TECHNICAL REPORT

IEC TR 61000-2-14

First edition
2006-12

Electromagnetic compatibility (EMC) –

**Part 2-14:
Environment – Overvoltages on public electricity distribution networks**

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CONTENTS

FOREWORD....4
INTRODUCTION....6

1 Scope....7
2 Normative references....7
3 Terms and definitions....7
4 Description of overvoltages....10
4.1 General....10
4.2 External overvoltages....11
4.3 Internal overvoltages....11
4.4 Overvoltage waveshape....11
5 Long duration overvoltages....12
5.1 Sustained earth faults....12
5.2 Broken neutral on LV network....12
5.3 Maloperation of voltage regulating equipment....13
5.4 Overvoltages due to voltage unbalances....13
5.5 Dispersed generation....14
6 Short duration overvoltages....15
6.1 Earth faults....15
6.2 Load rejection (sudden load loss)....16
6.3 Self-excitation....16
6.4 Resonance and ferroresonance....16
7 Very short duration overvoltages (transients)....18
7.1 General description....18
7.2 Lightning....19
7.3 Switching....20
7.4 Summary of surge duration and cause....26
8 Effects of overvoltages on equipment....27
8.1 General considerations....27
8.2 Reduction in life of filament lamps....28
8.3 Effect of overvoltages on IT equipment....28
9 Case studies....29
9.1 General....29
9.2 Switching of LV power factor correction capacitor....29
9.3 Metal fusion furnace....30
9.4 Switching of MV power factor correction capacitor....31
9.5 DC traction system....32
9.6 Load switching....34
10 Protection against the effects of overvoltages....36
10.1 General considerations....36
10.2 Point on wave switching....36
10.3 Arcing horns and spark gaps....37
10.4 Overvoltage protection relays....38
10.5 Snubbers (high frequency RC filter)....38
10.6 Uninterruptible power supply (UPS) systems....39

10.7 Surge protection device (SPD) 39
11 Conclusions 41
12 Recommendations 42

Bibliography 43

Figure 1 – Lightning impulse test voltage characteristic 11
Figure 2 – Broken neutral on LV network 13
Figure 3 – The effect of distributed generation on network voltage 14
Figure 4 – Line – Neutral temporary overvoltage on healthy phase for single phase line – earth fault 15
Figure 5 – Typical transient overvoltage when energizing a capacitor bank 22
Figure 6 – Notching caused by power electronics switching 24
Figure 7 – ITI (CBEMA) curve for equipment connected to 120 V 60 Hz systems 29
Figure 8 – Voltage waveform distorted by the energization of a PFC capacitor 30
Figure 9 – Phase to ground overvoltage in case of a single (a) or multiple (b) faults 30
Figure 10 – Equivalent circuit 31
Figure 11 – Extruder connection – single line diagram 32
Figure 12 – Current waveforms (phases A and C) taken at the main LV circuit breaker 32
Figure 13 – Single line diagram of public transportation system 33
Figure 14 – Voltage waveforms associated with overvoltages on public transportation system 34
Figure 15 – 20 kV line-to-earth voltages during breaking transformer current 35
Figure 16 – Spark gap 37
Figure 17 – Two-stage surge protection scheme 40

Table 1 – Surges on the low voltage network 26
Table 2 – Surges on the medium voltage network 27
Table 3 – Reduction of filament lamp life 28
Table 4 – Protective levels for typical MV surge arresters (effectively earthed neutral systems) 41

INTERNATIONAL ELECTROTECHNICAL COMMISSION

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ELECTROMAGNETIC COMPATIBILITY (EMC) –

Part 2-14: Environment – Overvoltages on public electricity distribution networks

FOREWORD

1) The International Electrotechnical Commission (IEC) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, IEC publishes International Standards, Technical Specifications, Technical Reports, Publicly Available Specifications (PAS) and Guides (hereafter referred to as "IEC Publication(s)"). Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.
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The main task of IEC technical committees is to prepare International Standards. However, a technical committee may propose the publication of a technical report when it has collected data of a different kind from that which is normally published as an International Standard, for example "state of the art".

IEC 61000-2-14, which is a technical report, has been prepared by subcommittee 77A: Low frequency phenomena, of IEC technical committee 77: Electromagnetic compatibility.

The text of this technical report is based on the following documents:

Enquiry draft	Report on voting
77A/540/DTR	77A/547/RVC

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

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

The committee has decided that the contents of this publication will remain unchanged until the maintenance result date indicated on the IEC web site under "http://webstore.iec.ch" in the data related to the specific publication. At this date, the publication will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

A bilingual version of this publication may be issued at a later date.

INTRODUCTION

IEC 61000 is published in separate parts according to the following structure:

Part 1: General

General considerations (introduction, fundamental principles)

Definitions, terminology

Part 2: Environment

Description of the environment

Classification of the environment

Compatibility levels

Part 3: Limits

Emission limits

Immunity limits (in so far as they do not fall under the responsibility of the product committees)

Part 4: Testing and measurement techniques

Measurement techniques

Testing techniques

Part 5: Installation and mitigation guidelines

Installation guidelines

Mitigation methods and devices

Part 6: Generic standards

Part 9: Miscellaneous

Each part is further subdivided into several parts, published either as International Standards or as technical specifications or technical reports, some of which have already been published as sections. Others will be published with the part number followed by a dash and a second number identifying the subdivision (example: 61000-6-1).

ELECTROMAGNETIC COMPATIBILITY (EMC) –

Part 2-14: Environment – Overvoltages on public electricity distribution networks

1 Scope

This part of IEC 61000 describes the electromagnetic environment with respect to the voltages in excess of normal that are found on electricity supply networks operating at low and medium nominal voltages and that can be impressed on equipment connected to those networks, without considering further effects (e.g. amplification or attenuation) within an installation. Since these overvoltages have the potential to hinder the functioning of electrical and electronic equipment, they fall within the definition of *electromagnetic disturbance* in the field of EMC. Various categories of overvoltage are described, based on relative magnitude, duration and energy content.

This Technical Report describes the phenomena of overvoltages, it does not specify compatibility levels and does not directly specify emission and immunity levels.

The report describes the various phenomena and processes that cause overvoltages, including the transfer into the networks concerned of overvoltages that originate in or traverse other networks and installations, including higher voltage networks and the installations of electricity users. The effects of overvoltages on equipment are outlined. Some case studies of overvoltage events are presented.

Recommendations are made regarding the general technical approach to mitigating the risk of equipment being hindered from operating as intended by the effects of overvoltages. (It is not the function of IEC publications to assign responsibility for mitigating measures to any of the parties involved.)

The purpose of this report is to ensure that this important category of electromagnetic disturbance is included in the description of the environment in Part 2 of IEC 61000. For that purpose, only a brief description is provided of the various overvoltages and their causes and effects. A much more detailed treatment can be found in IEC 62066. A UIE publication – *Guide to quality of electrical supply for industrial installations, Part VI: Transient and temporary overvoltages and currents* – has a similar content. Measurement methods are specified in IEC 61000-4-30.

NOTE This Technical Report does not include detailed measurement results for overvoltages, therefore it is not possible to provide an assessment of the probability of occurrence.

2 Normative references

The following referenced documents are indispensable for the application 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 60050-161, *International Electrotechnical Vocabulary (IEV) – Chapter 161: Electromagnetic compatibility*

3 Terms and definitions

For the purposes of this document, the terms and definitions contained in IEC 60050-161 as well as the following terms and definitions apply.

3.1
back flashover
flashover of phase-to-earth insulation resulting from a lightning stroke to that part of the system which is normally at earth potential

3.2
breakdown
dielectric failure of an insulation under the effect of a strong electric field and/or by physico-chemical deterioration of the insulating material

3.3
direct lightning stroke
lightning striking a component of the network, e.g.: conductor, tower, substation equipment, etc.

3.4
declared supply voltage
U_c
normally the nominal voltage of the system. If by agreement between the electricity supplier and the consumer a voltage different from the nominal voltage is applied to the supply terminals, then this voltage is the declared voltage

3.5
disruptive discharge/flashover/sparkover
passage of an arc following dielectric breakdown

NOTE 1 The term “sparkover” (in French: “amorçage”) is used when a disruptive discharge occurs in a gaseous or liquid dielectric.

NOTE 2 The term “flashover” (in French: “contournement”) is used when a disruptive discharge occurs over the surface of a solid dielectric surrounded by a gaseous or liquid medium.

NOTE 3 The term “puncture” (in French: “perforation”) is used when a disruptive discharge occurs through a solid dielectric.

3.6
indirect lightning stroke
lightning stroke that does not strike directly any part of the network but that induces an overvoltage in that network

3.7
insulation coordination
selection of the dielectric strength of equipment in relation to the operating voltages and overvoltages which can appear on the system for which the equipment is intended to operate, taking into account the service environment and the characteristics of the available prevention and protective devices

[IEV 604-03-08, modified]

NOTE In this instance, the term "dielectric strength of the equipment" means its rated or its standard insulation level as defined in IEC 60071-1.

3.8
lightning arrester
surge diverter
/surge arrester/
surge protective device (SPD)
device designed to protect the electrical apparatus from high transient overvoltages and to limit the duration and frequently the amplitude of the follow-on current

3.9
lightning impulse
voltage impulse of a specified shape applied during dielectric tests with a virtual front duration of the order of 1 μs and a time to half value of the order of 50 μs

NOTE The lightning impulse is defined by the two figures giving these durations in microseconds; in particular the standard lightning impulse is: 1,2/50 μs.

3.10
long duration overvoltages
overvoltage with a duration in excess of 10 min

NOTE The magnitude of a long duration overvoltage is typically given as a r.m.s. value.

3.11
nominal voltage
U_N
the voltage by which a system is designated or identified

3.12
overvoltage
any voltage having a value, either peak or r.m.s., exceeding the maximum value of the corresponding declared voltage

3.13
per unit (p.u.)
methodology used to simplify equations and the presentation of electrical parameters by expressing them as a fraction of a reference parameter:

$$\text{p.u. value} = \left(\frac{\text{Actual}}{\text{Base}}\right)$$

where the Actual and Base values are of the same quantity, e.g. voltage, current, impedance etc.

NOTE Typically the Base value for voltage is the nominal voltage for fundamental frequency phenomena and the peak line to ground voltage for transients.

3.14
power frequency withstand voltage
r.m.s. value of sinusoidal power frequency voltage that the equipment can withstand during tests made under specified conditions and for a specified time

3.15
rise time (of a pulse)
the interval of time between the instants at which the instantaneous value of a pulse first reaches a specific lower value and then a specific upper value

NOTE Unless otherwise specified, the lower and upper values are fixed at 10 % and 90 % of the pulse magnitude.

3.16
short duration overvoltage
voltage swell
power frequency overvoltage with a duration lasting greater than one period (one cycle) and up to 10 min

NOTE The magnitude of a short duration overvoltage is typically given as a r.m.s. value.

3.17
surge
transient voltage wave propagating along a line or a circuit and characterized by a rapid increase followed by a slower decrease of the voltage

[IEV 161-8-11]

NOTE In some parts of the world the term "Impulse" is used to describe a short duration overvoltage characterised by a very rapid change in magnitude with a duration less than 200 µs.

3.18
temporary overvoltage
oscillatory overvoltage (at power frequency) at a given location, of relatively long duration and which is undamped or weakly damped

NOTE Temporary overvoltages usually originate from switching operations or faults (e.g. sudden load rejection, single-phase faults) and/or from non-linearities (ferroresonance effects, harmonics).

3.19
transient
pertaining to or designating a phenomenon or a quantity which varies between two consecutive steady states during a time interval short when compared with the time-scale of interest

[IEV 161-02-01]

3.20
very short duration overvoltage (transient)
overvoltage with a duration from less than a microsecond to several periods at fundamental frequency

NOTE The magnitude of a very short duration overvoltage is typically given as a peak value.

3.21
voltage impulse
transient voltage wave applied to a line or equipment, characterized by a rapid increase, followed generally by a slower non-oscillatory decrease of the voltage

3.22
front time
T_1
for a lightning impulse voltage T_1 is a virtual parameter defined as 1,67 times the interval T between the instants when the impulse is 30 % and 90 % of the peak value on the test voltage curve (points A and B, Figure 1)

3.23
time to half-value
T_2
for a lightning impulse voltage T_2 is a virtual parameter defined as the time interval between the virtual origin, O_1, and the instant when the test voltage curve has decreased to half the peak value

4 Description of overvoltages

4.1 General

Overvoltages are an intrinsic phenomena present on all networks. Overvoltage events can be created in the public network or in the electricity user's installation. The dynamic response of a network to load switching, both planned and unplanned (faults) will result in the storage and release of energy. This transfer of energy will cause an overvoltage to be propagated within the network.

4.2 External overvoltages

Overvoltages that are caused by events that are external to an installation, for example: lightning strokes and faults on adjacent higher voltage networks, are generally very short term overvoltage travelling waves. They attenuate with distance and the wave front becomes less steep. In addition there are longer term overvoltages caused by load rejection, open circuit neutrals, faulty voltage control equipment and the effect of distributed generation.

4.3 Internal overvoltages

Events within an installation can give rise to overvoltages, for example: the switching of non-linear load, switch arcing, and fuse operation.

4.4 Overvoltage waveshape

A common method of representing the waveshape of a very short term overvoltage is shown in Figure 1. The important values are the front time, T_1 and the time to half-value, T_2. For example, typical values for a transient overvoltage caused by lightning are 1,2 µs for the front time and 50 µs for the time to half-value (a 1,2/50 µs waveform).

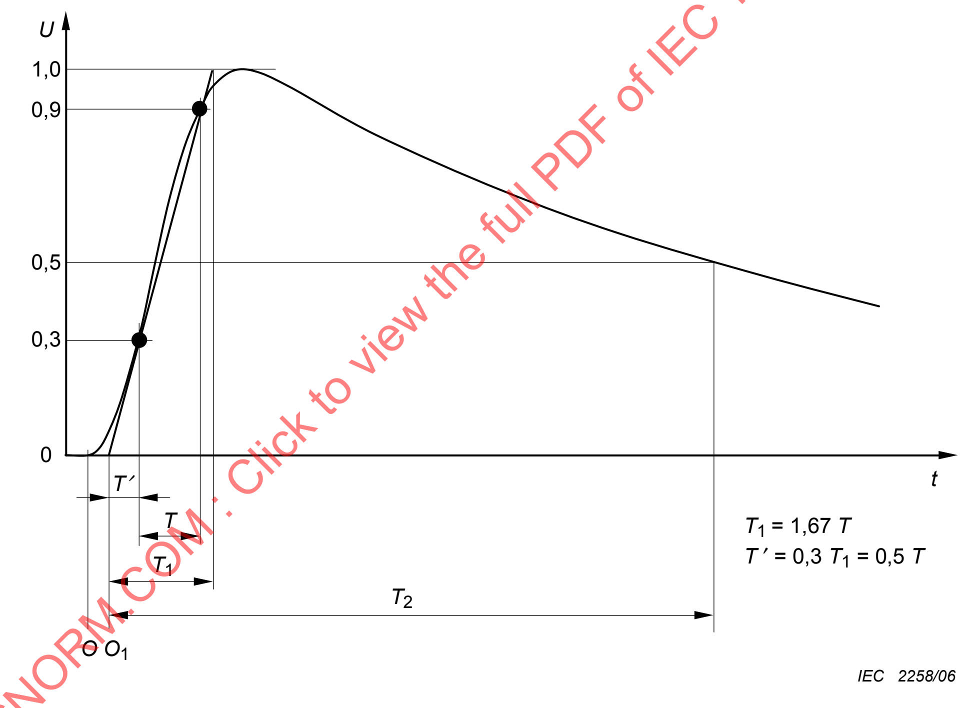


Figure 1 – Lightning impulse test voltage characteristic

NOTE Figure 1 is only meant to represent an example of one type of overvoltage. Other types of overvoltage are described in IEC 60071-2.

Other very short duration overvoltages having the shape of a damped high frequency oscillation can be caused by events such as energizing capacitor banks, although their amplitude is often much lower than an overvoltage caused by a lightning stroke, and the rate of occurrence can often be higher. This type of very short duration overvoltage can propagate over long distances and across voltage levels, hence adverse effects can often be seen some distance from the point of initiation. This is particularly true when the overvoltages are transferred to the lower voltage networks where the resilience of equipment is at its lowest. The situation at all voltage levels can be further exacerbated if a resonance condition is created, i.e. when the frequency of the transient overvoltage is close to the natural frequency of the network and or equipment connected to the network.

When more than one type of overvoltage event occurs simultaneously, it can lead to overvoltages in excess of the values quoted for a single event.

5 Long duration overvoltages

The overvoltages presented in this clause are typically described as being of long duration, however it should be noted that there will be instances where for a particular event the overvoltage could last for less than 10 min.

The overvoltages presented in this section are 50/60 Hz overvoltages.

5.1 Sustained earth faults

In MV networks with isolated or high-impedance grounded neutral, this kind of fault will produce line to earth temporary overvoltages on the healthy phases. The overvoltage will last for the duration of the fault, this can be anything from parts of a second for conventionally earthed systems up to some hours for systems earthed via a tuned reactance (Petersen coil earthing). Generally the magnitude of the overvoltage will not exceed twice the nominal phase to earth voltage, i.e. $\sqrt{3} \times U$, where U can be up to $1{,}1 \times U_N$ if the voltage is at the maximum of the acceptable MV range. The overvoltages last until the faulted section of network is disconnected.

Earth faults on the MV network can result in temporary power frequency overvoltages between live conductors and earth on the LV network. The duration and magnitude of these overvoltages will be dependent on the fault conditions and the MV earth impedance, as described above.

The majority of public LV distribution systems are operated with a solidly earthed (grounded) neutral. Therefore when earth faults occur on the MV network that raise the ground potential in the vicinity of the LV network it is possible for an overvoltage to exist between the phase and earth conductors of the LV network. The duration is limited by the time taken for the MV protection and circuit breaker to clear the fault, typically no more than 5 s. The magnitude of the overvoltage will generally not exceed 1,5 kV r.m.s., however this is dependent upon the impedance of the LV ground connection and the magnitude of the MV earth fault current. IEC 62066 contains a comprehensive description of this type of overvoltage.

5.2 Broken neutral on LV network

For a three-phase LV network supplied from a star (wye) transformer winding or for a two phase network supplied from a transformer with a centre-tapped neutral at LV (sometimes referred to as a three-wire network), if the neutral becomes disconnected (e.g. broken due to a fault), single-phase loads beyond the break could experience an overvoltage up to the line voltage of the network. The exact magnitude of the voltage will be dependent upon the ratio of the impedance (loads) connected across each phase of the network – see Figure 2 below. This type of overvoltage can persist for several hours or, in rare cases, days until the neutral has been reconnected or the faulty network has been disconnected in readiness for repair. This disconnection is often by manual intervention following complaints of severe voltage fluctuations which occur as a result of changes in load.

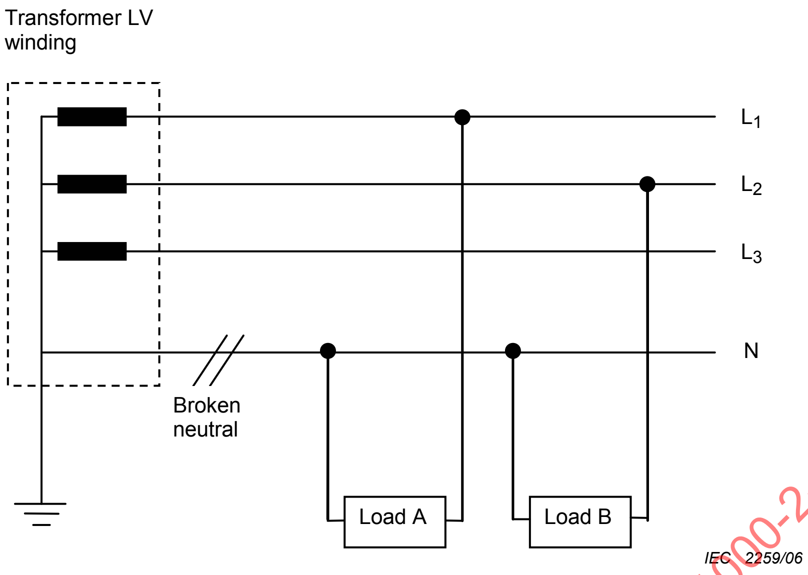


Figure 2 – Broken neutral on LV network

In the event of a broken neutral as shown in Figure 2 above, the voltage that appears across load A and load B is determined by the relative magnitude of these two loads, i.e.:

$$\text{Voltage across load A } (U_A) = U_{L_1L_2} \cdot \left(\frac{Z_A}{Z_A + Z_B}\right); \text{ and}$$

$$\text{Voltage across load B } (U_B) = U_{L_1L_2} - U_A$$

Hence, depending upon the values of Z_A and Z_B it is possible for U_A to vary between near zero and full line voltage ($U_{L_1L_2}$).

NOTE Depending on the impedances and their phase shift, the voltage on the unloaded phase, phase L_3 (L_3-N), could theoretically be higher than the full line voltage.

5.3 Maloperation of voltage regulating equipment

Maloperation of automatic voltage regulation systems can sometimes lead to long duration overvoltages between 1,1 and 1,2 p.u. at most. For instance, this could be due to a loss of regulator voltage reference causing the tap changer to boost the voltage at its maximum, or inadequate line drop compensation settings following unplanned load transfer on a regulating transformer. Appropriate voltage regulator blocking relays can minimize risks of such situations.

5.4 Overvoltages due to voltage unbalances

The combined effect of voltage unbalances and steady state voltage close to the maximum agreed voltage tolerance can result in long duration overvoltages. This is the case in particular for effectively earthed distribution systems supplying single-phase loads connected line-to-neutral through an equivalent Y-y earthed MV/LV transformer connection (typical in North America). In such cases, not only negative-sequence voltages can be transferred due to load unbalance, but also zero-sequence voltages as well. The latter also depends on the zero-sequence system impedance. In some cases, the combination of steady state voltages near the upper limit, and the negative-sequence plus the zero-sequence voltage unbalances can lead to permanent line-to-neutral voltages on some phases in the range of 1,1 p.u. at MV and LV. Voltage regulators whose voltage reference is connected line-to-neutral can however compensate the effect of zero sequence voltage unbalance thus reducing risks of this kind of overvoltage.

5.5 Dispersed generation

In the absence of distributed generation it is typical for public distribution networks to have been designed on the basis that energy flows in one direction i.e. from the source (substation) to the point of utilization. Therefore it is typical for the voltage to be a maximum at the source and to decrease with distance away from the source.

In some areas it is typical for MV/LV transformers to have an adjustable transformation ratio (tap setting). The tap setting can only be adjusted off load and is selected with a view to offsetting the voltage drop in the MV network.

MV and LV networks are designed such that under conditions of no load the voltage at source, be it MV or LV, is as close as possible to the maximum agreed voltage tolerance. This should ensure that the supply delivered to loads at the remote end of the network will remain within agreed tolerances at times of peak demand.

The presence of distributed generation within the network can have the effect of increasing the voltage level at the point of connection and therefore modifying the voltage distribution profile. In Figure 3, the lower curve shows how the network voltage decreases with distance from source, while the upper curve shows how the voltage profile can be raised if distributed generation (DG) is connected between the source and the receiving end. This effect is exacerbated if generation export coincides with periods of low demand (load) on the network.

NOTE For the purposes of describing Figure 3, only the terms U_R and U_{RDG} are introduced.

In the absence of distributed generation the voltage at the receiving end is U_R and as mentioned previously, MV/LV transformers with off-load tap settings have been adjusted to compensate for the line voltage drop ΔV. If distributed generation is connected to the network, the receiving end voltage is raised to U_{RDG} and the LV will also rise. In the absence of suitable voltage regulation or overvoltage protection it is possible that the distributed generation could cause the network voltage to exceed agreed tolerance levels.

For networks with high source impedance (sometimes referred to as “weak networks”) the risk of voltage rise could be the limiting factor in determining the amount of distributed generation that can be connected.

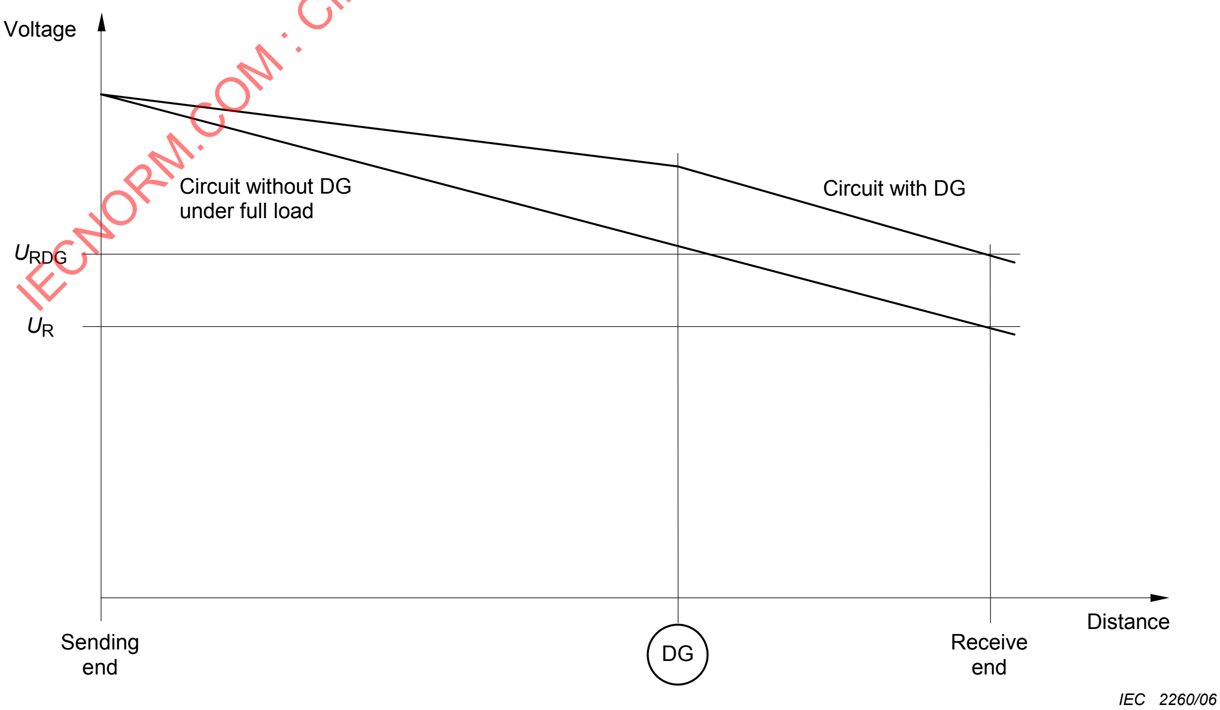


Figure 3 – The effect of distributed generation on network voltage

6 Short duration overvoltages

6.1 Earth faults

As explained in section 4 the method of earthing and the value of the neutral to earth impedance will determine the magnitude of overvoltage that will occur on the healthy phases during earth faults. Various types of neutral earthing are used from solid or effective to the high impedance earthing.

The term *effectively earthed neutral* applies to a system, or portion of the system, where the ratio of zero-sequence reactance to positive-sequence reactance is positive and not greater than 3 and the ratio of zero-sequence resistance to positive-sequence reactance is positive and not greater than 1, as viewed from a considered location for any condition of operation:

$$0 \le X_0/X_1 \le 3 \text{ and } 0 \le R_0/X_1 \le 1$$

where

X_1 is the positive-sequence reactance;

X_0 is the zero-sequence reactance;

R_0 is the zero-sequence resistance.

For effectively earthed neutral systems, the overvoltage on the healthy phases is limited to less than 1,4 p.u.

Figure 4 below illustrates the maximum line to neutral (L-N) overvoltage on healthy phases for different values of the impedance factors X_0/X_1 and R_0/X_1 used for defining the effectiveness of the neutral earthing

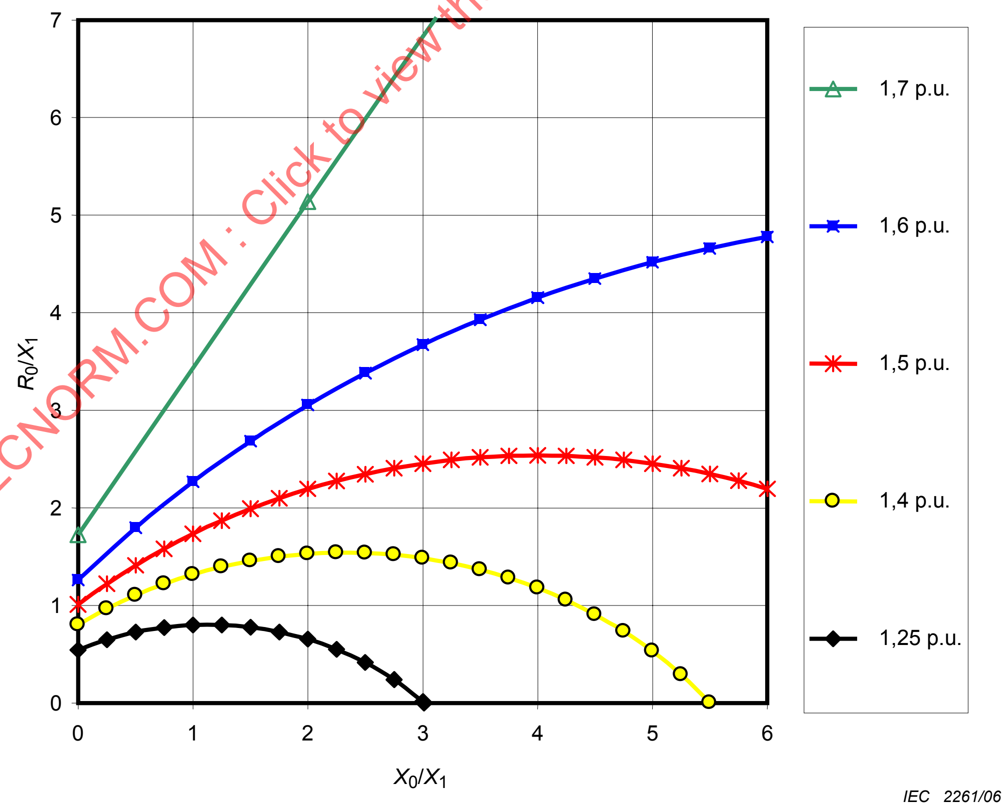


Figure 4 – Line–neutral temporary overvoltage on healthy phase for single phase line – earth fault

In some countries, in order to reduce earth fault currents, networks are earthed via a high impedance component (resistor/reactor), this requires that all network components have to be rated for full line voltage.

6.2 Load rejection (sudden load loss)

Sudden loss of load on the MV or HV networks can result in a temporary overvoltage before the automatic voltage control can correct the situation and bring the voltage back within limits. The magnitude of the overvoltage depends on the magnitude of the source impedance (lower impedance systems will see less change in voltage) and the size and characteristics of the load. Typically the overvoltage will be in the range of U_N + 3 %, but in rare cases, such as faults, it could be up to 6 %. Typically it can take up to three minutes before the tap changer can stabilise the situation and bring the voltage back within limits.

Higher overvoltages are possible in the case of weak supply systems (high source impedance) or isolated power plants where the dynamic response of machines adds to over-voltages, and in particular when a relatively long line or cable is left connected to the generator following load rejection at the receiving end. This condition can even lead to the Ferranti effect.

The Ferranti effect is a condition where the voltage at the receiving end of the line can rise to a value in excess of that at the sending end of the line or cable. This phenomenon is due to the voltage gain across the capacitive elements of the line or cable. The Ferranti effect can result in significant overvoltages appearing at the receiving end of very long lines, therefore it is more often a associated with HV and EHV networks and rarely a problem for MV networks. The Ferranti effect also poses a risk of resonance and ferroresonance when the long lines are terminated by unloaded transformer, leading to transformer saturation and an overvoltage with a distorted waveshape. Where it is identified that overvoltages due to load rejection are likely to reach an unacceptable level, protective systems need to be implemented to ensure that such overvoltages will be of short duration.

6.3 Self-excitation

Self-excitation can occur where the load on a generator becomes capacitive or where a motor is left disconnected with capacitors in parallel.

In the case of synchronous machines, the armature reaction can cause excessive voltage rise as a result of an increase of the exciting flux. To maintain the voltage within the acceptable range of values, a negative field may be needed, but it is not always sufficient.

Additionally, if the generator suddenly becomes islanded on a capacitive load following load rejection, the generator will accelerate. The machine reactance increases with frequency while the capacitive reactance decreases. Therefore it is important to make sure that self excitation does not occur, not only at nominal frequency, but also as a consequence of frequency variations resulting from load rejection. When self-excitation is possible during overspeed conditions, it is important to ensure that the generator is disconnected quickly before reaching the critical frequency in order to avoid losing control of the voltage.

Self excitation is also possible for induction generators and motors. As a countermeasure, it is often recommended to limit the amount of reactive power compensation to less than about 30 %, of the motor or generator rating, to reduce the risk of self excitation in the case of islanding or load rejection.

6.4 Resonance and ferroresonance

6.4.1 Resonance

As a result of the interaction between the reactive and inductive components that are part of every power system, each system will be inherently resonant at a certain frequency or frequencies. As such resonance itself is not an exceptional phenomenon, however resonance as a cause of overvoltage may be exceptional, but should be recognised. There are two general conditions that need to be satisfied before the normal voltage can be amplified by resonance:

– there needs to be sources of harmonics at the right frequency or frequencies in order to excite resonances;
– system damping (e.g. resistive loads) must be relatively small.

Therefore, resonance is more likely to cause overvoltages when combined with other sources of overvoltages that create favourable conditions. For instance, overvoltages due to load rejection may cause transformer saturation leading to harmonics which may be amplified by resonance and add to overvoltages. Resonance is also possible during switching transients such as switching-in an unloaded transformer with a harmonic rich content of inrush current. This is a particular problem when switching a transformer that only has a capacitive load e.g. energizing capacitors or filters or a long section of cable.

6.4.2 Ferroresonance

6.4.2.1 General

Ferroresonance is a rare phenomenon compared to single line earth faults. It is associated with the saturation of magnetic cores in conjunction with relatively small system capacitances. Steady-state oscillations occur under special low damping conditions only. The overvoltages that result are not power frequency overvoltages, but are characterised by a heavy distortion due to the presence of sub-harmonic and harmonic voltage components, generally from a few Hz up to 3 × fundamental frequency.

NOTE For a more detailed explanation of ferroresonance the reader is directed to a report by Schneider Electric: Cahier technique n° 190 Ferroresonance (see the Bibliography).

A particular characteristic of ferroresonance is that it is very dependent upon the point on wave that the network is energized and the magnetic condition of the inductor core, this allows more than one possible voltage and current condition to exist for 'the same' circuit connections. This can lead to confusion since the phenomenon is not easy to predict with certainty.

For the ferroresonance to occur there has to be at least one distribution transformer (single or 3-phase; pole or ground-mounted) connected to a minimum amount of capacitance (e.g. a length of MV underground cable) in the network section downstream of the 'break'. The risk is always greatest when the transformer(s) are unloaded or very lightly loaded.

To interrupt a ferroresonance condition once it has become sustained, all MV phases must either be disconnected or else all reconnected. For unearthed systems the ferroresonance can be controlled by earthing the network; and for unloaded networks the addition of load will act to reduce the overvoltage by damping the resonance.

In practice two conditions are known to cause ferroresonance in MV networks, as described in 6.4.2.2 and 6.4.2.3.

6.4.2.2 Ferroresonance – Open circuit condition

This condition stems from one or two-phase open circuits (fuse operation, broken conductors, etc.) that remain energized by the healthy phase, via an unearthed primary winding of a MV/LV transformer under light load condition.

For example ferroresonance has been known to occur after a previously healthy network has 'lost' one or two phases, or while a previously dead network is being re-energized phase-by-phase e.g. as during 'live-line' work on the MV network. Although voltage values are potentially high (up to 5 x nominal MV line to earth voltage on the disconnected phase(s)). Where MV surge arresters are fitted, the overvoltage will be limited to 2,4 p.u, the current drawn from the healthy phase(s) is relatively small, appearing as a very low level earth fault to the circuit protection – which will not usually cause the circuit protection to operate, hence the condition could persist for some time.

6.4.2.3 Ferroresonance – Earthed magnetic voltage transformers in MV networks with an isolated neutral

Typically this phenomenon occurs in relatively small MV networks, or small sections of larger networks. In order to avoid such oscillations, damping resistors can be connected to the open delta windings of all voltage transformers in the section of network. The resistor size depends on the transformer design and rating. Alternatively, the system affected can be grounded temporarily or continuously, e.g. via a grounding transformer

Phase to earth overvoltages appear due to ferroresonance effects if excited by a sudden change in the network, for example fault application/clearing, switching operations, etc.

The maximum magnitude of the overvoltage is in the range 1,8 p.u. – 2,5 p.u. with a waveform affected by sub-harmonic and/or harmonic distortion (from a few Hz to three times the fundamental frequency). Oscillations due to ferroresonance in balanced 3-phase systems are a zero-sequence phenomenon only, i.e. they can be measured in line-to-ground voltages only. Line-to-line voltages are not affected.

7 Very short duration overvoltages (transients)

7.1 General description

Very short duration overvoltages often referred to as “Transient overvoltages” present very different characteristics to the more stable longer duration overvoltages. It is common practice to classify very short duration overvoltages in relation to amplitude and duration/frequency; in addition the following characteristics can also be cited: surge main frequency, rate of voltage change and energy content.

Several phenomena, including the operation of switches and fuses and the occurrence of lightning strokes in proximity to the supply networks, give rise to transient overvoltages in low-voltage power supply systems and in the installations connected to them. The overvoltages may be either oscillatory or non-oscillatory, are usually highly damped, and have rise times ranging from less than 1 μs to a few milliseconds.

The magnitude, duration, and energy-content of transient overvoltages vary with their origin. Generally, those of atmospheric origin have the higher amplitude, and those due to switching are longer in duration and usually contain the greater energy.

Transients propagate differently depending on the rate of rise (steepness) of the overvoltage waveform. Steep front lightning surges generally do not propagate over long distances because of more losses at high frequencies and because of the corona effect associated with these types of overvoltages. Lightning surges are reflected or transmitted through the network according to the surge impedance of lines, cables or other type of apparatus connected at terminations. In the case of power transformers, transfer characteristics of an incidental lightning surge at different voltage levels will be determined by the stray and mutual capacitances of windings.

Very short duration overvoltages on the low voltage distribution network will generally not exceed 6 kV peak, but higher values may occur in some areas that are subject to severe lightning conditions. The rise time covers a wide range from milliseconds down to much less than a microsecond.

7.2 Lightning

7.2.1 General discussion on lightning

The magnitude of a lightning stroke is typically in the range 20 kA – 50 kA but can be as high as 200 kA. The more common lightning stroke is within the cloud but it is the less common stroke to the ground that has the most noticeable effect by inducing overvoltages in electricity networks.

NOTE The energy content of lightning strokes will vary with latitude. It has been recognized for more than sixty years that atmospheric electric activity takes place with great concentration between the tropics of Cancer and Capricorn. See IEC 62305.

There are two main mechanisms by which lightning causes overvoltages to appear in electrical networks.

– The lightning stroke causes a high current to flow through the conductors (lines, earth, fuses, surge arresters etc.). The passage of this current through the impedance of the lines and components will lead to the generation of overvoltages across these impedances.

– The current flow from a lightning stroke generates an electromagnetic field that induces an overvoltage into adjacent equipment. This induction can cause significant differences of potential between circuits and or earthed equipment.

Due to the construction of HV and EHV lines, high metallic towers with an overrunning earth wire, these networks frequently suffer direct lightning strokes to the tower itself, but not to the phase conductors because the earth wires act as a shield to intercept a majority of the high intensity lightning strokes. MV and LV networks typically use wood or concrete poles and they are shorter in height than HV and EHV structures, hence they are less prone to direct lightning strokes, however their phase conductors may be hit by direct lightning strokes unless they are also protected by overhead earth wires. In any configuration, the severity of overvoltages due to lightning strokes increases with the value of earth resistances.

An overvoltage applied on the primary side of a transformer is transmitted to the secondary side by capacitive coupling between the windings and by inductive coupling. As far as public distribution MV/LV transformers are concerned, the overvoltage transmitted on the secondary side is typically not higher than 10 % of the overvoltage on the primary side. However, if the transformer is open circuit on the LV side, the overvoltage could exceed 10 %.

The following subclauses will describe four scenarios:

– direct lightning strokes:
– indirect or induced strokes;
– back flashover;
– lightning strokes on structures connected to the electricity network.

7.2.2 Direct lightning stroke

When lightning strikes an overhead line an overvoltage transient is propagated in each direction. The magnitude of the overvoltage is dependent upon the magnitude of the stroke current and the surge impedance of the overhead line. Upon reaching a node (termination etc.) the transient overvoltage is partially reflected and partially transmitted beyond the node, dependent upon the ratio of the surge impedances on each side of the node.

In primary HV/MV substations and MV/LV secondary substations overvoltages are limited by protection equipment fitted at these locations – surge arresters, arc gaps and/or diverters.

7.2.3 Indirect or induced lightning stroke

When lightning strikes the ground or a structure in the vicinity of electrical apparatus, a current is induced in the apparatus. Whilst the magnitude is less than it would be for a direct stroke the wave shape of the overvoltage is similar.

Typically for MV lines operating at 50 kV or less, one of the most frequent causes of insulation breakdown due to lightning is the induced lightning overvoltage. In this case, the stroke is indirect because the lightning stroke hits the ground or a structure in the vicinity rather than on the line itself, but due to electromagnetic coupling, an overvoltage is induced on the adjacent line conductors. This induced overvoltage and the travelling wave which results from it can build up overvoltages exceeding the withstand of the MV line insulator string. It has been shown that overhead earth wires have a beneficial effect in reducing the induced overvoltages.

7.2.4 Lightning back flashover

In this case the tower and /or earth wire suffer a direct lightning stroke which produces a voltage between the tower and the phase conductor(s) (lines) in excess of the withstand rating of the line insulators. This type of breakdown mechanism is typical of high voltage lines because they are normally well protected against direct strokes to the phase conductor(s) and their insulation can withstand induced lightning strokes. The transient overvoltage associated with a “back flashover” will depend upon several factors, the main ones being the magnitude of the incidental lightning stroke, the stiffness of the wavefront, the surge impedance of the tower and earth wires, and tower footing resistance. A countermeasure to reduce the risk of back flashover is to reduce the tower footing resistance as much as possible, e.g. by using buried ground conductors, so-called “counterpoises”.

7.2.5 Lightning strokes on structures connected to the electricity network

If lightning strikes a building or structure directly, then high values of overvoltage can be impressed on the electrical installations and equipment within the structure. Current division and various coupling effects can cause the overvoltage to be transferred into the low voltage network to which the installation is connected, affecting other installations on the same network.

Moreover, if a lightning surge strikes or is induced in any metallic path, such as a telecommunication, signalling or control system that is connected to the electricity network or an electric power circuit within an installation or individual item of equipment, interactions at an interface between those systems can extend the overvoltage to a system other than that initially affected. In particular, the electricity network or a power circuit within equipment can be subject to overvoltage arising from:

– large change in one of the earthing reference potentials, due to the flow of lightning current;
– inductive and capacitive coupling close to a lightning path, due to the high electromagnetic fields generated by the lightning current.

7.3 Switching

7.3.1 Fault switching

The operation of network circuit breakers, switches and protective fuses all result in an arc being struck across the contacts or fuse element. As the contacts of the circuit breaker start to part, or the element of the fuse starts to melt, there is a rapid rise of voltage across the contacts. This is called the reignition voltage, it is a high frequency transient caused by the rapid redistribution of energy across the *R*, *L* and *C* components of the network. Each time the arc is extinguished, the energy stored in the inductance ($W = ½ LI^2$) of the circuit is transferred to the capacitance ($W = ½ CU^2$). In the dynamics of fault clearance the capacitance across the circuit breaker (or fuse element) can become a major component of the overall capacitance of the circuit: as the gap widens the capacitance decreases, therefore the reignition voltage must increase.

Once the fault current has been interrupted, the voltage that appears across the open contacts of the circuit breaker is known as the recovery voltage. For weak systems the recovery voltage can be less than the normal system voltage until the effects of armature reaction have ceased. The redistribution of energy associated with the original fault current can continue after the circuit breaker has opened, this can result in a transient voltage being superimposed on to the recovery voltage. The frequency and energy content of this transient are related to the relative values of *R*, *L* and *C*, and the point on wave at which the circuit is interrupted. Typically overvoltage transients associated with fault clearance will not exceed 2 × nominal voltage, however for circuits containing a significant amount of capacitance this figure can rise to 3 × nominal voltage.

7.3.2 Routine switching

Routine switching on the distribution and transmission networks can generate overvoltages due to the charging/discharging of components (capacitors and inductors). The magnitude and frequency of the overvoltage will depend upon the relative values of the reactive components (*L* and *C*), the 'point on wave' at which the active components are energized, i.e. the phase angle at which the supply voltage is switched on, the source impedance of the network.

Interruption of line current at a point on the wave other than at a natural current zero will result in the electromagnetic energy in the circuit being rapidly converted into electrostatic energy. For highly inductive circuits, switching currents at non-zero crossings can result in transient overvoltages being propagated through the system.

7.3.3 Shunt capacitor and cable switching

7.3.3.1 General

This subclause will focus on the effects caused by switching discrete capacitors, however it should be recognised that similar effects occur when switching sections of underground cables.

Shunt connected power factor correction capacitor banks are installed at strategic locations on a network in order to produce the capacitive reactance necessary to compensate the reactive power demands (caused by the inductive reactance of the network loads) and so minimise the flow of reactive power throughout the network.

In order to achieve an optimal control of the steady state voltage, the capacitor banks are switched on and off in response to load variations and changes in system configuration. However the switching operation produces transient overvoltages that are propagated across the voltage levels. It has been known for these overvoltages to cause disturbance or even damage to sensitive equipment connected at lower utilisation voltage levels.

7.3.3.2 Energizing

Energization of capacitor banks is a common cause of transient overvoltages, typically the value at the point of incidence will not exceed twice the nominal voltage. However, wave reflections and voltage magnification can occur as the overvoltage transient is propagated along a line, amplifying the overvoltage incident on connected equipment. This needs to be taken into account if immunity is being considered for particular equipment or installations.

When a single uncharged capacitor bank is switched on, the energization generally takes place in a window around the peak of the voltage. This is because of pre-arcing across the circuit breaker contacts. This does not necessarily apply to vacuum and gas insulated circuit breakers (VCBs and GIS), where the closing instance is more random than for other types of switchgear. At the instant of energization the system voltage instantaneously collapses at the capacitor before being restored following a damped oscillation, the frequency of which depends on the natural frequency determined by the source inductance together with any current limiting reactor (*L*) and the capacitance (*C*) of the bank being switched on. Figure 5 illustrates a typical voltage waveform when a single capacitor bank is energized.

This transient oscillation, whose frequency is typically between 200 Hz – 1 500 Hz, is superimposed onto the power frequency voltage waveform (be it 50 Hz or 60 Hz), resulting in a transient overvoltage whose peak is generally lower than 2,0 p.u. due to load damping. Typical values are 1,5 to 1,7 p.u. The transient oscillation attenuates almost completely after a few tens of milliseconds depending on the load and network characteristics.

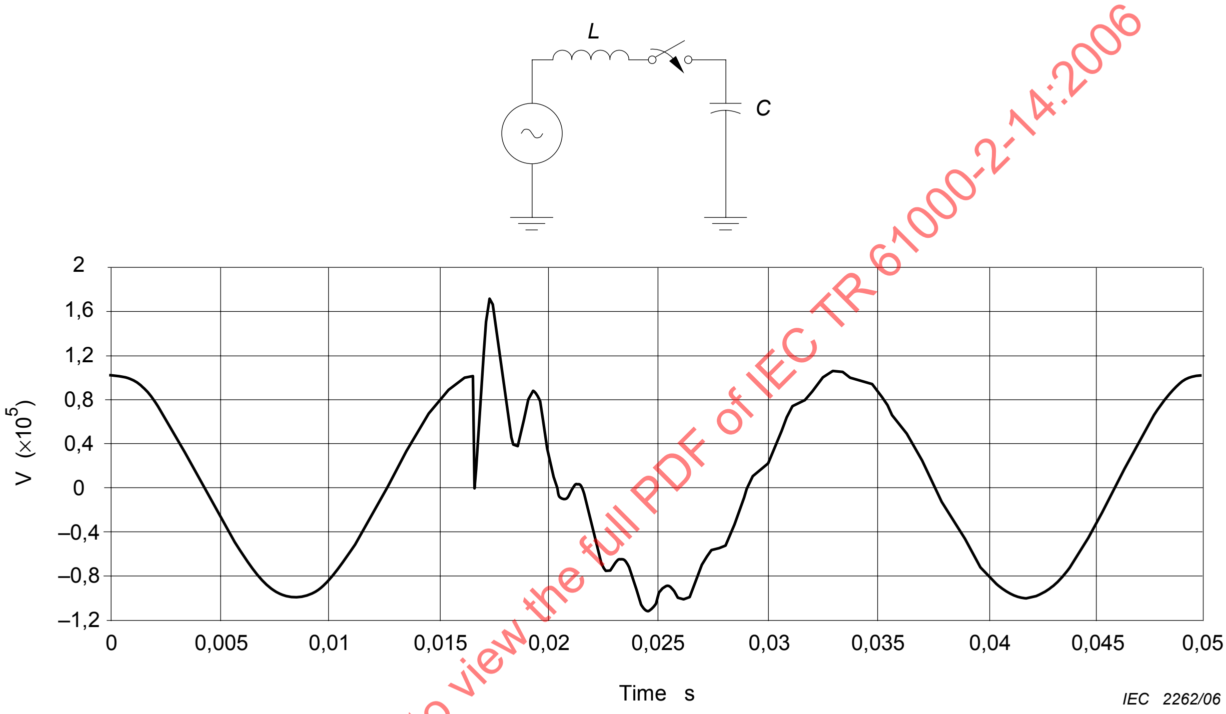


Figure 5 – Typical transient overvoltage when energizing a capacitor bank

When a second capacitor bank is switched on in parallel with an already energized capacitor, two different transient oscillations arise. The first is due to the portion of energizing current supplied by the network, so its frequency is determined by the source inductance (*L*) and the parallel combination of the two capacitor banks (C and C_2). Since *C* is pre-charged at 1 p.u. the current inrush from the supply system and the corresponding transient voltage will be less (typically half for banks of equal size) than in the case of a single capacitor bank. The second transient is associated with a larger energizing current due to the oscillation between the first and the second capacitor banks. This high frequency transient will typically have a frequency in the range of 2 kHz to 10 kHz and will last for a few milliseconds. The characteristics of the overvoltage are determined by the circuit components, C and C_2 in series with the inductance *L* between them, where *L* is generally small compared to the source inductance. *L* represents the busbar inductance and the current limiting reactor, where fitted.

The transient overvoltages injected into the network during staged switching of capacitor banks is found to be lower than overvoltage caused by switching a single capacitor bank because the pre-charged adjacent capacitor bank supplies a large part of the inrush current.

In the absence of pre-striking, transient overvoltages due to the energization of capacitor banks seldom cause a problem to the equipment connected adjacent to the capacitor bank at MV or HV. This is because MV and HV equipment is, in general, designed and protected to operate satisfactorily under such conditions. IEC 60664-1 and IEC 62066 provide more details on insulation co-ordination.

However, since overvoltage transients can propagate to lower voltage levels, they may cause overvoltages in excess of the insulation withstand of some equipment, in particular power electronics. Moreover, as we will see later along with the propagation of transients, resonances may occur at lower voltage levels and cause magnification of the incidental overvoltage. Travelling waves may also produce excessive phase-to-phase overvoltages at remote locations at MV or HV.

7.3.3.3 Voltage magnification

Voltage magnification typically occurs when a capacitor bank (C_{HV}) forming a closed circuit with the HV source inductance is energized while another capacitor bank is already connected at a lower voltage level (C_{MV-LV}) forming a second closed circuit in series with the transformer inductance.

Voltage magnification is a maximum when the HV capacitor bank is much larger than the MV or LV one (C_{HV}>>C_{MV-LV}) which is often the case, and when the natural frequencies of the two closed circuits coincide ($f_{HV} \approx f_{MV-LV}$), the situation is further exacerbated when there is too little damping in the circuits. The MV or LV capacitor bank actually behaves like a low impedance path to the overvoltage transient produced at HV and thus draws a high current which in turn amplifies the overvoltage transient at MV or LV; therefore the lower voltage levels may be subjected to severe overvoltages (>3 p.u.).

Voltage magnification can cascade across several voltage levels due to the interaction with other type of equipment such as cables, filters, or even capacitors on the d.c. side of an adjustable speed drive (ASD). The resulting overvoltage at MV or LV will be composed of several frequencies due to this cascading effect, and its amplitude will depend on the actual damping of the load for each of the frequencies of interest.

7.3.3.4 De-energizing capacitor banks

At the instant a mainly capacitive circuit is interrupted the capacitor will still be charged up to a maximum of the peak value of system voltage (V_p), half a cycle later the system voltage will be $-V_p$ and out of phase with the trapped voltage in the capacitor giving a gap voltage of 2 V_p which is added to the system voltage giving a maximum voltage of 3 V_p. If this overvoltage is sufficient to break down the medium between the switch contacts (breaker restrike) an oscillatory voltage wave will be set up. This oscillatory overvoltage will be propagated through the network. Under certain circumstances such as in the case of capacitor banks with an unearthed star point it is possible for the maximum overvoltage to be increased beyond $3V_p$, possibly as high as $4V_p$ for asynchronous opening of circuit breaker contacts, however transient overvoltages on the network will be limited by adjacent surge arresters. As a general rule, restrike-free circuit breakers are essential for the switching of capacitor banks.

7.3.3.5 Travelling waves

The sudden voltage collapse at the first instant of energizing a capacitor bank creates a steep fronted travelling wave, which is propagated along the lines connected to the same busbar as the capacitor bank. Lines terminated by high surge impedance (e.g. transformers) can be subjected to a natural high frequency oscillation due to waves travelling back and forth with doubling effects and changes in polarity.

This high frequency component decreases very quickly as it is reflected or transmitted at terminations and produces line-to-earth overvoltages typically up to 2,7 p.u. under some conditions – limited in value by surge arresters. However, these high frequency transients may also produce phase-to-phase overvoltages (4 p.u. or more, even if line-to-earth surge arresters are present) that could exceed the phase-to-phase insulation withstand levels (for three-phase equipment).

7.3.4 Commutation oscillations

Commutation of power electronics leads to voltage oscillations. These oscillations can set up resonances at the natural frequency of the circuit, if the circuit is undamped, these resonances can lead to damaging overvoltages. These oscillations are not normally transferred across transformers. The probability of oscillations occurring is increased when there is a low value of 'decoupling' inductance between the converter and the supply system; and the risk of resonance is increased by low system damping. Typical oscillation frequencies lie in the kHz range, up to 20 kHz. The magnitude of the oscillation can be up to 1,5 p.u, however typical magnitudes are in the range of 1,1 to 1,2 p.u. Due to the repetitive nature of commutation oscillations they can cause a thermal overload of surge protection devices, e.g. varistors frequently used for the protection of LV electronics. Figure 6 below shows the voltage waveform distorted by commutation notches.

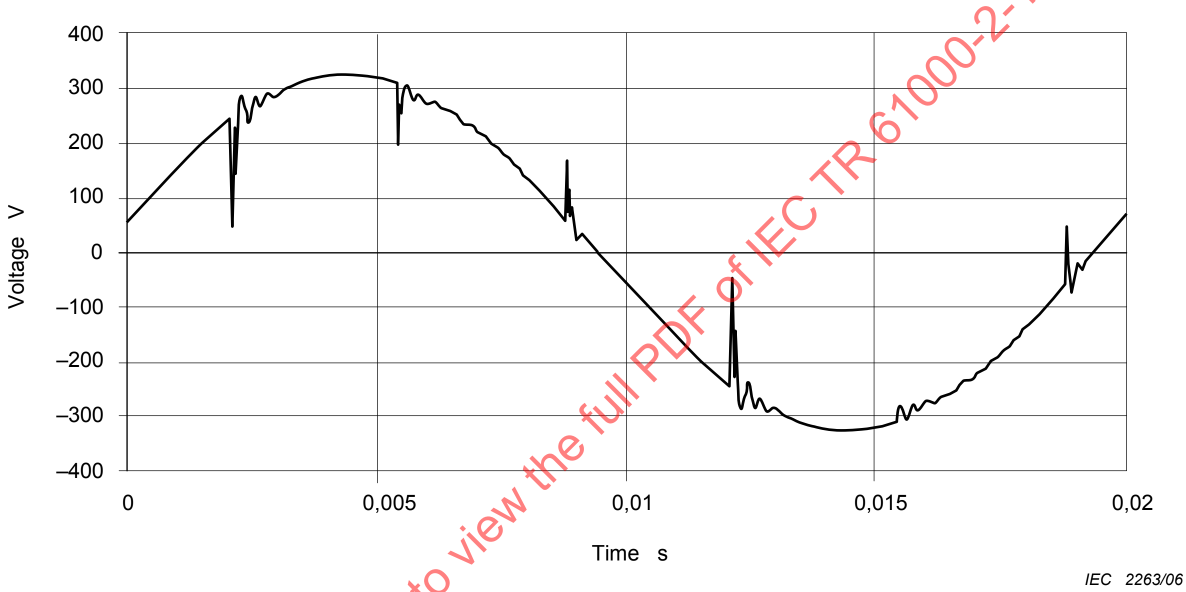


Figure 6 – Notching caused by power electronics switching

IEC 61800-3 specifies 1,5 p.u. as the maximum peak overvoltage.

7.3.5 Switching of shunt reactors

Switching of shunt reactors generates transients both in energization and de-energization. In de-energization there are two sources of overvoltage: current chopping and reignitions. Chopping overvoltages due to interrupting the inductive current before its natural zero depend on the characteristics of the circuit breaker (including arcing time), reactor size, and the presence of capacitance, but are generally less than 1,5 p.u. Reignition overvoltages are normally somewhat more severe, and arise when the voltage between the circuit breaker contacts after initial interruption exceeds the dielectric withstand of the contact gap. The rate of rise of voltage during reignition is between lightning and fast-front transients, while chopping overvoltages are equivalent to slow-front transients.

Multiple re-ignitions may excite internal resonances of the reactor or may lead to virtual current chopping for some types of breakers followed often by destructive overvoltages. Mitigation measures such as surge arresters and R-C-damping circuits are generally required.

7.3.6 Switching of transformers

Energization of transformers can produce high inrush currents which amplitude and waveform depend on the point of wave and residual flux at the instant of closing. The inrush currents are rich in low order harmonics. Transformers can generate overvoltages if resonances with other components occur. Harmonic components in the inrush magnetising current when an unloaded transformer is energized can resonate with capacitive elements on the network, generating overvoltages of up to 2 p.u.

When a transformer is energized there is a very high rate of change of voltage (d*v*/d*t*) across the primary winding, which creates an overvoltage in the secondary winding due to the transformer capacitance. Although this kind of overvoltage is not very severe, peak values of 2 kV and 1 µs have been measured on the LV side of an MV/LV transformer. Note that mitigation for this type of overvoltage can be implemented by a shield between HV and LV windings.

Transient overvoltages due to disconnection of the transformer depend mainly on the load during the instant of switching, the type of circuit breaker used and the system configuration. Switching currents with high reactive component (power factor (pf) below 0,7, e.g. short circuit at the secondary side or mainly reactive load) increases the probability of high switching overvoltages. In this case, phenomena are similar to de-energization of shunt reactors. Mitigation measures are installed generally in case of frequent switching under critical loading conditions only. Switching mainly active currents generally creates overvoltages not exceeding 2 p.u.

7.3.7 Controlled switching of circuit breakers

Since many of the overvoltages arising from switching are caused by the fact that circuit breaker contacts close or open at unfavourable points of the alternating voltage or current cycle, a possible strategy to reduce overvoltages is to control the instant at which the contacts close or part. In its most elementary form, this is done by means of an electronic control module applied to a more or less standard circuit breaker. In that case, however, the contacts on the three phases operate more or less simultaneously. Also, many circuit breakers exhibit considerable variation in the length of the interval between the delivery of the operating signal and the effective instant of contact movement.

For full control it is necessary to design the circuit-breaker mechanism to permit close and independent control of the three phases separately. It is necessary also for the circuit breaker to have a suitable dielectric capability, including the rate of decrease of dielectric strength (RDDS). The control module performs complex measurements of the many variables that influence the operating instant – for example, operating times tend to drift with age, number of operations, ambient conditions, etc.

This method is moderate in cost and adaptative control techniques can ensure that the control will continue to function correctly in the long term. It has been applied mainly on transmission networks, where it has been reasonably effective.

7.4 Summary of surge duration and cause

Tables 1 and 2 summarize the causes of surges on low voltage networks and medium voltage networks respectively.

Table 1 – Surges on the low voltage network

Rise time	Cause
> 100 μs	• Operation of current-limiting fuses (generally the amplitude will be up to 1 kV – 2 kV). • Energization of power factor correction capacitors (generally amplitude up to 2 – 3 times nominal peak voltage. • Transference of switching transient overvoltages from MV to LV across MV/LV transformers by electromagnetic coupling, amplitude up to 1 kV.
1 μs to 100 μs	• Direct lightning stroke on the LV line conductors, amplitude up to 20 kV. Magnitudes depend mainly on insulation distances within the local installations which may vary in a wide range. Highest magnitudes can be expected normally at LV OHLs and the equipment connected. Typical maximum magnitudes in household or office installations are much smaller in the range of 2 kV to 3 kV peak voltage; see IEC 62066 for detailed considerations. • Induction coupling of a lightning stroke in the vicinity of an LV line. Generally the amplitude will not exceed 6 kV (can be up to 20 kV in rare cases) with high energy levels. • Resistive coupling associated with lightning currents flowing in the common earth paths of a network, generally the amplitude will not exceed 10 kV. • Transference of surges from MV to LV by capacitive transformer coupling. Where the surge is due to a direct lightning stroke on the MV, this in turn can lead to a rapid drop in voltage caused by the operation of gap-type arresters to clear the fault. The amplitude of the overvoltage on the LV network will generally not exceed 6 kV. • Operation of fuses can cause the generation of overvoltages with a peak magnitude that is several times that of the nominal voltage, typically not exceeding 2 kV, but in rare cases can be up to 10 x nominal. These overvoltages generally have a low energy content and attenuate quickly with distance. • Switching on low voltage networks can result in the generation of overvoltage transients with durations between 1 µs and < 100 µs. Generally the overvoltages caused by switching will not exceed 4 kV.
< 1 μs	• Local load switching of small inductive currents and short wiring (amplitude generally up to 1 kV – 2 kV. • Fast transients due to switching in LV by air-gap switches (relays and contactors) giving a succession of clearings and reignitions (bursts of surges, one surge: rise time of about 5 ns, duration of about 50 ns)

Table 2 – Surges on the medium voltage network

Rise time	Cause
> 100 µs	• These overvoltages are mainly caused by switching events such as energization of power factor compensating capacitors, fault application, arcing ground faults, transient overvoltages transferred from HV to MV of the transformer by electromagnetic coupling. The amplitude of the overvoltage is generally up to 2 – 3 x peak line to earth voltage, with an oscillatory waveform and a frequency in the range from a few hundred Hz to a few kHz.
1 µs to 100 µs	• Circuit breaker operation, mainly vacuum or SF6 type circuit breakers including effects such as re-ignition, virtual current chopping etc. The amplitude of the overvoltage can be up to 8 – 10 times the peak value of the nominal line to earth voltage, generally with an oscillatory waveform. • Induction from lightning strokes in the vicinity of MV lines and less commonly from direct lightning strokes on MV lines. • In both cases the amplitude of the overvoltage is often limited to the level of overvoltage protection that has been installed at strategic points on the network e.g. arc gap and surge arresters.
< 1 µs	• Switching of gas insulated switchgear (GIS). The overvoltage is of relatively low energy content and therefore only radiates over short distances, typically the overvoltage will not extend beyond the switching substation.

8 Effects of overvoltages on equipment

8.1 General considerations

In this part of IEC 61000, the relevant effects are those relating to EMC, i.e. the possible degradation of the performance of equipment. As an EMC phenomenon, overvoltages are very difficult to cater for completely because of the unpredictability of occurrence and wide variation in both magnitude and duration. However it should be possible to provide a generic level of EMC protection to cover typical values of overvoltage and also provide guidance for the extreme cases where it is necessary to protect specific items of equipment from all probable values of overvoltage.

Overvoltages have become an important type of disturbance during the last decade. The wide use of industrial equipment using electronic components has largely contributed to this situation because their capability to withstand overvoltages is often lower than that of conventional equipment. In addition, the use of shunt capacitor banks either on the network or within industrial installations, or both, may give rise to interactions such as resonance that can increase or amplify transients.

The effect of overvoltage on any particular item of equipment is dependent upon the magnitude and duration of the overvoltage and the resilience of the equipment. The effect can range from slight degradation of performance through to catastrophic failure. The following paragraphs list some of the more common equipment and detail the effect that overvoltages can have on their performance.

The level of immunity inherent within each item of equipment should be proportional to the risk of being subject to an overvoltage, which in turn is related to the location within an installation at which the item of equipment is to be connected, i.e. the insulation on equipment should be co-ordinated with the expected level of overvoltage. The principles and requirements for insulation co-ordination are fully described in IEC 60664.

8.2 Reduction in life of filament lamps

The reduction in the life of a typical filament lamp when operating for sustained periods at a voltage above nominal, assuming a typical usage pattern, can be approximated using the following formula:

$$LL = \left(\frac{100}{V(p.u.)^{\Psi}} \right)$$

where

LL = Lamp life, expressed as a percentage of lamp life at rated voltage

Ψ = an empirical figure used in the lighting industry and generally accepted as being between 12 and 14.

Using the exponents of 12 and 14, Table 3 below shows the lamp life for lamps operating at voltages of 105 % and 110 % of rated voltage.

Table 3 – Reduction of filament lamp life

Voltage as % of nominal	**Lamp life** %
100	100
105	51 – 56
110	26 – 32

Therefore, assuming a 230 V rated lamp has an average life of 1 000 h at nominal voltage, if it is operated at 253 V (230 V + 10 %) the life of the lamp will be reduced to somewhere between 260 – 320 h.

For discharge lamps the ballast (control gear) tends to act as a regulator. The effect on discharge lamps, which, unlike incandescent lamps, are negative resistance devices, is really a function for how well the ballast controls the lamp operating current when the line voltage goes above the rated value. Typically systems are designed to operate fairly well over U_n ±10 %, but somewhat shorter lamp life and ballast life can result nonetheless, although it would not be nearly as severe as the incandescent case.

For transient overvoltages the impact varies depending on the class of product. Ballasts and systems designed for the commercial and industrial environment, especially industrial, are typically designed to withstand transient voltage excursions of several kV, sometimes as high as 4 kV - 6 kV. Products designed for residential applications may range between 1,5 kV and about 2,5 kV depending upon the manufacturer. IEC 61547 gives minimum immunity for lighting equipment, however in the US these requirements are generally not seen as adequate hence more conservative requirements are often employed.

8.3 Effect of overvoltages on IT equipment

Figure 7 shows upper (and lower) limits of the input voltage to information technology equipment, developed in 1996 by Information Technology Information Council (ITIC), and replacing the previous CBEMA curve. The developers present it as an input voltage boundary of what typically can be tolerated (no interruption in function) by most information technology equipment (ITE), but it is not intended as a design specification for either products or the supply system. It is published together with an Application Note, both comprising a single document and not to be considered separately from each other. The Application Note states that it is applicable to 120 V nominal voltages on 60 Hz systems but that it is the responsibility of the user to determine its applicability to other nominal voltages and frequencies.

NOTE Parts of the curve refer variously to r.m.s. and peak voltage values.

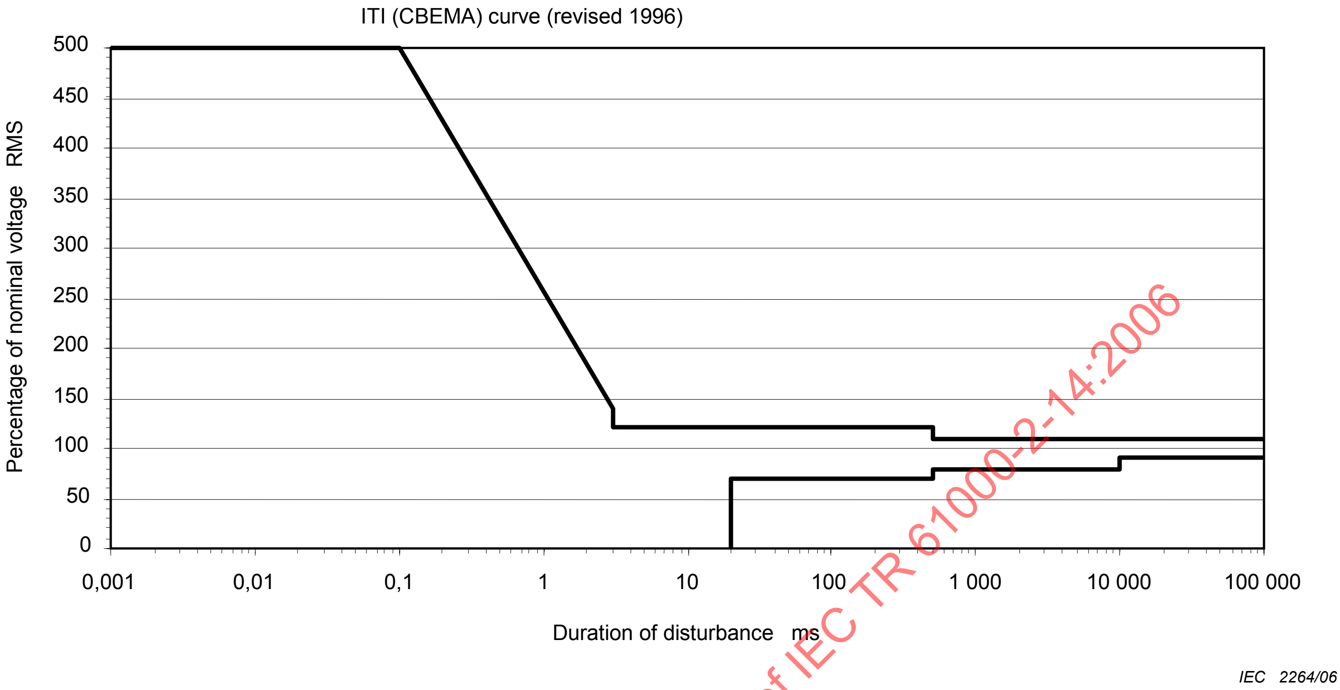


Figure 7 – ITI (CBEMA) curve for equipment connected to 120 V 60 Hz systems

NOTE The ITI (CBEMA) Curve Application Note, 1997, Information Technology Industry Council can be found at the following web address: www.itic.org/archives/iticurv.pdf. Last checked 10 March 2006.

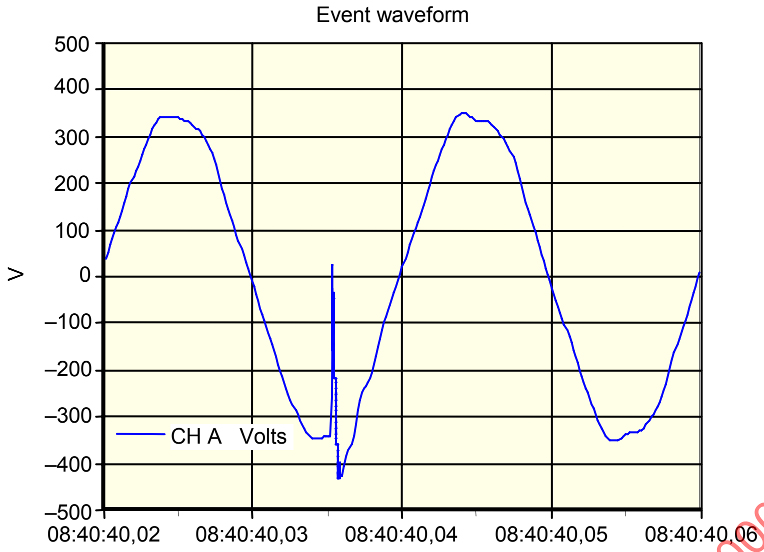
9 Case studies

9.1 General

This section lists some actual cases where overvoltages have been measured on public distribution networks. In each case the cause of the overvoltage is identified and where available the text describes the effect of the overvoltage on adjacent equipment and the actions taken to remedy the situation.

9.2 Switching of LV power factor correction capacitor

Figure 8 below shows the line–neutral voltage waveform seen at the terminals of an LV load when a power factor correction (PFC) capacitor was switched on within an adjacent installation. This waveform was captured by the local distribution network operator (DNO) when they were called in to investigate why the contactor within a switch panel was failing to latch correctly. The printout from the measuring instrument shows a negative impulse of 366 V followed by a positive impulse with a peak in the region of 420 V. However as the negative impulse occurred first it was this that triggered and was recorded by the instrument. The problem was solved by replacing the contactor with a unit to a higher specification. This was seen as the most pragmatic and cost effective method of resolving the problem, as the alternative would have been to install a sophisticated control system to manage the switching of the PFC capacitor to ensure that the switching takes place at a voltage zero.



AV Impulse event at 08/06/00 08:40:40,02

	PrevRMS	MinRMS	MaxRMS	WorstIMP	Phase	HFHits
AV (Volts)	247,3	248,1	249,2	366,0	277 deg	1
BI (Amps)	0,72	0,36	3,64	0,00	0 deg	0

IEC 2265/06

Figure 8 – Voltage waveform distorted by the energization of a PFC capacitor

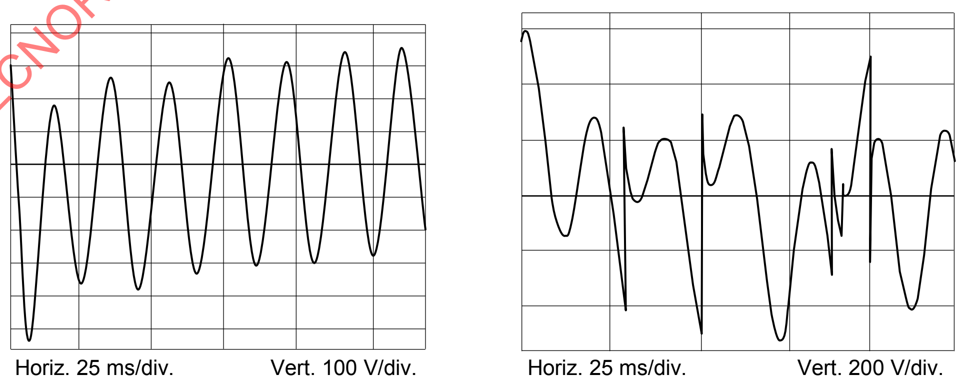
9.3 Metal fusion furnace

The disturbed network supplies a metal fusion furnace (purely resistive) and several presses to inject liquid metal in casting matrices. The presses use induction motors.

Frequent maloperation of regulation devices (electronic cards) were reported. Dielectric breakdowns were observed on heating parts, presses and other elements of the low voltage network (nominal voltage: 230 V).

Measurements performed in the system using a transient recorder showed that there were no phase to phase faults and no phase to neutral faults. However, frequent phase to ground faults were recorded.

Voltage peaks were very short but they caused a displacement of the phase to ground voltages, see Figure 9 below.



IEC 2266/06

IEC 2267/06

(a)

(b)

Figure 9 – Phase to ground overvoltage in case of a single (a) or multiple (b) faults

A detailed inspection of the machine showed the origin of the fault to be an induction motor associated with the liquid metal injection press. During a specific phase of the machine's operation, a sudden torque variation was applied to the motor, causing a vibration and, as a consequence, an internal insulation problem.

Once the fault was located, transient current recordings were performed on this motor. These recordings showed the occurrence of a second fault, as a consequence of a first fault between phase 1 and the ground.

This can be analysed as follows.

– The motor showed a temporary insulation fault on one of its phases. This fault appears as a consequence of a very high torque.
– Consequently, there was a rise in the potential between the sound phases and the ground, with a sometimes violent transient.
– The phenomenon could evolve in a double fault which caused a short circuit.

Until the motor was refurbished, a temporary mitigation solution was implemented. It consisted in inserting a 1 000 Ω impedance between the transformer's neutral terminal and the earth. The impedance had a damping effect on the transient overvoltages. Figure 10 below shows the equivalent circuit which can be seen as a resistance in parallel with the resonant circuit formed by the transformer's inductance and the capacitance of the network.

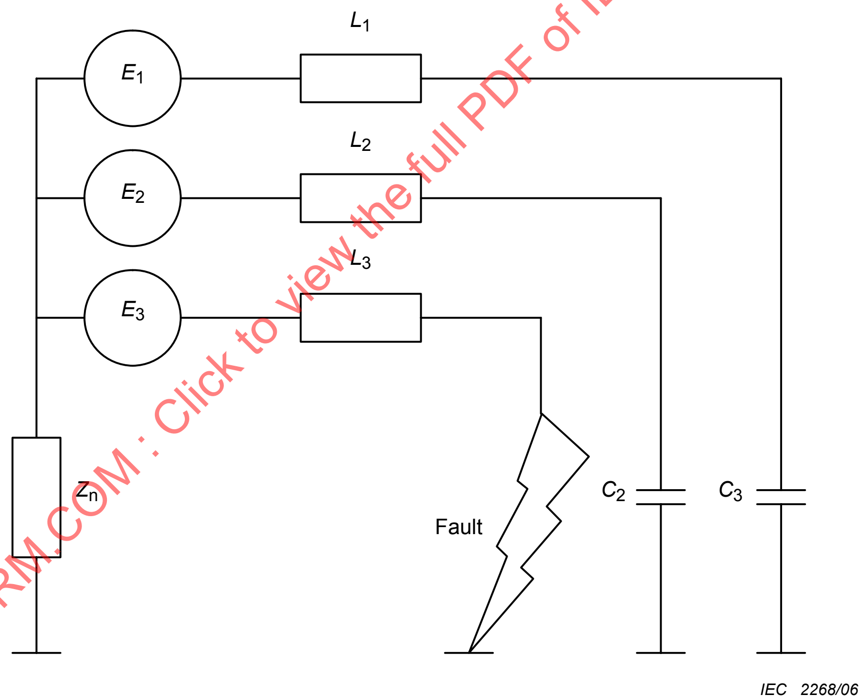


Figure 10 – Equivalent circuit

The equipment implemented was a standard impedance designed for the earthing of industrial networks. No specific calculation was needed.

9.4 Switching of MV power factor correction capacitor

9.4.1 Circumstances

Following the installation of power factor correction capacitors in a PVC moulding plant, a number of operations of the main LV circuit breaker occurred. Although the disturbances were very short, the plant suffered very long restoration times due to the nature of the process. The installation is supplied from the 25 kV network through a step down transformer (25,0/0,6 kV) as shown in the single line diagram in Figure 11 below.

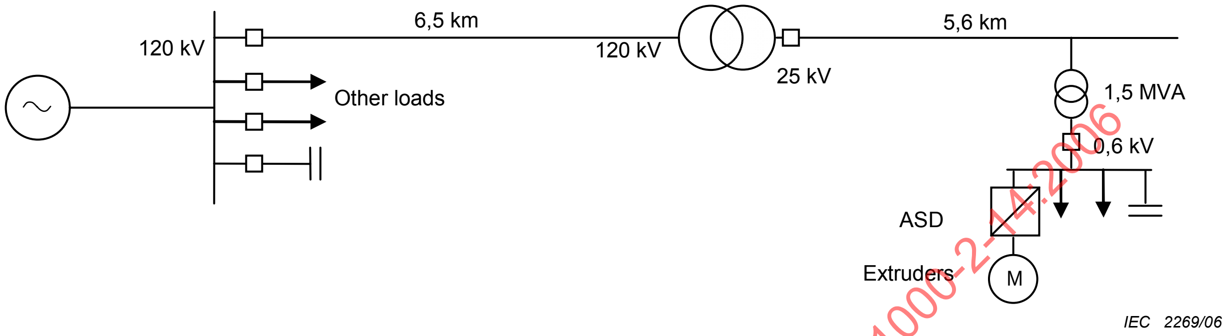


Figure 11 – Extruder connection – single line diagram

9.4.2 Causes

It was identified that the main LV circuit breaker tripped at the same time as the switching-in of the 120 kV capacitor bank at the substation upstream. Investigation revealed that the natural frequency of the 120 kV capacitor bank (near the 8th harmonic) was very close to the resonant frequency of the plant capacitor banks for certain configurations. Also, the main LV breaker had an instantaneous current relay pick-up set as low as 2 p.u. Oscillograms of the current waveforms revealed that transient currents in the order of 3 kA were present at LV at the instant of the 120 kV capacitor switching – see the waveforms in Figure 12 below.

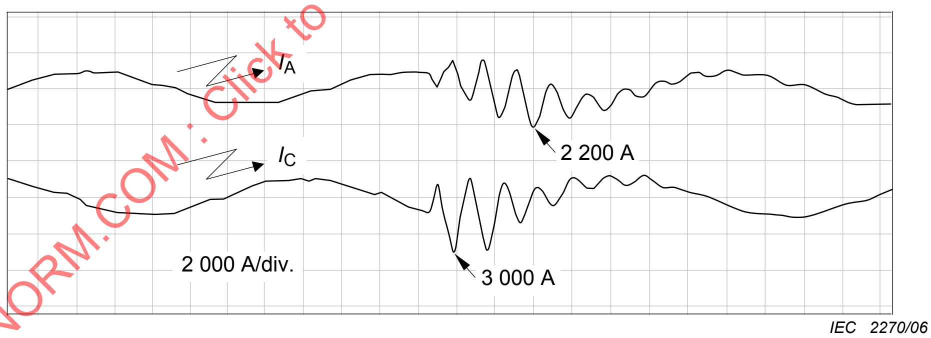


Figure 12 – Current waveforms (phases A and C) taken at the main LV circuit breaker

9.4.3 Solution

The first solution was to change the protection settings on the main LV circuit breaker for a higher value while still maintaining coordination. It was also recommended to detune the LV capacitor banks in order to minimize risks of transient amplification.

9.5 DC traction system

9.5.1 Circumstances

The operation of a public transportation subway line was regularly interrupted during rush hours. There were also cases of converter diodes being damaged. The simplified single line diagram is shown in Figure 13 below. Each 12 kV feeder could supply 4 to 5 d.c. converters stations spread along the subway line. Total cable length per 12 kV feeder was between 8 km and 19 km.

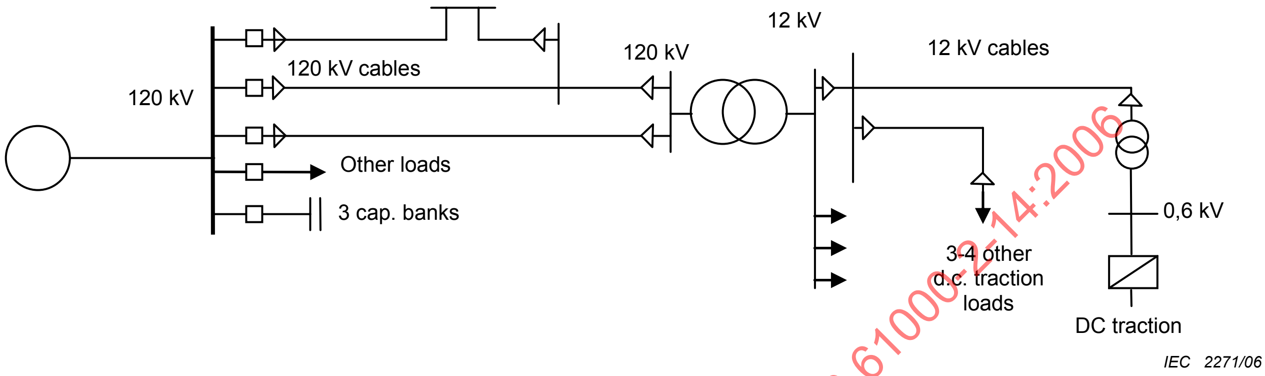


Figure 13 – Single line diagram of public transportation system

9.5.2 Causes

Two problems relating to overvoltage transients were identified during the investigation.

– Troubles coincided with a 120 kV upstream capacitor bank that was regularly switched-in at peak hours in the morning and in the afternoon. The incidental overvoltages were found not to be excessive (typical values between 1,2 p.u. and 1,5 p.u. with a frequency component between 250 Hz and 600 Hz.). Waveforms recorded on the 12 kV primary side of the d.c. converter stations showed high frequency oscillations (between 1,5 kHz and 2 kHz) being superimposed on the normal system voltage. The high frequency oscillations were due to the travelling waves on the 12 kV cable network feeding the different substations spread along the d.c. traction line. Although these overvoltages were in general not high enough to explain the damages that occurred to the converters, it explained the numerous nuisance tripping on the d.c. converters due to a special protection. Indeed in order to quickly detect blown tires on a train, special protection relays on the d.c. side monitor di/dt and trip the system at preset limits (in case of a blown tire, steel wires may short circuit intermittently the d.c. traction circuits). The relay was more sensitive to the lower frequency oscillations in the 500 Hz range.

– Further investigation at the 120 kV upstream substation also revealed that some of the breakers used for switching the capacitor bank were prone to restriking. At a particular occasion, the restriking was severe enough (above 2,1 p.u. which was the limit of the measuring instrument) to damage some of the 120 kV cables and the electronics of the d.c. converters (damaged diodes).

Figure 14 below shows the signal seen by the di/dt relays and the three voltage waveforms identified X_1, X_2 and X_3 measured at the d.c. converters with the superimposed transient oscillations apparent mainly on phase X_3 at the time of switching the 120 kV capacitor bank.

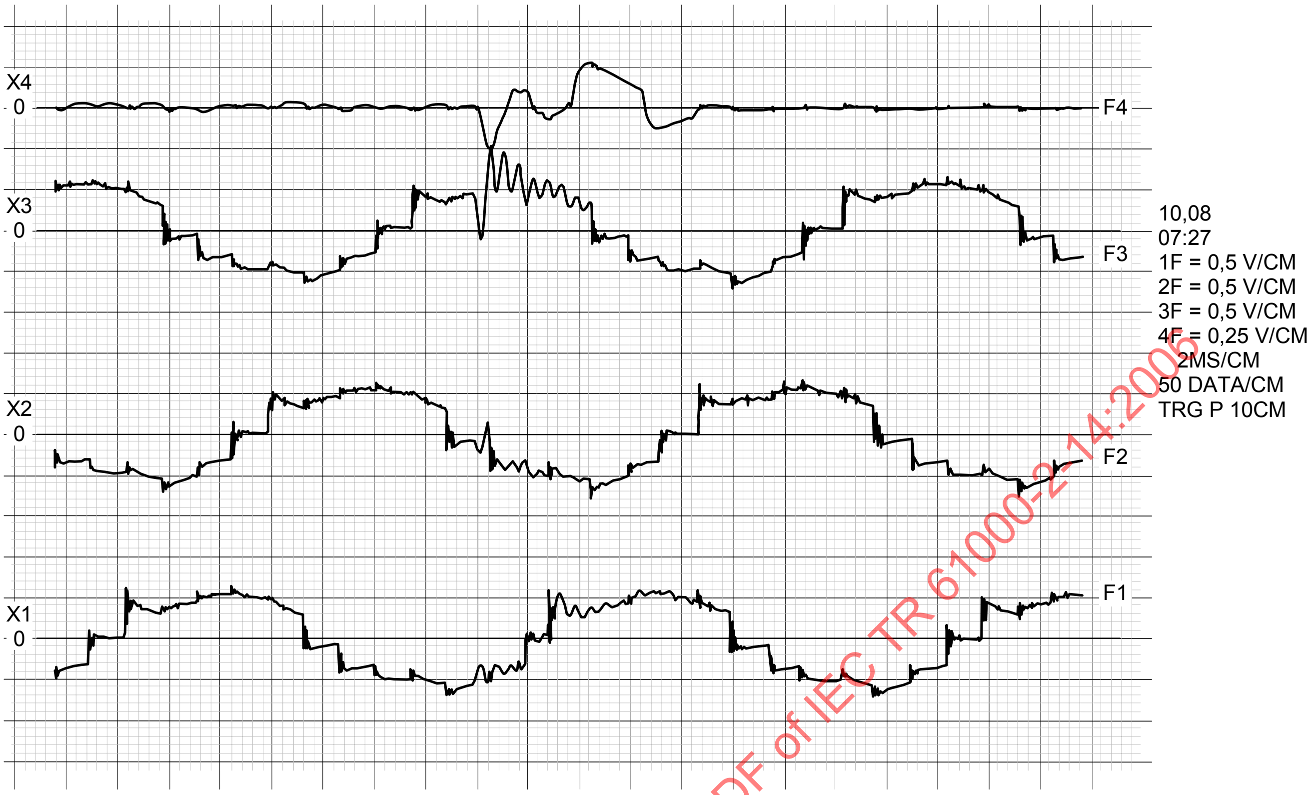


Figure 14 – Voltage waveforms associated with overvoltages on public transportation system

9.5.3 Solutions

The faulty capacitor circuit breakers had to be replaced by restrike free circuit breakers. Controlled switching devices were also implemented with the new circuit breakers in order to minimize the incidental transients due to capacitor switching.

NOTE A full description of this case can be found in paper No. 305 presented to the Joint CIGRE-IEEE Symposium on Quality and Security of Electric Power Delivery Systems in Montreal in October 2003.

9.6 Load switching

9.6.1 Situation

A 20 kV transformer, supplied via about 25 m of cable and switched by a vacuum circuit breaker (VCB) shows multiple re-ignitions (phase 1) and subsequent virtual current chopping at phase 2. The overvoltage caused by virtual current chopping is limited by line-to-earth surge arresters. The load during switching is about 20 A and is almost purely capacitive. The voltage waveforms for this system are shown in Figure 15 below.

9.6.2 Solution

The existing line-to-earth surge arresters limited the L-E overvoltage, but in order to achieve sufficient protection against line-to-line overvoltages, another set of surge arresters was proposed to be installed between the phases. The installation of RC damping elements would reduce the number of re-ignitions and so protect the transformer from resonance overvoltages.