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TECHNICAL SPECIFICATION

colour inside

UHV AC transmission systems –
Part 101: Voltage regulation and insulation design

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UHV AC TRANSMISSION SYSTEMS –

Part 101: Voltage regulation and insulation design

FOREWORD

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Technical Specifications are subject to review within three years of publication to decide whether they can be transformed into International Standards.

IEC TS 63042-101, which is a Technical Specification, has been prepared by IEC technical committee 122: UHV AC transmission systems.

The text of this Technical Specification is based on the following documents:

Enquiry draft	Report on voting
122/60/DTS	122/70A/RVDTS

Full information on the voting for the approval of this Technical Specification 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.

A list of all parts in the IEC 63042 series, published under the general title *UHV AC transmission systems*, can be found on the IEC website.

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- withdrawn,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.

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

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INTRODUCTION

Large-scale power sources including renewable energy have recently been developed. To meet the requirements for large power transmission capacity, some countries have introduced, or are considering introducing, ultra high voltage (UHV) transmission systems, overlaying these on the existing transmission systems at lower voltages such as 420 kV and 550 kV.

However, the introduction of UHV AC also presents many challenges to planners and operators. One of the major challenges is the management and control of system voltage and reactive power control. Reactive power control is normally used to address power frequency voltage requirements and maintain the voltage under transient conditions. Suitable insulation designs and coordination procedures are adopted in order to control transient overvoltages and prevent damage to equipment.

The objective of UHV AC power system design is to achieve both economic efficiency and high reliability, considering its impact on systems at lower voltages such as 420 kV and 550 kV. Long-distance transmission lines in particular generate a large amount of charging reactive power (Mvar) that could cause the system voltage to rise significantly. For example, when energizing a transmission line, the terminal voltage at the remote end could reach an unacceptable level. Reactive power compensation is implemented to ensure that the UHV AC system operates within an adequate voltage range under normal conditions and any contingency conditions that the system is designed to withstand.

Moreover, effective insulation design that limits internal electric field stress is important for minimizing and optimizing the size and structure of UHV AC transmission lines and substation apparatus. This document provides technical specifications on insulation design and coordination, reactive power compensation design and voltage regulation that are essential for maintaining UHV AC transmission systems so that they operate safely and efficiently.

UHV AC TRANSMISSION SYSTEMS –

Part 101: Voltage regulation and insulation design

1 Scope

This part of IEC 63042 specifies reactive power compensation design, voltage regulation and control, and insulation design for the coordination of UHV AC transmission systems.

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 60071-1, *Insulation co-ordination – Part 1: Definitions, principles and rules*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

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

3.1
voltage deviation
difference between the actual voltage and nominal system voltage under continuous operating conditions

3.2
network node
<in power networks> any point where two or more transmission lines meet

3.3
controllable shunt reactor
CSR
high voltage shunt reactor whose capacity can be adjusted

3.4
continuous controllable shunt reactor
CCSR
high voltage shunt reactor whose capacity can be adjusted continuously

3.5
multi-stage controllable shunt reactor
MCSR
type of controllable shunt reactor, based on the principle of high impedance transformers whose reactive power output usually varies in discrete stages and is achieved by controlling transistors, circuit-breakers and other devices

4 Reactive power compensation for UHV AC transmission systems

4.1 General principles

An appropriate amount of reactive power supply should be planned and installed in UHV AC systems to meet the system voltage regulation requirements and reduce the amount of unintended reactive power transfers between different network nodes/voltage levels.

A sufficient amount of reactive power supply with flexible capacity, including an adequate amount of reactive power reserve, should be maintained.

The capacity, type and location of reactive power compensators should be selected to improve power transmission capabilities and enhance system stability limits.

Planning and design of reactive power compensators for UHV AC systems should meet the overvoltage limit requirements for UHV AC systems.

A compensation ratio of between 90 % to 110 % is considered reasonable in planning reactive compensation to minimize the reactive power exchange between UHV and lower voltage level systems. The compensation should be judiciously implemented between line and bus reactive compensation so that it is able to control voltage during various switching operations and to prevent oscillations due to high levels of compensation.

4.2 Configuration of reactive power compensation – consider placing after general functions

In general, reactive power compensation should be distributed at the primary, secondary and tertiary side of the UHV transformer based on the overall requirements for voltage regulation and to minimize the overall cost. The principle of locating reactive power compensation at the primary and secondary sides of the UHV transformer is the same except for the cost of reactive power compensation and its effectiveness in regulating voltage at the primary side of the UHV transformer. In this way, they are treated in the same manner.

The major processes in configuring reactive power compensation for UHV AC systems are as follows:

a) Identify the range of likely active power flow across the UHV line, then calculate and analyse the characteristics of reactive power and voltage profiles along the UHV line, taking into account charging reactive power produced by UHV lines and reactive power loss under different power flow conditions. Simulations need to be repeated for each scenario to determine the compensation that keeps the voltage within acceptable limits. One of the methods for this is to determine the compensation required at each bus by using a static Var compensator (STATCOM) with a large range. The calculated output of the STATCOM that maintains bus voltage at 1,0 p.u. is the required compensation at that bus.

b) Select UHV transformer tap positions to avoid overvoltage under a range of operating conditions taking into account UHV substation location, number of transmission lines connected, and system operation mode.

c) Select capacity and location of UHV line shunt reactors with the following considerations:

   1) limiting temporary overvoltage and reducing secondary arc current;

   2) balancing charging power of lines and flexibly controlling bus voltage.

d) Identify total and unit capacity of compensators installed on the tertiary side of the transformer. Total capacity should be selected to reduce the reactive power exchange between different voltage levels and maintain bus voltage within the admissible range; the selection of single bank capacity should take into account the maintaining of voltage fluctuations induced by the switching of a single capacitor bank or reactor within a reasonable range. Set the dynamic reactive power limits provided by generators within the desired capability range.

e) Check whether the dynamic reactive power reserve provided by generators is adequate within their reactive power capability range. If it is adequate, then the process stops; otherwise return to d).

Figure 1 shows the process of configuring reactive power compensation.

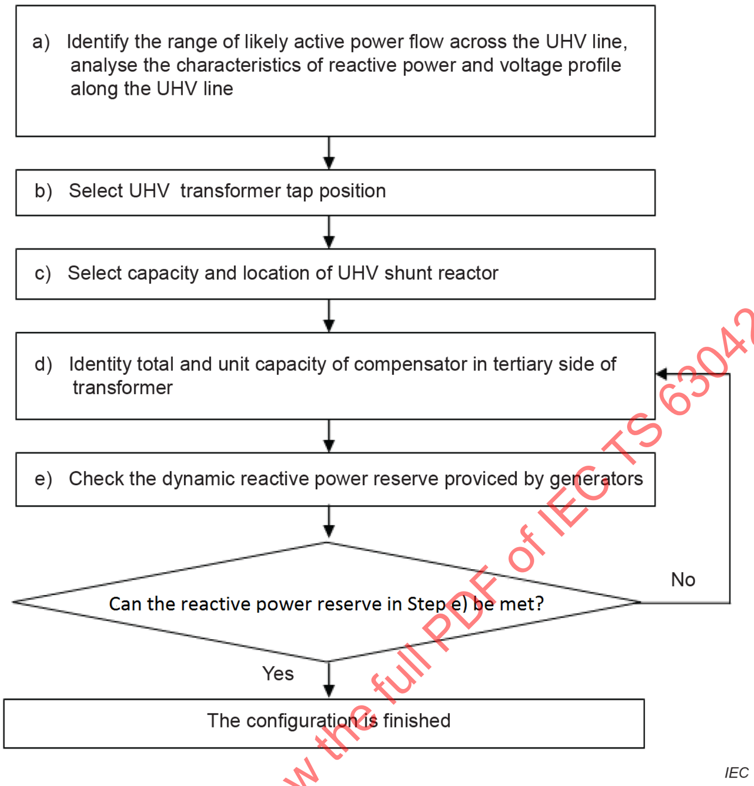


Figure 1 – Flowchart for reactive power compensation configuration

4.3 Determining reactive power compensation

4.3.1 Reactive compensation at UHV side

Reactive power compensation at the UHV side (primary side) refers to equipment that is directly connected to the UHV AC line or bus, including fixed capacity and controllable shunt reactors. UHV shunt reactive power compensation is mainly used to compensate the charging power of a UHV transmission line, limit temporary overvoltage and limit voltage to below the maximum operation voltage in transmission line energization. In addition, a shunt reactor with a neutral point reactor can be used to limit secondary arc current.

A shunt reactor connected to UHV transmission lines is used for reactive power compensation and overvoltage limiting. For substations with some short lines, the shunt reactor is normally connected to the bus, which is mainly used to compensate the charging power of the UHV transmission line.

4.3.2 Compensation at tertiary side of UHV transformers

Reactive power compensation connected at the tertiary side of UHV transformers mainly includes shunt capacitors, shunt reactors and static Var compensators (STATCOM), which are mainly used to meet the reactive power compensation requirements of the UHV AC system, to reduce the transformer‘s reactive power loss, and to regulate the system voltage.

4.3.3 Reactive power compensation at UHV side

For a shunt reactor connected to the terminal of transmission lines, its capacity can be calculated by Formula (1) below.

$$Q_{\text{HR-total}} = k_{\text{L}} \times Q_{\text{B}} \tag{1}$$

where

$Q_{\text{HR-total}}$ is the capacity of shunt reactive power compensation required at both sides of the UHV line because of this line;

Q_{B} is the no-load charging reactive power of this UHV line;

k_{L} is the compensation coefficient;

k_{L} is normally obtained based on the overvoltage calculation and reactive power balance, which is normally less than 0,85, to avoid oscillations during switching. If the line is short and line reactors are not required then the reactive power requirement can be considered in the bus reactive compensation. The requirement of a shunt reactor on the line has to be determined by the Ferranti effect during energization and temporary overvoltage studies. The nearest Mvar to the calculated value can be considered. In general, it is the compensation at each terminal of the transmission line.

For the shunt reactor connected to the bus, the capacity can be calculated by Formula (2).

$$Q_{\text{bus}} = k_{\text{B}}\left(\sum \frac{1}{2}\left(Q_{\text{B}} - Q_{\text{X}}\right) - \sum Q_{\text{HR}}\right) \tag{2}$$

where

k_{B} is the compensation coefficient, which is normally close to 100 %;

Q_{x} is the reactive power loss of the transmission line under no-load conditions, which is nearly zero;

$\sum \frac{1}{2}\left(Q_{\text{B}} - Q_{\text{X}}\right)$ is the sum of charging power and reactive power loss of half the line length of all transmission lines connected to the bus;

Q_{HR} is half of $Q_{\text{HR-total}}$.

$\sum Q_{\text{HR}}$ is the total capacity of all reactors directly connected to the UHV lines at the bus.

In general, k_{B} for the receiving end should be higher than that for the sending end. Furthermore, reactors at the generator bus and receiving end bus for light load conditions should be available. The determination of line and bus reactors as described above should be tested through simulation.

To gainfully utilize the line reactor when the line is not in service, a disconnector can be provided between the line termination and the point of connection of the line reactor. When the line is out of service, the disconnectors can be opened and the line reactor can be used like a bus reactor without the line. Provision of circuit-breakers can be considered when reactive compensation is not required for temporary overvoltage.

4.3.4 Shunt capacitor configuration at tertiary side of UHV transformers

The configuration of tertiary shunt capacitors should compensate for the reactive power loss of transformers and half of the net reactive power loss of transmission lines connected at the primary and secondary side of the UHV transformer.

The capacity of tertiary shunt capacitors can be calculated according to Formula (3) to Formula (8).

$$Q_{\mathrm{cap}} = Q_{\mathrm{Tloss}} - Q_{\mathrm{Hhalf}} - Q_{\mathrm{Mhalf}} \tag{3}$$

where

Q_{cap} is the total capacity of capacitive compensation.

$$Q_{\mathrm{Hhalf}} = \sum\left(\frac{1}{2}\left(Q_{\mathrm{BH}} - Q_{\mathrm{Hloss}}\right) + Q_{\mathrm{HC}}\right) - \sum Q_{\mathrm{HR}} \tag{4}$$

where

Q_{BH} is the charging power of the UHV line connected to the primary side of the UHV transformer;

Q_{Hloss} is the reactive power loss of the UHV line connected to the primary side of the UHV transformer;

Q_{HC} is the series compensation capacity of the UHV line connected to the primary side of the UHV transformer;

$\sum Q_{\mathrm{HR}}$ is the capacity sum of all reactors connected to the UHV lines at the primary side of the UHV transformer.

The capacity of the series capacitor is obtained as follows:

$$Q_{\mathrm{HC}} = I_{\mathrm{H}}^{2} \times X_{\mathrm{HC}} \tag{5}$$

where

I_{H} is the rated current connected to the UHV line at the primary side of the UHV transformer;

X_{HC} is the reactance of series compensation connected to the UHV line at the primary side of the UHV transformer.

$$Q_{\text{Mhalf}} = \sum \left(\frac{1}{2} \left(Q_{\text{BM}} - Q_{\text{Mloss}} \right) + Q_{\text{MC}} \right) - \sum Q_{\text{MR}} \tag{6}$$

where

Q_{BM} is the charging power of the lines connected to the secondary side of the UHV transformer;

Q_{Mloss} is the reactive power loss of the lines connected to the secondary side of the UHV transformer;

Q_{MC} is the series compensation capacity of the lines connected to the secondary side of the UHV transformer;

Q_{MR} is the capacity of the reactor connected to the line at the secondary side of the UHV transformer.

The capacity of the series capacitor is obtained as follows:

$$Q_{\text{MC}} = I_{\text{M}}{}^{2} \times X_{\text{MC}} \tag{7}$$

where

I_{M} is the rated current of the line connected to the secondary side of the UHV transformer;

X_{MC} is the series compensation reactance of the line connected to the secondary side of the UHV transformer.

Transformer loss is expressed as follows:

$$Q_{\text{Tloss}} = \left(S_{\text{N}} / U_{\text{N}} \right)^{2} \times X \tag{8}$$

where

Q_{Tloss} is the reactive power loss of the transformers;

S_{N} is the apparent power of the UHV transformer;

U_{N} is the voltage effective value of the UHV transformer;

X is the reactance of the UHV transformer.

4.3.5 Shunt reactor configuration at tertiary side of UHV transformers

In general, the charging power of transmission lines should almost be compensated by UHV and tertiary connected shunt reactors.

The capacity of tertiary shunt reactors is calculated by Formula (9).

$$Q_{\mathrm{rea}} = \sum \frac{1}{2} Q_{\mathrm{BH}} - \sum Q_{\mathrm{HR}} \tag{9}$$

where

Q_{rea} is the capacity of the tertiary shunt reactors;

Q_{BH} is the charging power of the UHV line connected to the primary side of the UHV transformer;

Q_{HR} is the capacity of the reactor connected to the UHV lines at the primary side of the UHV transformer.

4.4 Controllable shunt reactor at UHV side

4.4.1 General

A controllable shunt reactor (CSR) can be used to meet the requirement of limiting temporary overvoltage and balancing the charging power of the UHV transmission line under a range of UHV line loading conditions, such as light and heavy loads.

A CSR is composed of two parts, fixed and controllable. At present, there are two types of CSRs: multi-stage and continuous controllable shunt reactors. Multi-stage controllable shunt reactors (MCSR) vary the reactive power output in discrete steps, whereas continuous controllable shunt reactors (CCSR) vary the output smoothly.

4.4.2 Capacity selection

The CSR can have a value equal to the compensation required to control parameters as mentioned in 4.3.3 and to cater to heavy load conditions the same can be made variable.

4.4.3 Tap-changer

For the MCSR, voltage fluctuations caused by shifting tap-changers should be within the admissible voltage deviation range. The tap-changer range should be selected according to the voltage regulation requirements and overall cost.

4.4.4 Response speed of CSR

The response speed of a CSR should meet the requirements for overvoltage control, secondary arc current limiting and rapid voltage regulation.

For a CSR connected to transmission lines, the response speed should meet the requirements for temporary overvoltage control and secondary arc current limiting. For a CSR connected to the bus, the same response speed may be required if voltage regulation is considered necessary for temporary overvoltage control.

Where the CSR is connected to a transmission line and a single phase auto-reclose scheme is adopted, the response speed should be able to meet the requirements for secondary arc extinguishing.

In addition, the response speed of a CSR should also be able to meet the requirements for suppressing sharp voltage fluctuations caused by system faults.

4.4.5 Control mode

4.4.5.1 General

CSRs can be configured to operate in automatic and manual control modes. Automatic control mode includes temporal, voltage-based and reactive power loss based control modes. When a single phase fault occurs on the connected transmission line or in cases of load rejection, temporary control should be employed. Otherwise, the CSRs can be configured to operate in automatic and manual control modes.

4.4.5.2 Voltage control mode

Under normal operating conditions a CSR regulates its reactive power output (in stages for MCSR and smoothly for CCSR) based on the deviation in the actual operating voltage from a reference voltage. If, for example under system faults, the voltage exceeds the upper or lower voltage limits, it can rapidly be increased to the maximum or decreased to the minimum of its capacity.

4.4.5.3 Reactive power loss control mode

In this mode, the total reactive power loss of transmission lines and UHV transformers can be calculated automatically and CSR reactive power output can be regulated to help ensure that the change in total reactive power loss between two successive calculations does not exceed a pre-determined threshold.

4.4.5.4 Temporary control

For a CSR connected to a transmission line, this mode will allow it to increase its output to the maximum to limit secondary arc current when a single phase fault occurs on the connected transmission line or to control the temporary overvoltage in cases of load rejection.

4.4.5.5 Manual control

A CSR can switch to the manual control mode under certain conditions such as maintenance, tests.

4.5 Other requirements for compensation at tertiary side of UHV transformers

4.5.1 Configuration of shunt compensator banks

Configuration of individual tertiary shunt capacitor or reactor banks should ensure that voltage step change caused by the switching in/out of individual banks does not exceed that caused by the on-load tap-changers (OLTC) of the UHV transformers.

4.5.2 Connection

Tertiary shunt capacitors and reactors should have auto switching functions with circuit-breakers installed for each capacitor/reactor bank.

4.5.3 Dynamic reactive compensation

Dynamic reactive compensation, such as STATCOM, can be installed at places with UHV transmission lines or inter-area tie lines with frequent power flow changes, and UHV substations with inadequate reactive compensation or voltage regulation capabilities. The response speed should satisfy the requirements for temporary voltage control and rapid reactive power regulation.

5 Voltage regulation

5.1 General

The UHV AC system should operate within the admissible voltage deviation range.

The voltage regulation range and regulation method for transformer taps in the UHV AC system should be properly selected according to the grid structure and operating conditions.

5.2 Voltage regulation for UHV transformers

5.2.1 Voltage regulation via transformer tap changes

Changing the tap position of a transformer is one of the voltage regulation methods and it is commonly used to regulate the reactive power distribution and voltage level. If tap-changers are not used, reactive power compensation should be sufficient to control voltage.

5.2.2 Selection of transformer taps

Selection of transformer taps should meet the requirements for voltage control at power plant and substation buses, taking into consideration rated voltage, regulation mode, voltage range and tap values.

5.2.3 Voltage selection for transformers

The rated voltage at the UHV side of a step-up and step-down transformer should be determined via calculation and analysis.

5.2.4 Types of tap-changers

There are two types of UHV transformer tap-changers: on-load and de-energized tap-changer (DETC). Selection of tap-changer type should be based on the system operation conditions and system analysis. An on-load tap-changer should be used in conditions of large voltage variations.

5.2.5 UHV transformer tap range

The regulation range of transformer taps is determined via system analysis. The upper limit for UHV transformer taps should be selected to avoid over-excitation, and the lower limit should be selected to avoid overcurrent.

The range of individual taps should be determined to help ensure that voltage step change caused by each tap does not exceed the permissible range, which is generally considered to be 2,5 %. The range of an individual tap is normally up to 0,65 % (on-load) and 1,25 % to 2,5 % (no-load).

5.2.6 Selection of transformer tap position during operation

In actual operation, the selection of transformer taps should consider the impact of transmission line energization and de-energization, and the power flow of transmission lines and transformers under heavy loads or light loads.

The configuration procedure is as follows:

a) Initially identify the voltage operating range for both primary and secondary buses, taking into consideration equipment insulation and tolerance capabilities, as well as the voltage regulation capacity of the grid.

b) Calculate the voltage variation induced by transmission line energization and de-energization under different tap-changer schemes, then select the scheme in which voltage variation does not exceed the permissible range.

NOTE While charging with no load, voltage along the line will increase due to the charging capacitive current of the line flowing through the line inductance. For a lossless line, voltage at the open circuit terminal can be derived by Formula (10).

$$U = \frac{E_S}{\cos(\beta l) + Y_{end} Z_c \sin(\beta l)} \quad (10)$$

where

β is the propagation constant, indicated by $\beta = \omega\sqrt{L_o C_o}$;

L_o is the inductive reactance of the line per unit length;

C_o is the charging capacitor of the line per unit length;

E_s is the voltage at the bus where the transmission line is energized;

l indicates total line length;

U is the voltage at the terminal;

Y_{end} is the susceptance of the UHV shunt reactor at the open circuit terminal;

Z_c is the wave impedance, expressed by $Z_c = \sqrt{\frac{L_o}{C_o}}$.

c) Evaluate whether different transformer tapping schemes can meet the regulation requirements for variable operating conditions according to the regulation capabilities of existing voltage regulation and reactive power compensation devices.

d) As per the analysis and calculation in b) and c), identify transformer tap configuration.

6 Generator reactive power control

6.1 General

The generators in a UHV AC system should have rapid response in reactive power output and strong control capabilities. They are an important source of regulation for the UHV AC system voltage and reactive power distribution. A generator connected to the UHV AC system should be capable of generating and absorbing reactive power.

Generators in a UHV AC system are generally located far from the load centre. The charging reactive power of the line is large and excessive overvoltage may occur; thus, generators are required to have a certain leading phase capability to control the bus voltage at a reasonable level. In general, a generator connected to the UHV AC system should have 0,95 leading and 0,85 lagging capabilities under rated power. This means that generators with a rated capacity of 1 000 MW should be capable of absorbing about 300 Mvar of reactive power and generating about 600 Mvar.

6.2 Coordination among reactive devices

The UHV AC system should have a reactive power reserve with rapid response. Rapid response reactive capacity should be made reserve capacity in reactive power supply in running generators, shunt capacitors and dynamic reactive power compensation devices, so that there will be a rapid increase in reactive power output to maintain stable operation of the power system in the case of excessively low voltage caused by insufficient reactive power in the grid.

There are many reactive devices which would respond to changes in grid parameters. It is not desirable for all the resources to respond together. The sources which would participate for an event should be finalized depending on the response speed, variable range, etc., and depending on the grid event, and the voltage change system should respond. At any point in time sufficient reserve in both fixed and variable controllers should be available to cater to grid events like line/generator/compensating device outages.

7 Insulation design and coordination procedure for transmission line and substation design

7.1 General

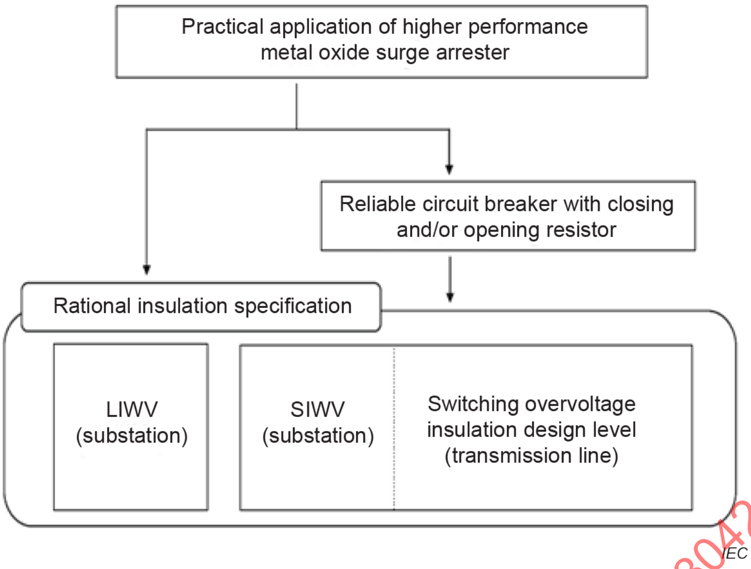
Economical and highly reliable transmission lines and substation equipment with environmental considerations are essential in a UHV AC system. UHV AC systems should be formulated to maintain an adequate voltage level. Overvoltage is mainly generated by lightning and the switching of circuit-breakers/disconnectors so it is necessary to suppress this overvoltage to within the required insulation levels.

If system design were carried out to counter each phenomenon, such as lightning overvoltage and switching overvoltage, individually for substations and transmission lines, the overall network system would become too redundant. To avoid this, insulation coordination is necessary. IEC 60071-1 standardizes rated insulation levels. This document focuses on UHV and specifies UHV design procedures in selecting appropriate insulation parameter values in reference to IEC 60071-1.

For most instances of the highest voltage for equipment, several rated insulation levels are standardized to allow for the application of different performance criteria or overvoltage patterns. The selection should be made by considering a system configuration which characterizes the degree of exposure to lightning and switching overvoltages, and the type of overvoltage limiting devices.

To reduce the size of transmission and substation equipment, surge arresters with low protection levels, as well as circuit-breakers with closing and/or opening pre-insertion resistors, are commonly applied to suppress overvoltage.

Insulation design for a UHV AC system should achieve high reliability considering the impact of contingencies. UHV equipment also tends to be large in size compared to that of lower voltages, such as 420 kV and 550 kV. When evaluating the insulation level for UHV the impact on the system should also be considered. For a new substation, insulation for both UHV and the lower voltages can be designed in a coordinated manner to achieve reliability and economy. It is also necessary to consider the impact of UHV insulation coordination on the lower voltages. See Figure 2.



Key

LIWV Lightning impulse withstand voltage

SIWV Switching impulse withstand voltage

Figure 2 – Flow chart for rational insulation specification for UHV

7.2 Insulation design procedure

Generally, overvoltage, which needs to be considered in designing UHV transmission lines and substation equipment, is classified into four categories depending on the voltage characteristics, as shown in Figure 3.

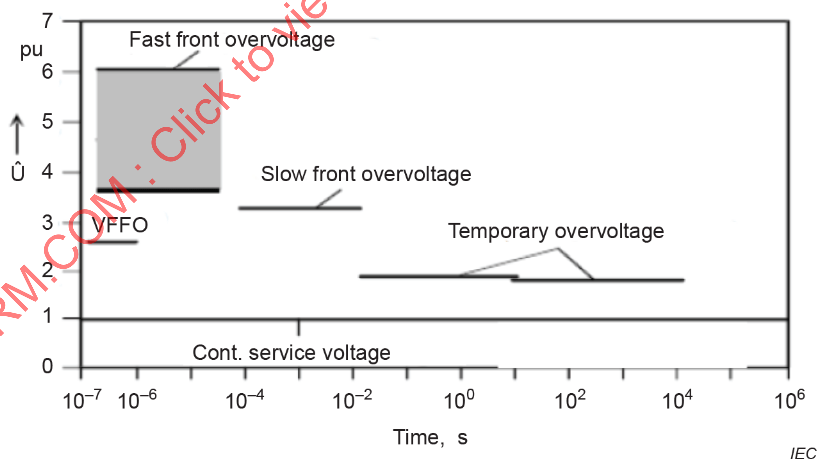


Figure 3 – Overvoltage categorized by time domain

It is important to analyse the overvoltage using an adequate simulation model for each time domain to understand the phenomena that occur in UHV AC systems.

7.3 UHV AC system overvoltage

7.3.1 General

In a UHV AC system, “highest voltage for equipment” should be checked taking into consideration UHV AC system overvoltage characteristics.

Standard values for each equipment should refer to IEC 60071-1.

The highest voltage for the equipment should always be used. Some product standards currently provide “rated voltage” assuming normal environmental conditions so “highest voltage for equipment” may not be checked. The highest voltage affects the countermeasures for protecting the equipment so it is necessary to consider it.

In addition, the rate of direct lightning in a UHV transmission line is larger than that in lower voltages, such as 550 kV, transmission line in outage, so it is also necessary to consider this.

7.3.2 Temporary overvoltage (TOV)

7.3.2.1 General

TOV refers to overvoltage between healthy phases and earth following a line to earth fault and also due to load rejections.

7.3.2.2 TOV due to load rejection and/or earth fault

A fault on single phase-to-earth in a three phase transmission system causes overvoltage, which influences the two other healthy phases at any point in the system. A load rejection results in TOV of phase-to-earth depending on the disconnected load, system configuration after rejection and control characteristics of the source, including the speed and voltage regulator of the generator. Moreover, in some cases, the Ferranti effect leads to an increase in voltage at the remote end of a long transmission line after load rejection. In such cases, a shunt reactor is adopted as one of the solutions to suppress the TOV. For combination load rejection after an earth fault, overvoltage may lead to the most severe level. After a fault occurs on the line, an open operation of the circuit-breaker at the load side system is performed and load rejection overvoltage is caused by the disconnected load until the circuit-breaker opens in the supply side system.

The amplitude and the duration of the overvoltage depend on the configuration of the transmission system, specifications of the equipment (including arresters and protection systems) and so on. To consider the various conditions of a power network such as these, calculations are useful to provide an accurate estimation of the TOV waveform and its occurrence probability. TOV affects decisions regarding surge arrester specifications as well as the insulation design of equipment. As lower protection levels of surge arrester are selected, the TOV duty of the surge arrester increases. The energy dissipation capability of surge arresters is the predominant factor for determination of their protection characteristics. The necessary energy capability of the surge arrester under TOV depends on the overvoltage amplitude and duration. The amplitude of the TOV level in a UHV AC system is higher than that in systems at lower voltages such as 420 kV and 550 kV and therefore is required to be controlled to reduce.

Information on presumed TOV amplitudes and durations in the system would help in designing equipment with suitable insulation design, coordination procedures, energy absorption and magnetic core.

7.3.3 Switching overvoltage (slow-front overvoltage)

Slow-front overvoltage is caused by the closing, reclosing and opening of circuit-breakers, and earth faults are of particular importance for UHV AC systems. If earth fault overvoltages occur there are generally no effective means of controlling them, except for those near substations that can be reduced via surge arresters. In contrast, closing and opening overvoltage can be controlled effectively via the insertion of closing and opening resistors, surge arresters and controlled switching. The target for the reduction of switching overvoltage is basically the earth fault overvoltage level.

Overvoltage due to fault clearing occurs when the line with the fault is switched off. A subsequent insulation failure may occur on the part of the system still in operation. This type of overvoltage should be carefully investigated.

The amplitudes of the overvoltages tend to depend on the length of the energized line, number of connections and length of other lines which are energized/re-energized, type of circuit-breaker (closing/opening resistor or not), arrangement and specification of arresters and so on.

The occurrence probability of slow-front overvoltage is one of the factors in evaluating representative values.

Controlled switching and line arresters can be utilized as a mitigation measure for insulation level reduction, although they have not been commercially applied to UHV AC systems.

7.3.4 Lightning overvoltage (fast-front overvoltage)

7.3.4.1 General

Fast-front overvoltage, such as lightning overvoltage, has a front time of several micro-seconds, and is one of the important factors in determining insulation designs for substation equipment. In a UHV transmission system, both back-flashover overvoltage and direct lightning overvoltage should be studied to evaluate the lightning overvoltage.

7.3.4.2 Lightning overvoltage caused by back-flashover and direct lightning

In the insulation design of substation equipment, the predominant overvoltage is lightning overvoltage. Lightning impulse withstand voltages (LIWV) are evaluated based on lightning overvoltages.

The lightning overvoltages occurring in a substation are due to back-flashover at the transmission tower or direct lightning strikes to the power line, as illustrated in Figure 4. When back-flashover at the transmission tower or a direct lightning strike to the power line occurs, a lightning surge will propagate on the transmission line and enter the substation. While lightning overvoltages in a substation can effectively be suppressed by utilizing a surge arrester, they depend greatly on the assumed lightning strike conditions and the configuration of substation circuits. In the case where the peak value of a lightning strike current is large and the duration of the wave front is short (the steepness of the wave front being large), or when the branches of circuits are few and the distance from the surge arrester is great, lightning overvoltages will generally be high.

LIWVs should be determined assuming severe conditions such as a large lightning current and/or other unusual circuit conditions. This will provide a margin for the overvoltage generated under normal conditions. Overvoltage calculation conditions are an important aspect of the system design policy for insulation design and coordination procedures.

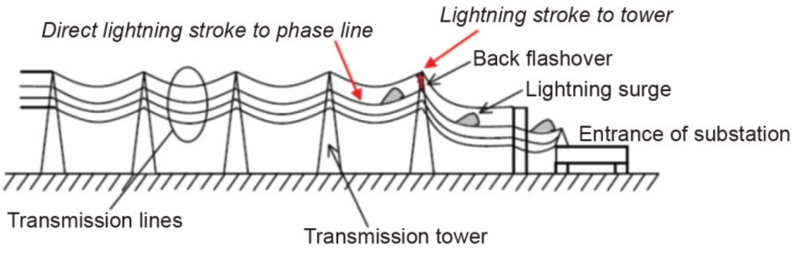


Figure 4 – Overvoltage mechanism caused by back-flashover and direct lightning

7.3.5 Very fast front overvoltage (VFFO)

Re-strikes and pre-strikes during disconnector switching generate oscillating surges with very high frequencies of up to tens of MHz. A disconnector re-striking surge can exceed the lightning impulse overvoltage in UHV GIS-type substations; these substations' insulation designs should be coordinated accordingly. The generation and propagation of VFFO from their original location throughout a GIS can produce internal and external transient overvoltage. The maximum value of the VFFO depends on the voltage difference across the contacts just before striking and the location considered. For this case, the maximum VFFO peak in a GIS configuration has a typical value of between 1,5 p.u. and 2,8 p.u.

In particular, VFFO can damage the insulation of GIS and the turn to turn insulation of transformers, and cause transient enclosure voltage (TEV) and electromagnetic interference (EMI) in low voltage control systems. The amplitude and wave shape of VFFO is decided by the practical conditions of the two sides of the disconnector, such as the length of the bus bar, the position of impedance changing. In the design of GIS and Hybrid-IS, the influence of VFFO should be considered. VFFO in GIS are of greater concern for UHV, for which the ratio of the LIWV to the system voltage is lower.

If the breaker at the energizing end of an open-circuited line is opened at line charging-current-zero, the line voltage will be at peak and the charge will be trapped on the phase conductors. The only path for the discharge is leakage over the insulators, which usually have a very high resistance, so discharge can take several minutes. If the line is re-energized while trapped charge remains, it is possible for this to occur with opposite polarities between the supply and line sides of the breaker.

The VFFO depends mainly on the contact speed of the disconnector. The frequency of a disconnector re-striking surge is much higher than that of lightning surges because every disconnector operation potentially generates overvoltage, and the surge could impose negative effects not only on the main circuit insulation but also on secondary systems. One possible solution for damping of VFFO in GIS is the integration of a damping resistor.

7.4 Reduction of insulation levels using overvoltage suppression measures

7.4.1 General

Overvoltage in UHV causes extremely severe damage to equipment and various countermeasures to suppress it have been developed. In general, they are effective regardless of the system situation.

In this subclause, characteristic methods of typical overvoltage suppression measures are described.

7.4.2 Overvoltage suppression using surge arrester with low protective level

Surge arresters with low protection levels have been utilized to suppress LIWV and SIWV and they are recognized as an effective measure for suppressing power system overvoltage. Typical locations of these higher performance arresters are transmission bays, bus bars and transformer bays.

7.4.3 Resistor-fitted circuit-breakers with closing/opening resistor

To suppress switching overvoltage, a pre-insertion resistor is employed for UHV circuit-breakers, such as the resistor-closing technique and resistor-closing/opening technique. The resistance of this switching scheme is usually between 400 Ω to 700 Ω depending on the size of the UHV AC system and its characteristics.

7.4.4 Damping effect of resistor-fitted disconnectors employed in GIS to suppress VFFO

In gas insulated substations, resistor-fitted disconnectors are utilized to suppress VFFO.

Other measures may also be appropriate, such as an increasing of LIWV.

7.4.5 Damping effect of AIS for suppressing VFFO

In air-insulated circuit-breakers the impact of VFFO is limited to other equipment attached because of the damping and reflection factor of the transition from the gas-insulated circuit-breaker to the air-insulated equipment connected.

This is the case with live tank and dead tank circuit-breakers.

7.4.6 Fast insertion of switchable or controllable shunt reactors

High voltage shunt reactors can be applied on long UHV transmission lines with an adequate compensation degree to maintain the reactive power balance and suppress TOV.

The shunt reactors are primarily to provide compensation for transmission line capacitance and also reduce overvoltage levels, if connected. It is therefore recommended in this document to switch in disconnected reactors or control reactive power to the maximum, preferably prior to energizing or re-energizing and following load rejection.

7.4.7 Controlled switching

Controlled switching of high-voltage AC circuit-breakers has become an accepted means of reducing switching overvoltage in power systems. As the rated capacity of UHV transformers and shunt compensation devices connected at the tertiary is much larger than for lower voltage transformers, the inrush current and voltage distortion during energizing is much more severe. Controlled switching should be adopted to effectively suppress switching overvoltage.

7.5 Coordination of design requirements

7.5.1 General

The overvoltage level depends on the system configuration and, at the same time, the methods for countering such overvoltage influence the system planning itself. Therefore, insulation design should be carried out considering multilateral impacts.

UHV technology is characterized by a stringent need to reduce as far as possible the size, weight, cost and environmental impact of the overhead transmission lines and substations from an economic, societal and technical point of view.

7.5.2 Transmission line

The protection of transmission lines against overvoltages, especially lightning and switching overvoltages, is a critical issue. A UHV AC system has the feature that the rate of direct lightning in a UHV transmission line is larger than that of lower voltage classes such as 550 kV and 420 kV. 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 lightning overvoltages impinging on the substation.

Air clearance for a UHV transmission line, which determines the tower size, is directly related to the measures for mitigating switching overvoltage.

Line insulation design and coordination should take the following into consideration:

- lightning performance of overhead line derived from conductor configuration, shielding wires and tower earthing;
- amplitude of switching overvoltage due to line energization or re-energization, reduced practically by proper mitigation countermeasures;
- air clearance between the phase conductor and the earthing side of tower arms; where the design employs free-swinging insulators, the dielectric strength of air clearances should take into account conductor movement;
- insulator string length (number and type of insulators);
- conductor clearances at mid-span.

7.5.3 Substation

The protection of a UHV substation against overvoltages, especially lightning overvoltage, is a crucial issue. Furthermore, the insulation level of a UHV substation is greatly reduced compared to that for lower voltage classes, such as 550 kV and 420 kV, due to the surge arresters having a low protection level in order to reduce equipment size.

LIWV and SIWV for UHV transformers and switchgear are estimated by the following considerations:

- operational bus circuits and system, assuming severe conditions of a large amplitude of lightning and switching overvoltage;
- location and number of surge arresters with low protection level in UHV substation;
- wave shape (amplitude and front-time, etc.) of lightning striking UHV transmission line;
- insulation characteristics of UHV equipment and air clearance;
- thermal capability of UHV surge arrester due to the temporary overvoltage;
- special consideration for VFFO in UHV substation.

Annex A
(informative)

UHV multi-stage controllable shunt reactor

A multi-stage controllable shunt reactor (MCSR) is a type of controllable shunt reactor, based on the principle of high impedance transformers. Its reactive power output usually varies in discrete stages and is achieved by controlling transistors, circuit-breakers and other devices.

Under normal operating conditions, an MCSR can change its output to meet the system demand for reactive power compensation if a fault occurs on the transmission line.

As shown in Figure A.1, UHV transmission lines A-B and B-C are respectively 420 km and 290 km in length, and substations A, B, and C have three, two, and four UHV transformers, respectively. Transformer capacity is 3 000 MVA and short-circuit impedance is 18 % (between high voltage side and medium voltage side). A maximum of four sets of capacitive compensation devices (210 Mvar each, at a rated voltage of 126 kV) are installed at the tertiary side of the UHV transformer.

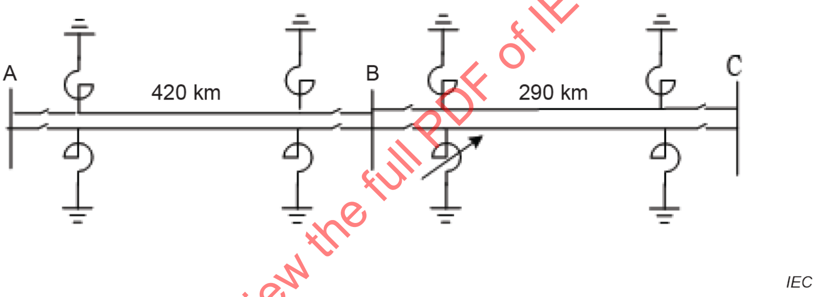


Figure A.1 – Illustrative example of a UHV project with an MCSR

The process of configuring a UHV MCSR is as follows:

a) Determine total compensation requirements for UHV shunt reactors

Based on the requirement of limiting overvoltage and secondary arc current, and the compensating charging power of transmission lines, analysis shows that there is a need for significant compensation in a UHV AC system. Specifically, two sets of UHV shunt reactors, each with capacities of 840 Mvar and 960 Mvar, are required at each end of double-circuit A-B, and four sets of shunt reactors, each of 600 Mvar, are required at each end of double circuit B-C.

b) Determine minimum requirements for the controllable shunt compensation

Analysis was carried out to assess the reactive power demand under normal operation and N-1 conditions. Assuming the maximum amount of capacitive compensation that can be connected at the tertiary side of the UHV transformers at substations A, B, and C, there is still a shortage of 355 Mvar capacitive reactive compensation at substation B (assuming the amount of shunt compensation as determined in Step a)). In addition, as P_2 (the power flow across line B-C) is significantly higher than P_1 (the power flow across line A-B), the reactive power shortage at line B-C is greater than that at line A-B. Therefore, an MCSR can be considered to be installed on side B of line B-C, and the controllable capacity should be greater than 355 Mvar.

c) Determine the capacity and number of stages

Generally, the voltage fluctuation caused by switching each MCSR stage should be less than 2,5 % of the rated voltage. The maximum capacity of each MCSR stage can be calculated based on the short circuit capacity of substation B, which can be obtained as 33 822 MVA. Therefore, the maximum capacity of each stage is as follows:

33 822 × 2,5 % = 846 Mvar

The number of stages is usually recommended to be three to four, of which the variable is two to three with equal capacity, taking into account the system margin requirements and ease of control.

d) Determine final configuration of UHV MCSR

From the analysis in b) and c), and available size of the MCSR, it is proposed to use an MCSR of 600 Mvar with three equal stages, of which 200 Mvar is fixed and 2 x 200 Mvar are controllable.

The voltage variation induced by switching different stages of UHV MCSR is shown in Table A.1. The voltage fluctuation rate of switching single-stage capacity is 0,55 % on the UHV side and 0,34 % on the secondary side.

Table A.1 – Impact of MSCR switching on voltage at station B

Nominal voltage	Initial voltage (with all three stages in) kV	Voltage (with one stage switched out) kV	Voltage (with two stages switched out) kV
1 000 kV (UHV side)	1 055	1 061	1 066
500 kV (secondary side)	524	526	528