharge et de surtension en tenant compte de la nature statistique des surtensions et des décharges par des procédures adaptées (en utilisant les méthodes de Monte-Carlo, par exemple).

Le taux d'indisponibilité du réseau par suite des défauts d'isolement peut être obtenu en répétant les calculs pour différents types d'isolations et différents états du réseau.

Ainsi, l'application de la méthode statistique de coordination de l'isolement permet d'estimer directement la fréquence des défaillances en fonction des paramètres de conception du réseau considéré. En principe, l'isolement peut même être optimisé, si les coûts de l'indisponibilité pouvaient être liés aux différents types de défauts. Dans la pratique, cela est très difficile à réaliser en raison de la difficulté d'évaluer les conséquences de défauts d'isolation dans différentes configurations d'exploitation du réseau, et à cause de l'incertitude concernant le coût de l'énergie non fournie. Par conséquent, il est généralement préférable de surdimensionner légèrement le système d'isolation plutôt que de l'optimiser. La conception du système d'isolation repose alors sur la comparaison des risques associés aux différentes solutions.

5.3.2 Procédures de coordination de l'isolement pour la tension permanente (à fréquence industrielle) et pour les surtensions temporaires

5.3.2.1 Généralités

La tension de tenue de coordination pour la tension permanente (à fréquence industrielle) est égale à la tension la plus élevée du réseau, pour l'isolation entre phases, et à cette tension divisée par $\sqrt{3}$ pour les isolations phase-terre (c'est-à-dire équivalente à la valeur maximale présumée des tensions représentatives données en 4.3.1) sur une période égale à la durée de vie du matériel.

Avec la méthode déterministe, la tension de tenue de coordination de courte durée est égale à la surtension temporaire représentative. Si une procédure statistique est adoptée et si la surtension temporaire représentative est donnée par une caractéristique de fréquence de distribution amplitude/durée (voir 4.3.2), l'isolement satisfaisant au critère de performance

doit être déterminé, et l'amplitude de la tension de tenue de coordination doit être égale à celle correspondant à une durée de 1 min sur la caractéristique amplitude/durée de l'isolation.

5.3.2.2 Pollution

En cas de pollution, la réaction de l'isolation externe à des tensions à fréquence industrielle devient importante et peut conditionner sa conception. Le contournement de l'isolation se produit généralement lorsque la surface est polluée et mouillée par une pluie légère, la neige, une rosée ou un brouillard sans effet de lavage notable.

Pour les besoins de la normalisation dans l'IEC TS 60815-1, cinq niveaux de sévérité caractérisant le site sont définis, de très faible à très important, comme suit:

- très faible;
- faible;
- moyen;
- important;
- très important.

Les isolateurs doivent supporter en permanence la tension la plus élevée du réseau dans des conditions de pollution avec un risque de contournement admissible. Les tensions de tenue de coordination sont prises égales aux surtensions représentatives, et le critère de performance est satisfait par le choix d'une classe pertinente de sévérité du site. Par conséquent, la tension de tenue de coordination à fréquence industrielle de longue durée doit correspondre à la tension la plus élevée du réseau pour les isolateurs entre phases et à cette valeur divisée par $\sqrt{3}$ pour les isolateurs phase-terre.

Pour le choix des isolateurs adaptés, des recommandations sont données dans l'IEC TS 60815-1, s'appuyant sur l'expérience, des mesurages et des essais.

5.3.3 Procédures de coordination de l'isolement pour les surtensions à front lent

5.3.3.1 Méthode déterministe

Cette méthode consiste à déterminer la tension maximale à laquelle est soumis un matériel, puis à choisir la rigidité diélectrique minimale de ce matériel avec une marge qui prend en compte les incertitudes inhérentes à la détermination de ces valeurs. La tension de tenue de coordination est obtenue en multipliant la valeur maximale présumée de la surtension représentative correspondante par le facteur de coordination déterministe K_{cd} .

Pour les matériels protégés par des parafoudres, la surtension maximale présumée est égale au niveau U_{ps} de protection contre les surtensions de manœuvre du parafoudre. Cependant, dans ces cas-là, une brutale rupture de pente dans la distribution statistique des surtensions peut se produire. Cette rupture de pente est d'autant plus prononcée que le niveau de protection est bas comparé aux amplitudes de surtensions à front lent prévisibles. De petites variations de la tenue de l'isolation (ou dans la valeur du niveau de protection des parafoudres) peuvent alors avoir un grand impact sur le risque de défaillance [4]. Pour tenir compte de cet effet, il est proposé de déterminer le facteur de coordination déterministe K_{cd} en fonction du rapport entre le niveau U_{ps} de protection au choc de manœuvre du parafoudre et la valeur 2 % des surtensions prévisibles phase-terre U_{e2} . La Figure 6 établit cette relation.

Pour les matériels non protégés par des parafoudres, la surtension maximale présumée est égale à la valeur de troncature (U_{et} ou U_{pt}) d'après 4.3.3.2, et le facteur de coordination déterministe est $K_{cd} = 1$.

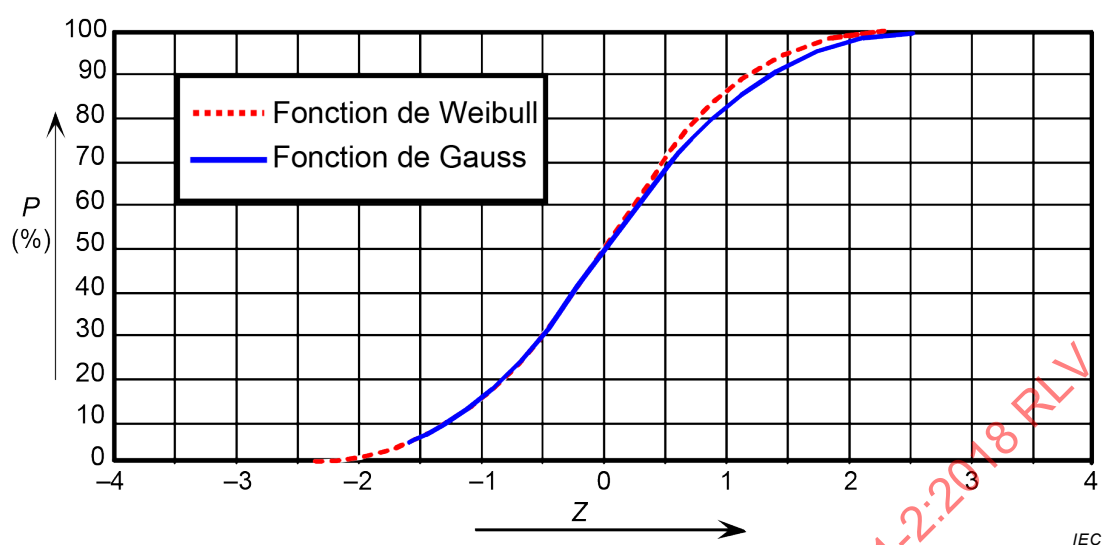


Figure 4 – Probabilité de décharge disruptive d'une isolation autorégénératrice sur une échelle linéaire

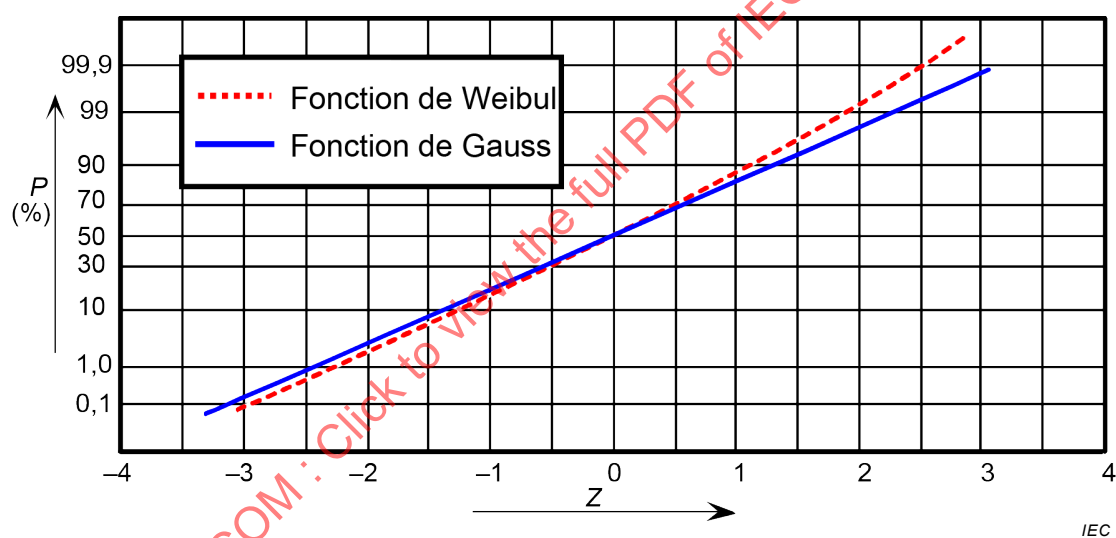
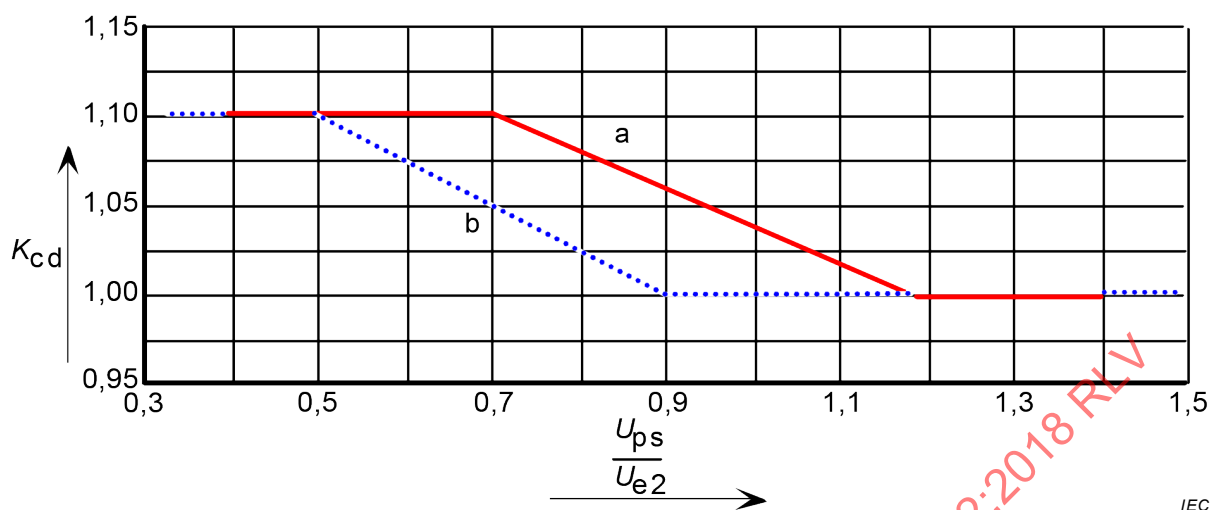


Figure 5 – Probabilité de décharge disruptive d'une isolation autorégénératrice sur une échelle gaussienne



Légende

- a facteur de coordination appliqué au niveau de protection par parafoudre pour obtenir la tension de tenue de coordination entre phase et terre (applicable également à l'isolation longitudinale);
- b facteur de coordination appliqué au double du niveau de protection par parafoudre pour obtenir la tension de tenue de coordination entre phases.

Figure 6 – Évaluation du facteur de coordination déterministe K_{cd}

5.3.3.2 Méthode statistique (et risque de défaillance correspondant)

Pour appliquer la méthode statistique, il est d'abord nécessaire de fixer un risque de défaillance acceptable (voir 5.2) en s'appuyant sur une analyse technique et économique et sur l'expérience acquise en service.

Le risque de défaillance donne la probabilité de défaut d'isolement. Le taux de défaillance est exprimé par la fréquence moyenne prévue de défauts de l'isolation (le nombre de défauts annuel, par exemple), défauts liés à des événements entraînant des contraintes de surtension. Pour évaluer ce taux, les événements entraînant ces surtensions ainsi que leur nombre doivent être étudiés. Heureusement, les types d'événements significatifs pour la conception des isolations sont peu nombreux, ce qui rend cette méthode applicable.

La méthode statistique recommandée dans le présent document s'appuie sur la valeur de crête des chocs. La distribution de fréquence des surtensions entre phase et terre pour un événement particulier est déterminée à partir des hypothèses suivantes:

- les crêtes autres que les crêtes les plus élevées d'une surtension donnée ne sont pas prises en considération;
- la forme de la crête la plus élevée est prise égale à celle de l'onde de la tension normalisée de choc de manœuvre;
- les crêtes de surtension les plus élevées sont considérées comme présentant toutes la même polarité, à savoir la plus sévère pour l'isolation.

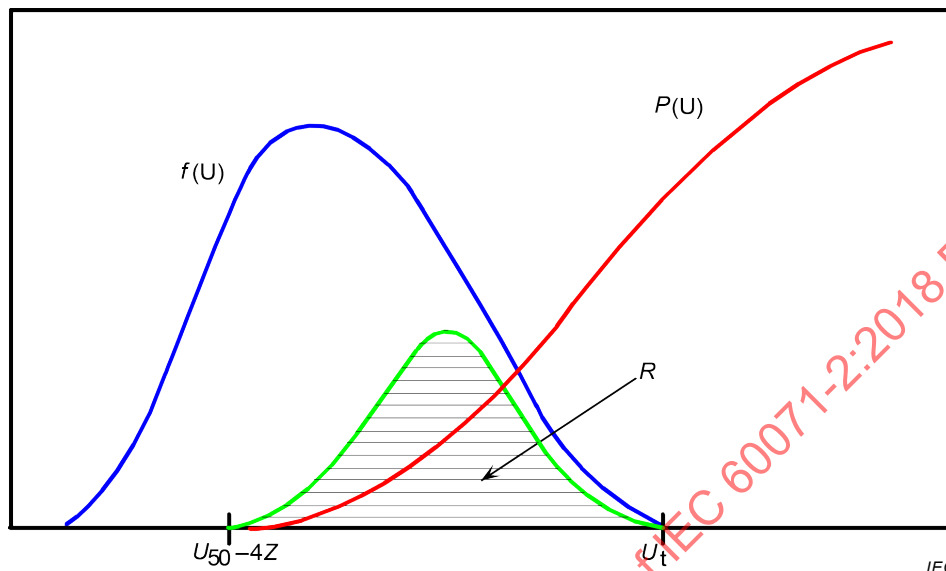
Une fois obtenues la distribution de fréquence des surtensions et la fonction de répartition de claquage correspondante de l'isolation, le risque de défaillance de l'isolation entre phase et terre peut être calculé comme suit:

$$R = \int_0^{\infty} f(U) \times P(U) dU \quad (8)$$

où

$f(U)$ est la densité de probabilité des surtensions;

$P(U)$ est la probabilité de contournement de l'isolation en cas de choc de valeur U (voir la Figure 7).



$$R = \int_{U_{50-4Z}}^{U_t} f(U) \times P(U) dU$$

où

$f(U)$ est la densité de probabilité d'occurrence d'une surtension décrite par une fonction de Gauss tronquée ou une fonction de Weibull;

$P(U)$ est la probabilité de décharge de l'isolation décrite par une fonction de Weibull modifiée;

U_t est la valeur de troncature de la fonction de répartition de surtension;

$U_{50} - 4Z$ est la valeur de troncature de la fonction de répartition de décharge.

Figure 7 – Évaluation du risque de défaillance

S'il se produit plus d'une crête indépendante, le risque total pour une phase peut être calculé en tenant compte du risque de défaillance de toutes les crêtes. Par exemple, si une surtension de manœuvre sur une phase donnée comporte trois crêtes positives entraînant les risques de défaillance R_1 , R_2 et R_3 , le risque de défaillance phase-terre en cas de manœuvre est:

$$R = 1 - (1 - R_1) (1 - R_2) (1 - R_3) \quad (9)$$

Si la distribution de surtension est basée sur la méthode valeur de crête par phase (voir 4.3.3.2.1), et si les isolations des trois phases sont identiques, le risque total de défaillance est:

$$R_{\text{total}} = 1 - (1 - R)^3 \quad (10)$$

Si la méthode valeur de crête par cas (voir 4.3.3.2.1) est utilisée, le risque total est: $R_{\text{total}} = R$.

Si l'une des polarités de surtension est notablement plus sévère pour la tenue de l'isolation, les valeurs de risque peuvent être divisées par deux.

Les risques de défaillance pour les isolations phase-terre et entre phases peuvent être déterminés séparément selon cette méthode simple uniquement si la distance entre les deux

isolations est suffisamment grande pour que le contournement à la terre et entre phases ne soit pas dû au même événement physique. Cela est valable si les isolations phase-terre et entre phases n'ont aucune électrode commune. En revanche, si elles ont une électrode commune, le risque de défaillance est généralement plus petit que s'il était calculé séparément [6].

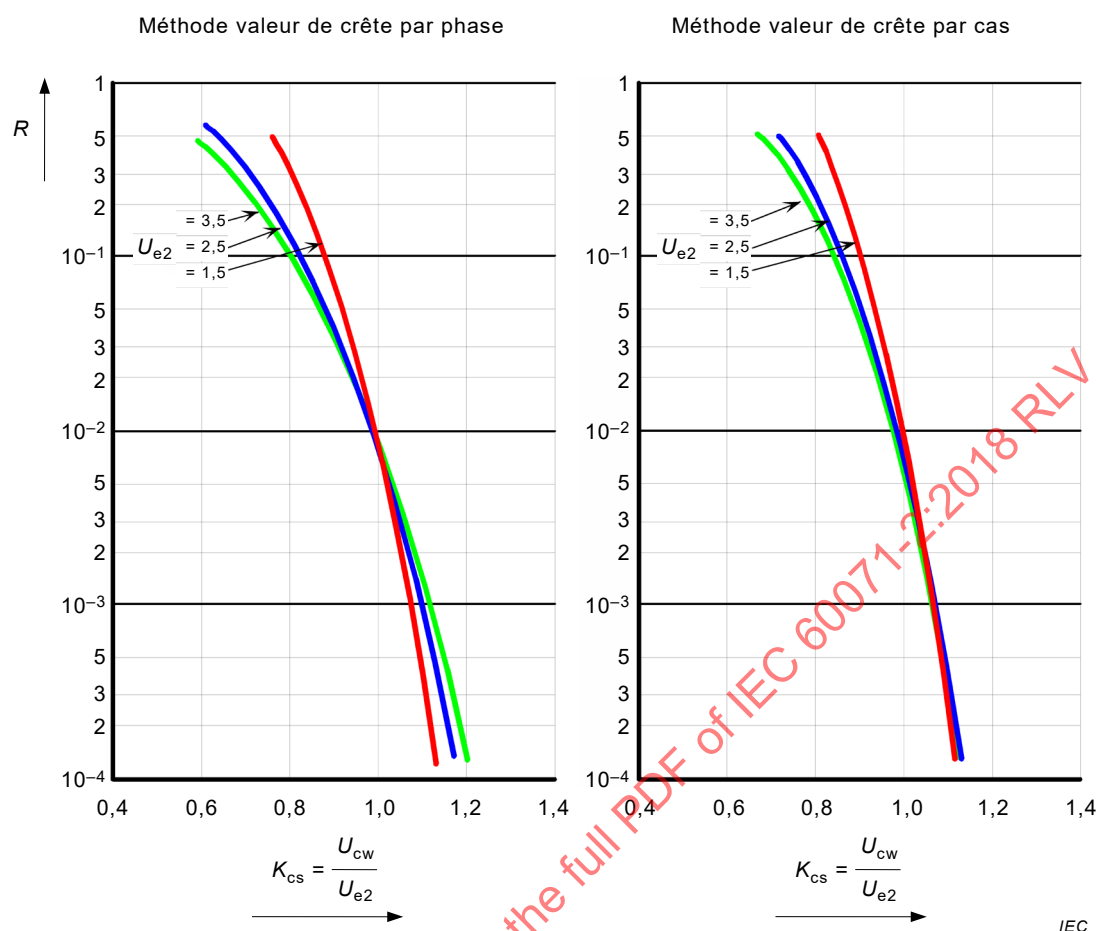
Pour le cas important de l'application du modèle statistique à un grand nombre d'isolations parallèles identiques, voir les éléments détaillés dans l'Annexe B.

Méthode statistique simplifiée pour les surtensions à front lent

La méthode statistique basée sur l'amplitude des chocs peut être simplifiée s'il s'avère éventuellement possible de définir la distribution des surtensions et de la résistance d'isolement par un point sur chacune des courbes correspondantes. La distribution de surtension est identifiée par la surtension statistique, qui est la surtension ayant une probabilité de dépassement de 2 %. La distribution de la résistance d'isolement est identifiée par la tension de tenue statistique, qui est la tension à laquelle l'isolation présente une probabilité de tenue de 90 %. Le facteur de coordination statistique (K_{cs}) est alors le rapport de la tension de tenue statistique à la surtension statistique.

La corrélation entre le facteur de coordination statistique et le risque de défaillance ne semble que très légèrement affectée par la modification des paramètres de la distribution des surtensions. Cela s'explique par le fait que la valeur à 2 % choisie comme probabilité de référence de la surtension se situe dans la partie de la distribution des surtensions qui contribue pour la plus large part au risque de défaillance dans la plage de risques envisagée.

La Figure 8 donne un exemple de la relation entre le risque de défaillance et le facteur de coordination statistique pour les méthodes valeur de crête par phase et valeur de crête par cas présentées à l'Annexe C, lorsque la distribution gaussienne et la loi de Weibull modifiée sont respectivement appliquées pour la contrainte et pour la tenue de l'isolation. Les courbes tiennent compte du fait que l'écart type est une fonction de la valeur de surtension à 2 % (voir l'Annexe C). Des variations extrêmes de l'écart de résistance d'isolement, une distribution de toute évidence non gaussienne des surtensions et, surtout, la forme de la surtension peuvent entraîner une erreur de courbe pouvant atteindre un ordre de grandeur. En revanche, les courbes indiquent qu'une variation du risque d'un ordre de grandeur correspond à une variation de seulement 5 % de la rigidité diélectrique.



Paramètres des surtensions: voir 4.3.3.2 et l'Annexe C.

Paramètres de tenue: voir 5.1.5.

Figure 8 – Risque de défaillance de l'isolation externe pour les surtensions à front lent en fonction du facteur de coordination statistique K_{cs}

5.3.4 Procédures de coordination de l'isolement pour les surtensions à front rapide

5.3.4.1 Méthode déterministe

Pour les surtensions de foudre à front rapide, le facteur de coordination déterministe $K_{cd} = 1$ est appliqué aux valeurs maximales présumées des surtensions. Cela est dû au fait que pour la foudre, la surtension représentative inclut les effets probabilistes. Pour les surtensions de manœuvre à front rapide, les mêmes relations que pour les surtensions à front lent s'appliquent (voir 5.3.3.1).

5.3.4.2 Méthode statistique

La méthode statistique recommandée dans le présent document repose sur la fonction de répartition de surtension de foudre représentative (voir l'Annexe E). La distribution de fréquence des surtensions étant obtenue en divisant leur taux de retour par le nombre total de surtensions, et la densité de probabilité $f(U)$ étant la dérivée du résultat, le risque de défaillance est calculé à partir des procédures présentées en 5.3.3.2. Le taux de défaut d'isolement est égal au risque de défaillance multiplié par le nombre total de surtensions de foudre.

Pour l'isolation interne, la tension de tenue présumée présente une probabilité de tenue de 100 % (voir la définition 3.23 de l'IEC 60071-1:2006). La probabilité de tenue aux tensions supérieures est censée être de 0 %. Cela signifie que la tension de tenue de coordination est

égale à l'amplitude de la surtension de foudre représentative à un taux de retour égal au taux de défaillance acceptable retenu.

NOTE Les surtensions à front rapide dues à la foudre sont évaluées sans tenir compte de la tension à fréquence industrielle instantanée. Les contraintes combinées dues à l'inversion de polarité sont par conséquent négligées. Cela est acceptable tant que l'amplitude de la tension à fréquence industrielle est faible par rapport à celle de la surtension à front rapide. Cela peut ne pas être prudent pour les matériels ayant une isolation interne huile-papier comme les transformateurs, dans la plage II, et les plus fortes valeurs de U_m de la plage I. De plus, dans ces appareils, les surtensions internes (telles qu'entre spires) dues aux contraintes apparaissant au niveau des bornes ne sont pas strictement prises en considération dans la méthode de coordination de l'isolement décrite dans le présent document.

Pour l'isolation externe, l'écart type de la probabilité de décharge est généralement petit comparé à la dispersion des surtensions. Pour simplifier, il peut être négligé et la même équation que pour l'isolation interne s'applique.

6 Tension de tenue exigée

6.1 Remarques générales

La tension de tenue exigée, à vérifier dans les conditions d'essai de type et atmosphère de référence normalisées, est déterminée en tenant compte de tous les facteurs qui peuvent réduire l'isolation en service, de sorte que la tension de tenue de coordination soit satisfaite par le matériel là où il est installé pendant toute sa durée de vie. Pour cela, deux principaux types de facteurs de correction doivent être pris en considération:

- le facteur de correction lié aux conditions atmosphériques;
- les facteurs de correction (appelés aussi "facteurs de sécurité") qui tiennent compte des différences entre les conditions réelles en service auxquelles l'isolation est soumise et les conditions de l'essai de tenue normalisé.

6.2 Correction atmosphérique

6.2.1 Remarques générales

Par hypothèse, les propriétés de l'isolement interne ne sont pas affectées par les conditions atmosphériques.

Les règles de correction des conditions atmosphériques des tensions de tenue de l'isolation externe sont spécifiées dans l'IEC 60060-1. Ces règles reposent sur des mesurages effectués jusqu'à 2 000 m d'altitude. Il convient de prendre des précautions pour les appliquer à de plus hautes altitudes. Les recommandations supplémentaires suivantes s'appliquent pour les besoins de la coordination de l'isolement:

- a) pour les distances dans l'air et les isolateurs propres, la correction doit être appliquée aux tensions de coordination de tenue de choc de manœuvre et aux tensions de coordination de tenue au choc de foudre. De plus, une correction de la tension de tenue à fréquence industrielle de longue durée est nécessaire pour les isolateurs devant faire l'objet d'un essai de pollution;
- b) pour déterminer le facteur de correction atmosphérique applicable, il peut être posé l'hypothèse que les effets de la température et de l'humidité ambiantes tendent à s'annuler. En conséquence, pour les besoins de la coordination de l'isolement, il suffit de prendre en considération la pression atmosphérique correspondant à l'altitude du lieu pour les isollements secs et mouillés.

NOTE Cette hypothèse peut être considérée comme étant correcte pour les formes d'isolateur pour lesquelles la pluie ne réduit pas trop la tension de tenue. Elle n'est pas complètement vraie pour les isolateurs dont la distance entre ailettes est petite et peut être franchie sous pluie.

Pour de plus amples informations relatives à la correction atmosphérique et de l'altitude, voir l'Annexe H.

6.2.2 Correction de l'altitude

Le facteur de correction K_a repose sur la relation entre la pression atmosphérique et l'altitude (voir l'ISO 2533:1975). La tension de tenue de coordination U_{cw} doit être multipliée par K_a pour calculer la tension de tenue exigée U_{rw} .

Le facteur de correction peut être calculé par:

$$K_a = e^{m \times \frac{H}{8150}} \quad (11)$$

où

H est l'altitude (en mètres) au-dessus du niveau de la mer;

m est définie comme suit:

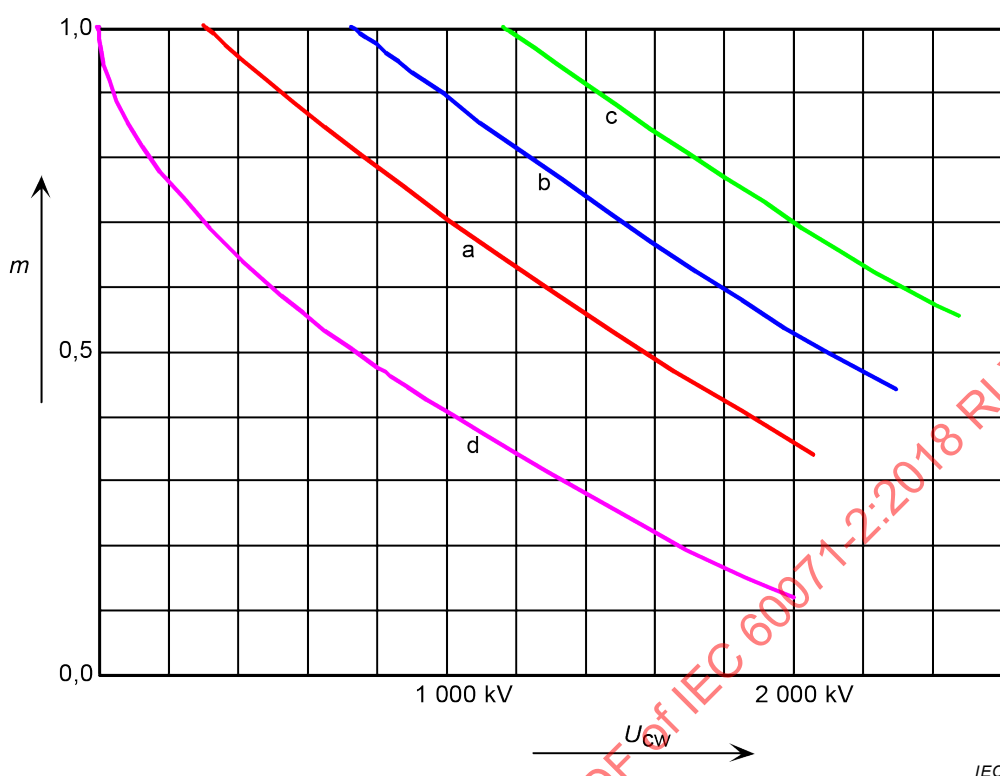
$m = 1,0$ pour les tensions de coordination de tenue au choc de foudre;

m est selon la Figure 9 pour les tensions de coordination de tenue au choc de manœuvre;

$m = 1,0$ pour les tensions de tenue à fréquence industrielle de courte durée des distances dans l'air et des isolateurs propres.

NOTE L'exposant m dépend de différents paramètres comme le chemin de décharge minimale qui n'est généralement pas connu au stade de la spécification. Cependant, pour les besoins de la coordination de l'isolement, les estimations prudentes de m indiquées à la Figure 9 peuvent être utilisées pour la correction des tensions de coordination de tenue de choc de manœuvre. L'exposant m est déterminé conformément à l'IEC 60060-1. De plus, des valeurs prudentes du facteur d'intervalle ont été utilisées pour tous les types d'isolements (voir l'Annexe G).

Pour les isolateurs pollués, la valeur de l'exposant m est à l'essai. Pour les essais de longue durée et, le cas échéant, à la tension de tenue à fréquence industrielle de courte durée des isolateurs pollués, l'exposant m peut être de 0,5 pour les isolateurs normaux et de 0,8 pour les isolateurs antipollution.



Légende

- a isolation phase-terre
- b isolation longitudinale
- c isolation entre phases
- d intervalle pointe-plan (intervalle de référence)

Pour les tensions à deux composantes, la valeur de tension est égale à la somme des composantes.

Figure 9 – Relation entre l'exposant m et la tension de coordination de tenue de choc de manœuvre

6.3 Facteurs de sécurité

6.3.1 Généralités

Les principaux facteurs d'influence et les modes de fonctionnement associés pour les isolations électriques sont indiqués à l'Annexe A de l'IEC 60505:2011. Ils correspondent aux contraintes opérationnelles suivantes:

- contraintes thermiques;
- contraintes électriques;
- contraintes d'environnement;
- contraintes mécaniques.

Les facteurs à appliquer compensent

- les différences lors du montage du matériel,
- la dispersion dans la qualité du produit,
- la qualité de l'installation,
- le vieillissement de l'isolation pendant la durée de vie prévue, et
- d'autres facteurs d'influence inconnus.

Le poids relatif de ces facteurs et de ces modes de fonctionnement peut varier selon les matériels.

6.3.2 Vieillessement

L'isolation électrique d'un matériel vieillit du fait de contraintes thermiques et/ou électriques et/ou chimiques et/ou mécaniques.

Pour les besoins de la coordination de l'isolement, les isolations externes sont censées ne pas vieillir. Les isolations comprenant des matériaux organiques font exception, leur vieillissement nécessitant de soigneuses investigations, en particulier lorsqu'elles sont utilisées à l'extérieur.

Le vieillissement des isolations internes peut être sensible, et il convient d'en tenir compte avec les facteurs de sécurité donnés en 6.3.5.

6.3.3 Dispersion due à la fabrication et au montage

Les tensions de tenue assignées sont vérifiées par un essai de type, souvent réalisé sur une partie représentative d'un ensemble, ou par un essai s'appliquant à une partie seulement du système d'isolement. Le matériel en service pouvant différer de celui qui a passé les essais de type par la différence de configuration ou de conditionnement, sa tension de tenue en service peut être inférieure à la valeur assignée.

Si le matériel est intégralement monté en usine, cette dispersion est négligeable pour les besoins de la coordination de l'isolement. Si le matériel est monté sur site, la tension de tenue réelle peut être inférieure à la tension de tenue exigée, ce qui doit être pris en considération dans les facteurs de sécurité en 6.3.5.

6.3.4 Inexactitude de la tension de tenue

Pour les isolations externes, des différences éventuelles entre le montage d'essai et le montage réel en service, ainsi que l'influence de l'environnement du laboratoire doivent être prises en considération en plus de l'inexactitude statistique inhérente à la procédure d'essai de type choisie. Ces différences doivent être couvertes par les facteurs de sécurité donnés en 6.3.5.

Les isolations internes, dont la probabilité de tenue est par hypothèse égale à 100 % (voir 3.23 de l'IEC 60071-1:2006) subissent habituellement trois chocs en essai de type, et l'incertitude statistique de cet essai doit être couverte par le facteur de sécurité donné en 6.3.5 (voir également 7.3.2).

6.3.5 Facteurs de sécurité recommandés (K_s)

S'ils ne sont pas spécifiés par les comités de produit concernés, il convient d'appliquer les facteurs de sécurité suivants:

- pour l'isolation interne: $K_s = 1,15$;
- pour l'isolation externe: $K_s = 1,05$.

Des facteurs de sécurité différents des valeurs recommandées peuvent être appliqués en fonction, par exemple, de l'expérience particulière en service positive ou négative, des améliorations technologiques, des niveaux de contrôle qualité plus élevés pendant la fabrication et le montage (plus particulièrement dans les réseaux haute tension) ou des approches exceptionnellement prudentes dans les études de réseau.

7 Tension de tenue normalisée et procédures d'essai

7.1 Remarques générales

7.1.1 Aperçu

Le Tableau 2 et le Tableau 3 de l'IEC 60071-1:2006 et l'IEC 60071-1:2006/AMD1:2010 spécifient respectivement les tensions de tenue normalisées U_w pour la plage I et la plage II. Dans chacun des deux tableaux, les tensions de tenue normalisées sont regroupées en niveaux d'isolement normalisés associés à chaque valeur de tension normalisée la plus haute pour le matériel U_m .

Dans la plage I, les tensions de tenue normalisées comprennent la tension de tenue à fréquence industrielle de courte durée et la tension de tenue aux chocs de foudre. Dans la plage II, les tensions de tenue normalisées comprennent la tension de tenue au choc de manœuvre et la tension de tenue au choc de foudre.

Les niveaux d'isolement normalisés donnés au Tableau 2 et au Tableau 3 de l'IEC 60071-1:2006 et l'IEC 60071-1:2006/AMD1:2010 reflètent l'expérience mondiale en matière de dispositifs de protection modernes et de méthodes de limitation des surtensions. Il convient de choisir un niveau d'isolement normalisé particulier en fonction de la procédure de coordination de l'isolement décrite dans le présent document, et qu'il tienne compte des caractéristiques d'isolement du matériel particulier considéré.

7.1.2 Tension normalisée de tenue au choc de manœuvre

Au Tableau 3 de l'IEC 60071-1:2006 et l'IEC 60071-1:2006/AMD1:2010, les tensions normalisées de tenue au choc de manœuvre associées à une tension la plus élevée particulière pour le matériel ont été choisies en tenant compte des points suivants:

- a) pour le matériel protégé par des parafoudres contre les surtensions de manœuvre:
 - les valeurs prévues de surtensions temporaires;
 - les caractéristiques des parafoudres actuellement disponibles;
 - les facteurs de coordination et les facteurs de sécurité entre le niveau de protection du parafoudre et la tension de tenue au choc de manœuvre du matériel;
- b) pour le matériel non protégé par parafoudre contre les surtensions de manœuvre:
 - le risque acceptable de décharge disruptive compte tenu de la plage probable de surtensions à l'emplacement du matériel;
 - le niveau de limitation de surtension raisonnable économiquement et pouvant être obtenu grâce à un choix minutieux des appareils de connexion et de la conception du réseau.

7.1.3 Tension normalisée de tenue au choc de foudre

Au Tableau 3 de l'IEC 60071-1:2006 et l'IEC 60071-1:2006/AMD1:2010, les tensions normalisées de tenue au choc de foudre associées à une tension normalisée de tenue au choc de manœuvre particulière ont été choisies en tenant compte des points suivants.

- a) Pour le matériel protégé par parafoudres, les valeurs basses du niveau de tenue au choc de foudre sont applicables. Elles sont choisies en tenant compte du rapport entre le niveau de protection au choc de foudre et le niveau de protection au choc de manœuvre susceptible d'être atteint avec les parafoudres, et en ajoutant les marges appropriées.
- b) Pour le matériel non protégé par parafoudres (ou pour lequel la protection n'est pas efficace), seules les plus grandes valeurs de tension de tenue au choc de foudre doivent être utilisées. Ces valeurs hautes sont définies par le rapport type entre la tension de tenue au choc de foudre et la tension de tenue au choc manœuvre de l'isolation externe des appareils (tels que disjoncteurs, sectionneurs, transformateurs de mesure). Elles sont

choisies de manière à déterminer la conception de l'isolation principalement par l'aptitude de l'isolation externe à tenir les tensions d'essai de choc de manœuvre.

- c) Dans quelques rares cas extrêmes, il convient de prendre des dispositions pour obtenir une valeur plus élevée de la tension de tenue au choc de foudre. Il convient de choisir cette valeur plus élevée dans la série de valeurs normalisées donnée en 5.6 et 5.7 de l'IEC 60071-1:2006 et l'IEC 60071-1:2006/AMD1:2010.

Dans la plage I, il convient que la tension normalisée de tenue à fréquence industrielle de courte durée ou que la tension normalisée de tenue au choc de foudre couvre les tensions de tenue au choc de manœuvre exigées phase-terre et entre phases, ainsi que la tension de tenue longitudinale exigée.

Dans la plage II, il convient que la tension normalisée de tenue au choc de manœuvre couvre la tension de tenue à fréquence industrielle de courte durée exigée et la tension permanente à fréquence industrielle, si aucune valeur n'a été spécifiée par le comité de produit concerné.

Pour satisfaire à ces exigences générales, il convient de convertir les tensions de tenue exigées en formes de tension pour lesquelles des tensions de tenue normalisées sont spécifiées, à l'aide des facteurs de conversion d'essai donnés en 7.2. Les facteurs de conversion d'essai sont déterminés à partir de résultats existants pour donner une valeur prudente des tensions de tenue normalisées. Il convient donc de ne les utiliser que dans le sens spécifié.

L'IEC 60071-1 laisse au comité de produit concerné le soin de préciser l'essai à fréquence industrielle de longue durée destiné à démontrer le comportement du matériel au vieillissement de l'isolation externe ou à la pollution externe (voir également l'IEC 60507).

7.2 Facteurs de conversion d'essai

7.2.1 Plage I

En l'absence de facteurs adaptés (ou spécifiés par le comité de produit concerné), les facteurs de conversion d'essai à appliquer aux tensions de tenue au choc de manœuvre exigées sont donnés au Tableau 1. Ces facteurs s'appliquent tant aux tensions de tenue exigées phase-terre qu'à la somme des composantes des tensions de tenue entre phases et des tensions de tenue longitudinales.

Tableau 1 – Facteurs de conversion d'essai pour la plage I, permettant de convertir les SIWV exigées en SDWV et en LIWV

Isolation	Tension de tenue à fréquence industrielle de courte durée ^a	Tension de tenue au choc de foudre
Isolation externe		
– distances dans l'air et isolateurs propres, secs:		
• phase-terre	$0,6 + U_{rw} / 8\,500$	$1,05 + U_{rw} / 6\,000$
• entre phases	$0,6 + U_{rw} / 12\,700$	$1,05 + U_{rw} / 9\,000$
– isolateurs propres, sous pluie	0,6	1,3
Isolation interne		
– GIS	0,7	1,25
– isolation par immersion dans un liquide	0,5	1,10
– Isolation solide	0,5	1,00
U_{rw} est la tension de tenue au choc de manœuvre exigée, en kV.		
^a Les facteurs de conversion d'essai comprennent un facteur de $1/\sqrt{2}$ pour convertir les valeurs de crête en valeurs efficaces.		

7.2.2 Plage II

En l'absence de facteurs adaptés (ou spécifiés par le comité de produit concerné), les facteurs de conversion d'essai pour la conversion de la tension de tenue à fréquence industrielle de courte durée exigée en tension de tenue au choc de manœuvre sont donnés au Tableau 2. Ils s'appliquent aussi à l'isolation longitudinale.

Tableau 2 – Facteurs de conversion d'essai pour la plage II, permettant de convertir les SDWV exigées en SIWV

Isolation	Tension de tenue au choc de manœuvre
Isolation externe	
– distances dans l'air et isolateurs propres, secs:	1,4
– isolateurs propres, sous pluie	1,7
Isolation interne	
– GIS	1,6
– isolation par immersion dans un liquide	2,3
– isolation solide	2,0
NOTE Les facteurs de conversion d'essai comprennent un facteur de $\sqrt{2}$ pour convertir les valeurs efficaces en valeurs de crête.	

7.3 Détermination de la tenue de l'isolement par des essais de type

7.3.1 Relation entre procédure d'essai et type d'isolement

La rigidité diélectrique de l'isolement est vérifiée par des essais. Le choix du type d'essai pour un matériel donné doit tenir compte de la nature de son ou ses isolations. Les paragraphes 3.4 et 3.5 de l'IEC 60071-1:2006 divisent l'isolation en "autorégénératrice" et "non autorégénératrice". Cela impose de choisir la procédure à adopter pour un matériel considéré dans la liste donnée en 6.3 de l'IEC 60071-1:2006, décrite de manière plus exhaustive dans l'IEC 60060-1.

Les informations et recommandations qui suivent aident au choix optimal de l'essai de type à partir de considérations en matière de coordination de l'isolement. Le fait que beaucoup de matériels comportent à la fois des isolations autorégénératrices et non autorégénératrices est pris en considération.

7.3.2 Isolation non autorégénératrice

Une décharge disruptive détériore les propriétés isolantes d'une isolation non autorégénératrice, qui peut même être affectée par des tensions d'essai ne produisant pas de décharge disruptive. Par exemple, les essais de surtension à fréquence industrielle et les essais de choc avec inversion de polarité peuvent initier des arborescences dans l'isolation par polymères et conduire à la génération de gaz dans l'isolation liquide ou imprégnée de liquide. Pour ces raisons, l'isolation non autorégénératrice est soumise à l'essai par l'application d'un nombre limité de tensions d'essai au niveau de tenue normalisé, c'est-à-dire par la procédure A, en 7.3.1.1 de l'IEC 60060-1:2010, dans laquelle trois chocs sont appliqués pour chaque polarité, l'essai étant concluant si aucune décharge disruptive ne se produit.

Pour les besoins de la coordination de l'isolement, il convient qu'un matériel qui réussit cet essai soit censé présenter une tension de tenue présumée égale à la tension d'essai appliquée (c'est-à-dire la tension de tenue assignée). Étant donné que le nombre de chocs d'essai est réduit et qu'aucune défaillance n'est admise, aucune information statistique utile ne peut être déduite concernant la tension de tenue réelle du matériel.

L'isolation de certains matériels constitués à la fois d'isolation non autorégénératrice et d'isolation autorégénératrice peut être considérée comme non autorégénératrice pour les besoins de l'essai, si une décharge disruptive pendant l'essai entraîne une dégradation significative de la partie non autorégénératrice de l'isolation (les transformateurs soumis aux essais avec des traversées dont la tension de tenue normalisée au choc est plus élevée, par exemple).

7.3.3 Isolation non autorégénératrice

Il est possible d'appliquer un grand nombre de tensions d'essai aux isolations autorégénératrices, nombre limité seulement par les contraintes d'essai et non par l'isolation elle-même, même en cas de décharge disruptive. L'application de nombreuses tensions d'essai présente l'avantage de permettre d'obtenir des renseignements statistiques relatifs à la tenue de l'isolement. L'IEC 60060-1 normalise trois méthodes différentes conduisant à l'estimation de la tension de tenue à 90 %. Pour la coordination de l'isolement, la méthode préférentielle est la méthode des suites croissantes et décroissantes avec sept chocs par groupe et au moins huit groupes pour déterminer U_{50} . U_{10} peut être déduit en faisant une hypothèse sur la valeur de l'écart type (voir 5.1.5) ou bien cette dernière peut être déterminée par des essais à plusieurs niveaux. Pour évaluer la signification statistique de cette méthode d'essai, il peut être fait référence à l'Annexe A de l'IEC 60060-1:2010.

7.3.4 Isolation mixte

Un compromis doit être trouvé quant à la méthode d'essai des matériels dont l'isolation autorégénératrice ne peut pas être soumise à l'essai séparément de son isolation non autorégénératrice (traversées et transformateurs de mesure, par exemple). Cela est nécessaire pour ne pas endommager une isolation non autorégénératrice satisfaisante, tout en s'assurant en même temps que l'essai permet de faire la distinction entre une isolation autorégénératrice satisfaisante et une autre qui ne l'est pas. D'une part, la partie non autorégénératrice de l'isolation n'amène qu'à peu d'applications de tension d'essai. D'autre part, la partie autorégénératrice de l'isolation nécessite de nombreuses applications de tension d'essai (dans un but de sélectivité). L'expérience montre que la procédure d'essai de tenue B, en 7.3.1.2 de l'IEC 60060-1:2010 (15 chocs et pas plus de deux décharges disruptives sur les parties autorégénératrices), est un compromis acceptable.

Sa sélectivité peut être indiquée par la différence entre les niveaux de tenue réels qui conduisent à des probabilités de 5 % et de 95 % de réussir l'essai. Voir le Tableau 3.

Tableau 3 – Sélectivité des procédures d'essai B et C de l'IEC 60060-1

Procédure d'essai de l'IEC	Nombre de chocs	Probabilité en % de réussir l'essai à U_{10}	Niveau de tenue pour une probabilité de 95 % de réussir l'essai	Niveau de tenue pour une probabilité de 5 % de réussir l'essai	Sélectivité
B	15/2	82	$U_{5,5}$ ($U_w + 0,32 Z$)	U_{36} ($U_w - 0,92 Z$)	1,24 Z
C	3 + 9	82	$U_{4,6}$ ($U_w + 0,40 Z$)	U_{63} ($U_w - 1,62 Z$)	2,02 Z

Ainsi, un matériel soumis à l'essai selon la procédure B, et dont la tenue réelle est à la limite de la conformité (dont la tension de tenue assignée et la tension d'essai correspondent à U_{10}), a une probabilité de 82 % de réussir l'essai. Un meilleur matériel, ayant une tension de tenue U_{10} dépassant la valeur normalisée U_w de 0,32 Z (dont la tension assignée et la tension d'essai correspondent à $U_{5,5}$), a une probabilité de 95 % de réussir l'essai. Un matériel médiocre, ayant une tension de tenue inférieure à la valeur normalisée U_w de 0,92 Z (dont la tension assignée et la tension d'essai correspondent à U_{36}), a une probabilité de 5 % de réussir l'essai. Cette sélectivité d'essai (1,24 Z) peut être encore mieux quantifiée en prenant par hypothèse des valeurs de Z égales à 3 % et à 6 % de U_{50} respectivement pour les chocs

de foudre et les chocs de manœuvre (il convient de noter que Z ne peut pas être déterminé par cet essai). La sélectivité de l'essai 15/2 est encore mieux représentée par la Figure 10 qui le compare à l'essai idéal.

Une variante à la procédure d'essai ci-dessus est la procédure d'essai C, en 7.3.1.3 de l'IEC 60060-1:2010, qui correspond à une modification de la procédure américaine. Cette procédure consiste à appliquer trois fois la tension d'essai et il est permis qu'une seule d'entre elles engendre une décharge disruptive sur l'isolation autorégénératrice, auquel cas la tension d'essai est appliquée encore neuf fois, les exigences d'essai étant satisfaites si aucune décharge disruptive ne se produit. Le Tableau 3 et la Figure 10 comparent la sélectivité de cette procédure à celle de l'essai 15/2.

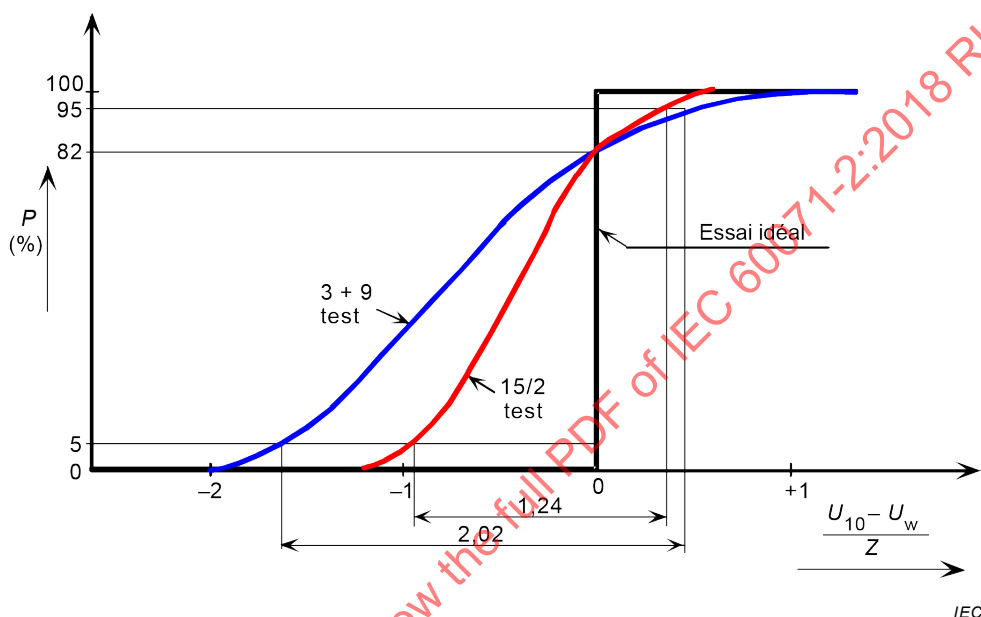


Figure 10 – Probabilité P qu'un matériel réussisse l'essai en fonction de la différence K entre la tension de tenue au choc réelle et la tension de tenue au choc assignée

7.3.5 Limitations des procédures d'essai

Le rétablissement de l'isolement après une décharge disruptive étant fonction du temps, un intervalle de temps suffisant entre les applications de la tension d'essai doit être prévu pour que l'isolation autorégénératrice retrouve sa rigidité diélectrique complète. Il convient que les comités de produit spécifient les limites acceptables (le cas échéant) des intervalles de temps entre les applications de tension d'essai dépendant du type d'isolation. Il convient également de tenir compte de l'éventuelle dégradation de l'isolation non autorégénératrice due aux applications répétées de la tension d'essai, même sans décharge disruptive.

7.3.6 Choix des procédures d'essai de type

Compte tenu de ce qui précède, les recommandations suivantes s'appliquent aux essais pour les besoins de la coordination de l'isolement:

- il convient de soumettre à l'essai l'isolation autorégénératrice par la méthode des suites croissantes et décroissantes (une des méthodes décrites par la procédure d'essai de tenue D, en 7.3.1.4 de l'IEC 60060-1:2010);
- il convient de soumettre à l'essai l'isolation non autorégénératrice avec l'essai de tenue à trois chocs (procédure d'essai de tenue A, en 7.3.1.1 de l'IEC 60060-1:2010);
- en général, il convient de soumettre à l'essai l'isolation mixte, qui comprend à la fois des isolations autorégénératrices et non autorégénératrices, avec l'essai 15/2 (procédure d'essai de tenue B, en 7.3.1.2 de l'IEC 60060-1:2010). Cependant, si le risque de propagation d'arborescence dans l'isolation non autorégénératrice est une préoccupation

essentielle, et si le nombre d'applications de tension apparaît trop important, l'essai 3 + 9 (procédure d'essai C, en 7.3.1.3 de l'IEC 60060-1:2010) est une alternative acceptable;

- de plus, si des essais à fréquence industrielle sont exigés pour la coordination de l'isolement, il convient d'appliquer les essais de tenue à fréquence industrielle de courte durée (IEC 60071-1) à l'isolation, qu'elle soit autorégénératrice ou non, ou mixte.

7.3.7 Choix des tensions d'essai de type

7.3.7.1 Généralités

L'essai des matériels n'ayant que des isolations externes dans l'air est effectué à la tension de tenue normalisée affectée des facteurs de correction atmosphériques spécifiés par l'IEC 60060-1.

L'essai des matériels n'ayant que des isolations internes est effectué uniquement à la tension de tenue normalisée (c'est-à-dire non affectée des facteurs de correction atmosphériques spécifiés par l'IEC 60060-1).

Pour les matériels comprenant à la fois des isolations internes et externes, il convient d'appliquer le facteur de correction atmosphérique et de procéder à l'essai avec la valeur corrigée, à condition que le facteur de correction soit compris entre 0,95 et 1,05. Si le facteur de correction est en dehors de cette plage, les variantes suivantes satisfont aux besoins de la coordination de l'isolement.

7.3.7.2 Tension d'essai de l'isolation externe supérieure à celle de l'isolation interne (facteur de correction atmosphérique > 1,05)

L'isolation externe ne peut être correctement soumise à l'essai que si l'isolation interne est surdimensionnée. Sinon, il convient de soumettre à l'essai l'isolation interne à la valeur normalisée, et les possibilités suivantes peuvent être étudiées pour l'isolation externe par les comités de produit ou dans le cadre d'un accord:

- il convient de soumettre à l'essai l'isolation externe uniquement sur des maquettes;
- interpolation entre des résultats déjà connus;
- estimation des tensions de tenue à partir des dimensions.

En général, l'essai de l'isolation externe n'est pas nécessaire si les distances dans l'air sont supérieures ou égales à celles que donne l'IEC 60071-1.

Pour l'essai sous pluie d'isolateurs verticaux, il convient que la forme de l'isolateur satisfasse à certaines exigences supplémentaires. En attendant de plus amples informations, ces exigences peuvent être considérées comme étant satisfaites si la forme de l'isolateur satisfait à celles de l'IEC TS 60815-1.

Des essais supplémentaires sur l'isolation externe à fréquence industrielle et sous pluie ne sont pas nécessaires si les distances dans l'air sont supérieures à la tension de tenue à fréquence industrielle assignée divisée par 230 kV/m et si la forme de l'isolateur satisfait aux exigences de l'IEC TS 60815-1.

7.3.7.3 Tension d'essai de l'isolation externe inférieure à celle de l'isolation interne (facteur de correction atmosphérique < 0,95)

L'isolation interne ne peut être correctement soumise à l'essai que si l'isolation externe est surdimensionnée. Sinon, il convient de soumettre à l'essai l'isolation externe aux valeurs corrigées, et les possibilités suivantes peuvent être étudiées pour l'isolation interne par les comités de produit ou dans le cadre d'un accord:

- essai de l'isolation interne avec des chocs d'une seule polarité (généralement négative);

- essai de l'isolation interne en augmentant la résistance d'isolement externe (au moyen d'électrodes de commande de couronne de différentes tailles d'intervalle, par exemple). Il convient que le moyen de renforcement n'affecte pas le comportement de l'isolation interne.

8 Points particuliers concernant les lignes aériennes

8.1 Remarques générales

Bien que la procédure de coordination de l'isolement des lignes aériennes suive les principes généraux de la coordination de l'isolement, les particularités suivantes doivent être prises en considération.

- Si la ligne est conçue avec des chaînes de suspension, il convient que la rigidité diélectrique des distances dans l'air tienne compte du mouvement des conducteurs.
- Les normes qui concernent les isolateurs spécifient les dimensions des éléments d'isolateur sans faire référence à la tension la plus élevée du matériel ou du réseau. Par conséquent, la procédure de coordination de l'isolement se termine par la détermination de la tension de tenue exigée U_{rw} . Il n'est pas nécessaire de sélectionner une tension assignée dans la liste donnée dans l'IEC 60071-1, et le Tableau 2 et le Tableau 3 de l'IEC 60071-1:2006 et l'IEC 60071-1:2006/AMD1:2010 ne sont pas applicables dans ce cas.
- La performance de l'isolement des lignes aériennes a une incidence importante sur celle des postes. Le taux de coupure de la ligne de transport pour cause de foudre détermine la fréquence des réenclenchements, tandis que le taux de performance vis-à-vis de la foudre à proximité du poste définit la fréquence d'occurrence des surtensions à front rapide qui arrivent dans le poste.

8.2 Coordination de l'isolement vis-à-vis des tensions de service et des surtensions temporaires

La tension de service et les surtensions temporaires déterminent la longueur de la chaîne exigée de l'isolateur et la forme des éléments isolants selon le degré de pollution du site. Dans le cas de réseaux à neutre directement mis à la terre et présentant des facteurs de défaut à la terre inférieurs ou égaux à 1,3, il suffit généralement de concevoir les isolateurs de manière à ce qu'ils tiennent la tension du réseau phase-terre la plus élevée. Si les facteurs de défaut à la terre sont supérieurs, comme c'est notamment le cas sur des réseaux à neutre isolé ou compensé par bobine d'extinction, il peut être nécessaire de prendre en considération les surtensions temporaires.

Si des chaînes de suspension doivent être prises en considération, il convient de déterminer les distances dans l'air dans des conditions de balancement extrême.

8.3 Coordination de l'isolement pour les surtensions à front lent

8.3.1 Généralités

Les surtensions à front lent qui sont à considérer dans le cas des lignes aériennes sont les surtensions de défaut à la terre, les surtensions à l'enclenchement et les surtensions au réenclenchement. Lors de la détermination des taux de défaillance admissibles, il convient de considérer

- qu'un défaut d'isolement provoqué par des surtensions dues à un défaut à la terre entraîne un double défaut à la terre, et
- qu'un défaut d'isolement provoqué par des surtensions au réenclenchement empêche la refermeture.

8.3.2 Surtensions de défaut à la terre

Il convient de tenir compte des surtensions de défaut à la terre dans le cas d'un réseau dont les facteurs de défaut à la terre sont élevés, c'est-à-dire les lignes de distribution ou les lignes de transport d'un réseau à neutre compensé par bobine d'extinction. Les taux de défaillance admissibles de ces lignes doivent être de l'ordre de grandeur du taux de coupure biphasé dû à la foudre. À titre indicatif, les taux de défaillance admissibles sont couramment compris entre 0,1 et 1 contournement par an.

Les lignes de la plage II, sur lesquelles les surtensions à l'enclenchement et au réenclenchement sont limitées à de faibles amplitudes, requièrent une attention particulière, car dans ce cas, les surtensions à front lent générées par les défauts à la terre peuvent être plus importantes.

8.3.3 Surtensions à l'enclenchement et au réenclenchement

Les surtensions à l'enclenchement présentent un intérêt pour toutes les lignes aériennes, et spécialement pour la plage II. Les taux de défaillance admissibles sont compris entre 0,005 et 0,05 contournement par an.

Les surtensions au réenclenchement exigent de l'attention dans le cas des lignes de transport, en cas de refermeture rapide triphasée (à cause des charges piégées). Les taux de défaillance admissibles sont compris entre 0,005 et 0,05 contournement par an.

Les surtensions au réenclenchement peuvent être négligées en cas de refermeture monophasée sur les lignes de transport ou sur les lignes de distribution dont les transformateurs demeurent connectés pendant cette opération.

Les surtensions à front lent sont l'un des facteurs qui déterminent les distances dans l'air, ainsi que les accessoires de montage de certains types d'isolateurs. L'importance de ce facteur est généralement limitée aux lignes de transport d'une tension de réseau égale ou supérieure à 123 kV. Si des chaînes de suspension sont utilisées, les distances dans l'air pour les surtensions à front lent sont généralement déterminées en prenant pour hypothèse des conditions de balancement modérées (moyennes). Sur les lignes de distribution, les distances dans l'air sont généralement fonction de l'isolateur (voir 8.2) et il n'est pas nécessaire de prendre en considération les surtensions à front lent.

8.4 Coordination de l'isolement vis-à-vis des surtensions de foudre

8.4.1 Généralités

La performance des lignes aériennes vis-à-vis de la foudre dépend d'un ensemble de facteurs, les plus importants étant

- la densité du foudroisement,
- la hauteur de la ligne aérienne,
- la configuration des conducteurs,
- la protection assurée par les câbles de garde,
- la mise à la terre des pylônes,
- la résistance d'isolement, et
- l'utilisation des parafoudres de ligne.

8.4.2 Lignes de distribution

Dans le cas des lignes de distribution, il convient de partir de l'hypothèse selon laquelle chaque coup de foudre direct sur la ligne provoque un contournement entre phases, avec ou sans contournement à la terre. La protection par câble de garde est inutile, dans la mesure où la mise à la terre des pylônes et la résistance d'isolement ne peuvent pas être améliorées

dans des conditions économiquement acceptables à un niveau permettant d'éviter tout amorçage en retour. La performance des lignes de distribution vis-à-vis de la foudre dépend donc largement de la densité du foudroïement et de la hauteur de ces lignes.

Dans le cas des lignes de distribution équipées de consoles non mises à la terre (lignes à poteaux en bois), les surtensions induites par des coups de foudre au sol tombant à proximité sont sans importance. Cependant, la rigidité diélectrique élevée par rapport à la terre entraîne des surtensions d'amplitudes élevées arrivant sur les postes. Dans ce cas, il convient de veiller à effectuer un choix approprié des parafoudres de poste (exigences énergétiques).

Dans le cas de lignes de distribution équipées de consoles mises à la terre, les surtensions induites peuvent affecter la tenue au choc de foudre exigée de l'isolation des lignes aériennes.

8.4.3 Lignes de transport

Sur les lignes de transport supérieures à 72,5 kV, les tensions induites peuvent être négligées, et seuls les coups de foudre directs tombant sur la ligne déterminent sa performance vis-à-vis de la foudre. Il n'est pas possible de fournir des recommandations d'ordre général sur un taux de performance approprié, dans la mesure où celui-ci dépend en grande partie des conséquences d'une coupure due à la foudre et des coûts de l'amélioration du blindage, de la mise à la terre et de la résistance d'isolement. Cependant, il est possible d'adopter, pour le tronçon de ligne situé en amont des postes, des taux de coupure moins élevés que sur les autres tronçons, afin de réduire les amplitudes et la fréquence des surtensions sur le poste et de réduire la probabilité de défauts proches en ligne (voir l'IEC 62271-100).

9 Points particuliers concernant les postes

9.1 Remarques générales

9.1.1 Aperçu

Les contraintes de tension qui peuvent se produire dans un poste (voir la Figure 11) sont décrites de 9.1.2 à 9.1.5 ci-dessous.

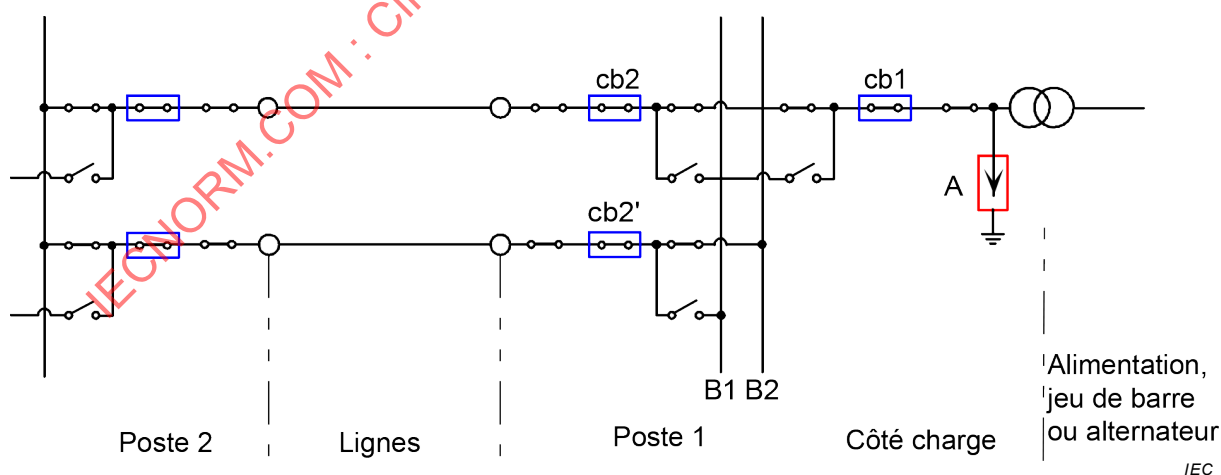


Figure 11 – Exemple de disposition schématique de poste utilisé pour la localisation des contraintes

9.1.2 Tension de service

Elle est par hypothèse égale à la tension la plus élevée du réseau. Tous les organes du poste font l'objet de contraintes égales.

9.1.3 Surtension temporaire

Les défauts à la terre du côté de la charge génèrent des contraintes identiques sur tous les éléments d'une phase du poste.

Des surtensions de perte de charge peuvent se produire dans le poste par suite d'un défaut dans le poste distant (poste 2). Selon la protection adoptée, tous les organes ou ceux qui sont placés entre le disjoncteur cb2 et le transformateur, sont soumis à des contraintes. En cas de défaut du poste lui-même (poste 1), seuls les organes situés entre le disjoncteur cb1 et le transformateur font l'objet de surtensions de perte de charge.

Si le transformateur est relié à un alternateur, des contraintes de surtension longitudinale peuvent se produire au niveau du disjoncteur cb1 pendant la phase de synchronisation. Si le jeu de barres B2 se trouve sur un réseau différent, l'isolation longitudinale des sectionneurs de jeu de barres peut être soumise à la tension de service sur le jeu de barres B2 et à la surtension de perte de charge sur le jeu de barres B1, en opposition de phase.

9.1.4 Surtensions à front lent

Les surtensions à l'enclenchement ou au réenclenchement de la ligne ne peuvent présenter des amplitudes élevées du côté aval qu'entre l'entrée de la ligne et le disjoncteur cb2. Les autres organes du poste sont soumis aux surtensions à l'entrée.

Tous les éléments du poste peuvent être affectés par des surtensions provoquées par des défauts ou par l'élimination de défauts.

9.1.5 Surtensions à front rapide

Tous les éléments du poste peuvent être soumis à des surtensions de foudre. L'amplitude de ces surtensions dépend toutefois de leur distance par rapport au parafoudre.

Des surtensions de manœuvre à front rapide ne peuvent se produire que sur les parties connectées du poste (sur le jeu de barres B2, par exemple) ou au niveau de l'un des disjoncteurs lorsqu'ils sont connectés par l'un des sectionneurs de jeu de barres.

Les différentes étapes de la coordination de l'isolement sont présentées dans trois exemples de l'Annexe G.

Le comité de produit concerné ayant notamment pour tâche de spécifier les tensions d'essai à fréquence industrielle de longue durée appropriées, les tensions de tenue spécifiées correspondantes ne sont pas vérifiées dans cet exemple.

Au départ, une seule ligne peut être sous tension. Il convient alors de prendre en considération les surtensions temporaires résultant d'une perte de charge consécutive à un défaut à la terre.

Si les transformateurs sont alimentés par une longue ligne, ils peuvent être affectés, ainsi que le jeu de barres, par des surtensions à front lent.

Il convient de prendre en considération sur les GIS les surtensions à front très rapide dues à des manœuvres du sectionneur.

9.2 Coordination de l'isolement vis-à-vis des surtensions

9.2.1 Postes sur des réseaux de distribution avec U_m jusqu'à 36 kV, dans la plage I

9.2.1.1 Généralités

Pour le matériel de cette plage de tensions, l'IEC 60071-1 spécifie la tension normalisée de tenue à fréquence industrielle de courte durée assignée et la tension normalisée de tenue au choc de foudre assignée.

À titre d'indication générale, il peut être pris pour hypothèse que, dans la plage de tensions de distribution, la tension de tenue au choc de manœuvre exigée phase-terre est couverte par la tension normalisée de tenue à fréquence industrielle de courte durée. La tension de tenue au choc de manœuvre exigée entre phases doit toutefois être prise en considération dans le choix de la tension normalisée de tenue au choc de foudre ou de la tension de tenue à fréquence industrielle de courte durée.

Si les surtensions entre phases à front lent ont été adaptées, un matériel adapté aux valeurs de tension normalisée de tenue au choc de foudre, issues du Tableau 2 de l'IEC 60071-1:2006, peut être utilisé, notamment, sur les installations suivantes:

- a) réseaux et installations industrielles non reliés à des lignes aériennes;
- b) réseaux et installations industrielles reliés à des lignes aériennes uniquement par des transformateurs, la capacité à la terre des câbles raccordés aux bornes basse tension de ces transformateurs étant au moins égale à 0,05 μ F par phase; si la capacité du câble par rapport à la terre est insuffisante, il convient d'ajouter des condensateurs côté transformateur de l'appareil, le plus près possible des bornes de ce dernier. La capacité combinée des câbles et des condensateurs supplémentaires par rapport à la terre est alors d'au moins 0,05 μ F par phase;
- c) réseaux et installations industrielles reliés directement à des lignes aériennes, des parafoudres assurant une protection appropriée contre les surtensions.

Dans tous les autres cas, ou lorsqu'un très haut niveau de sécurité est exigé, il convient d'utiliser un matériel adapté à la tension de tenue assignée au choc de foudre supérieure.

9.2.1.2 Matériel relié à une ligne aérienne par l'intermédiaire d'un transformateur

Le matériel relié au côté basse tension d'un transformateur alimenté côté haute tension par une ligne aérienne n'est pas directement soumis aux surtensions de foudre ou aux surtensions de manœuvre qui prennent naissance sur cette ligne. Cependant, ce matériel peut être soumis à des surtensions qui se transmettent de l'enroulement haute tension à l'enroulement basse tension du transformateur par couplage électrostatique et électromagnétique. Ces surtensions doivent être prises en considération dans la procédure de coordination de l'isolement, en envisageant éventuellement d'utiliser des systèmes de protection.

L'Annexe D donne l'expression analytique des composantes électrostatiques et électromagnétiques de la tension transmise.

9.2.1.3 Matériel relié à une ligne aérienne par l'intermédiaire d'un câble

Dans ce cas, la coordination de l'isolement passe non seulement par la protection du matériel du poste, mais aussi par celle du câble.

Lorsqu'un coup de foudre se propage le long d'une ligne aérienne et attaque un câble, il se décompose en une onde réfléchie et une onde transmise, l'amplitude de cette dernière étant beaucoup plus faible que celle de la surtension incidente. Cependant, les réflexions ultérieures à chaque extrémité du câble entraînent une augmentation importante de la tension le long du câble par rapport à cette valeur initiale. Il convient généralement de sélectionner les tensions de tenue assignées au choc de foudre normalisées supérieures dans le

Tableau 2 de l'IEC 60071-1:2006 et d'installer des parafoudres au niveau de la jonction ligne/câble. Si la ligne aérienne comporte des poteaux en bois et si une seule ligne peut être reliée au poste, il peut être nécessaire d'implanter des parafoudres supplémentaires à l'entrée du câble dans le poste.

9.2.2 Postes de réseaux de transport dont U_m est comprise entre 52,5 kV et 245 kV dans la plage I

Pour le matériel de cette plage de tensions, l'IEC 60071-1 spécifie la tension normalisée de tenue à fréquence industrielle de courte durée assignée et la tension normalisée de tenue au choc de foudre assignée.

À titre d'indication générale, il peut être pris pour hypothèse que, dans la plage I de tensions de transport, la tension de tenue au choc de manœuvre exigée phase-terre est couverte par la tension normalisée de tenue à fréquence industrielle de courte durée. Les tensions de tenue au choc de manœuvre exigées entre phases doivent toutefois être prises en considération lors du choix de la tension de tenue au choc de foudre ou de la tension normalisée de tenue à fréquence industrielle de courte durée applicable au matériel implanté à l'entrée de la ligne. Sinon, il peut être nécessaire de soumettre le matériel triphasé à des essais supplémentaires au choc de manœuvre entre phases.

Pour la détermination de la tension de tenue au choc de foudre, de nombreuses considérations relatives à la plage de tensions de distribution s'appliquent également à la plage de tensions de transport, à l'intérieur de la plage I. Cependant, dans la mesure où la disparité des matériels et de leurs implantations est moins grande, il est recommandé de suivre la procédure de coordination de l'isolement pour un certain nombre de combinaisons représentatives ligne aérienne-poste, en utilisant au moins les procédures simplifiées décrites à l'Annexe E.

9.2.3 Postes de réseaux de transport dans la plage II

Pour le matériel de cette plage de tensions, l'IEC 60071-1 spécifie la tension normalisée de tenue au choc de manœuvre assignée et la tension normalisée de tenue au choc de foudre assignée.

Dans cette plage de tensions, il convient généralement d'utiliser les méthodes statistiques pour la coordination de l'isolement. Il convient d'étudier avec attention la fréquence des surtensions, dues aussi bien à des manœuvres qu'à des défauts et des foudroiements, en tenant compte de l'emplacement du matériel dans le poste (en distinguant entre le matériel situé en entrée ou en sortie des lignes alimentées, par exemple). De plus, la méthode déterministe de coordination de l'isolement reposant sur les surtensions temporaires peut donner lieu à une détermination trop prudente des tensions de tenue normalisées. Il convient donc de mettre en œuvre des procédures plus précises, qui tiennent compte de la durée effective des surtensions et de la caractéristique tension-temps de tenue à la fréquence industrielle de l'isolation.

Annexe A (informative)

Détermination des surtensions temporaires dues à des défauts à la terre

Le facteur de défaut à la terre est, en un emplacement donné d'un réseau triphasé, et pour un schéma d'exploitation donné de ce réseau, le rapport entre, d'une part, la tension efficace la plus élevée, à la fréquence du réseau, entre une phase saine et la terre pendant un défaut à la terre affectant une phase quelconque ou plusieurs phases en un point quelconque du réseau, et d'autre part la valeur efficace de la tension entre phase et terre à la fréquence du réseau qui serait obtenue à l'emplacement considéré en l'absence du défaut (voir la définition 3.15 de l'IEC 60071-1:2006).

Le facteur de défaut à la terre est calculé à partir des impédances complexes Z_1 et Z_0 des systèmes direct et homopolaire, en tenant compte de la résistance de défaut R . Les relations suivantes sont à prendre en considération:

$Z_1 = R_1 + jX_1$: résistance et réactance des systèmes directs et inverses;

$Z_0 = R_0 + jX_0$: résistance et réactance du système homopolaire;

(les facteurs de défaut à la terre sont calculés à l'endroit du défaut).

Il convient de noter que dans les réseaux étendus compensés par bobine d'extinction, le facteur de défaut à la terre peut être plus élevé à des endroits autres que l'emplacement du défaut.

La Figure A.1 représente la situation globale lorsque $R_1 \ll X_1$ et $R = 0$.

La plage des valeurs élevées de X_0/X_1 , en positif et/ou en négatif, s'applique aux réseaux à neutre compensé par bobine d'extinction ou aux réseaux à neutre isolé.

La plage des faibles valeurs positives de X_0/X_1 est valide pour les réseaux à neutre à la terre.

La plage des faibles valeurs négatives de X_0/X_1 indiquée par des hachures ne convient pas à un usage pratique à cause de l'existence de résonances.

Pour les réseaux à neutre à la terre, les représentations de la Figure A.2 à Figure A.5 indiquent les facteurs de défaut à la terre sous la forme de familles de courbes correspondant à des valeurs particulières de R_1/X_1 .

Ces courbes sont composées de zones représentant les conditions de fonctionnement les plus critiques avec le repérage suivant:

- _____ La tension maximale apparaît, pendant un défaut à la terre, sur la phase qui est en avance par rapport à la phase en défaut.
- La tension maximale apparaît, pendant un défaut à la terre, sur la phase qui est en retard par rapport à la phase en défaut.
- La tension maximale apparaît pendant un défaut à la terre sur les phases saines.

Les courbes sont valides pour les valeurs de résistance de défaut produisant les facteurs de défaut à la terre les plus élevés.