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Indian Standard

IS/IEC 60071-2 : 2023

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भाग 2 अनुप्रयोग के दिशानिर्देश

(दूसरा पुनरीक्षण)

Insulation Co-ordination

Part 2 Application Guidelines

(Second Revision)

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NATIONAL FOREWORD

This Indian Standard (Part 2) (Second Revision) which is identical with IEC 60071-2 : 2023 'Insulation co-ordination — Part 2: Application guidelines' issued by the International Electrotechnical Commission (IEC) was adopted by the Bureau of Indian Standards on the recommendation of the High Voltage Engineering Sectional Committee and approval of the Electrotechnical Division Council.

This standard was first published in 2012 and subsequently revised in 2021 identical with IEC 60071-2 : 2018. This revision has been undertaken to align it with the latest version of IEC 60071-2 : 2023.

This standard is published in several parts. The other parts in this series are:

Part 1	Definitions, principles and rules
Part 4	Computational guide to insulation co-ordination and modeling of electrical networks
Part 5	Procedures for high-voltage direct current (HVDC) converter stations

The text of the IEC standard has been approved as suitable for publication as an Indian Standard without deviations. Certain conventions are, however, not identical to those used in Indian Standards. Attention is particularly drawn to the following:

a) Wherever the words 'International Standard' appears referring to this standard, they should be read as 'Indian Standard'; and

b) Comma (,) has been used as a decimal marker, while in Indian Standards the current practice is to use a point (.) as the decimal marker.

In this adopted standard, reference appears to International Standards for which Indian Standards also exist. The corresponding Indian Standards, which are to be substituted, are listed below along with their degree of equivalence for the editions indicated:

International Standard	*Corresponding Indian Standard*	*Degree of Equivalence*
IEC 60071-1 : 2019 Insulation co-ordination — Part 1: Definitions, principles and rules	IS/IEC 60071-1 : 2019 Insulation co-ordination: Part 1 Definition principles and rules (*first revision*)	Identical
IEC TS 60815-1 : 2008 Selection and dimensioning of high-voltage insulators intended for use in polluted conditions — Part 1: Definitions, information and general principles	IS 16683 (Part 1) : 2018/ IEC TS 60815-1 : 2008 Selection and dimensioning of high-voltage insulators intended for use in polluted conditions: Part 1 Definitions, information and general principles	Identical
IEC TR 60071-4 : 2004 Insulation co-ordination — Part 4 Computational guide to insulation coordination and modelling of electrical networks	IS/IEC TR 60071-4 : 2004 Insulation coordination: Part 4 Computational guide to insulation co-ordination and modeling of electrical networks	Identical

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Indian Standard

INSULATION CO-ORDINATION

PART 2 APPLICATION GUIDELINES

(Second Revision)

1 Scope

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

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

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

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

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

The content of this document strictly follows the flow chart of the insulation co-ordination process presented in Figure 1 of IEC 60071-1:2019. Clauses 5 to 8 correspond to the squares in this flow chart and give detailed information on the concepts governing the insulation co-ordination process which leads to the establishment of the required withstand levels.

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

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

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

2 Normative references

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

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

IEC 60071-1:2019, *Insulation co-ordination – Part 1: Definitions, principles and rules*

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

IEC TS 60815-1: 2008, *Selection and dimensioning of high-voltage insulators intended for use in polluted conditions – Part 1: Definitions, information and general principles*

IEC TR 60071-4:2004*, Insulation co-ordination – Part 4: Computational guide to insulation co-ordination and modelling of electrical networks*

3 Terms, definitions, abbreviated terms and symbols

3.1 Terms and definitions

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

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

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

3.1.1
insulation co-ordination
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 and taking into account the service environment and the characteristics of the available preventing and protective devices

Note 1 to entry: By "dielectric strength" of the equipment, is meant here its rated or its standard insulation level as defined in 3.36 and 3.37 of 60071-1:2019 respectively.

[IEC 60071-1:2019, 3.1]

3.1.2
earth fault factor
at a given location of a three-phase system, and for a given system configuration, the ratio of the highest RMS phase-to-earth power-frequency voltage on a healthy phase during a fault to earth affecting one or more phases at any point on the system to the RMS phase-to-earth power-frequency voltage which would be obtained at the given location in the absence of any such fault

[SOURCE: IEC 60071-1:2019, 3.15]

3.2 Abbreviated terms

AIS	air-insulated substation
EGLA	externally gapped line arrester
EHV	extra high voltage: the highest voltage for equipment above 245 kV and up to and including 800 kV
EMT	electro-magnetic transients
ESDD	equivalent salt deposit density
FFO	fast-front overvoltage
GIS	gas-insulated switchgear, gas-insulated substation
LIPL	lightning impulse protection level
LIWV	lightning impulse withstand voltage
LSA	line surge arrester

MOSA	metal-oxide surge arrester
MTBF	mean time between failure
NGLA	non-gapped line arrester
SDWV	short-duration power-frequency withstand voltage
SFO	slow-front overvoltage
SIPL	switching impulse protection level
SIWV	switching impulse withstand voltage
SVU	series varistor unit
TCV	trapped charge voltage
TOV	temporary overvoltages
UHV	ultra high voltage: the highest voltage for equipment above 800 kV
VFFO	very-fast-front overvoltage

3.3 Symbols

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

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

A	(kV)	parameter characterizing the influence of the lightning severity for the equipment depending on the type of overhead line connected to it
a_1	(m)	length of the lead connecting the surge arrester to the line
a_2	(m)	length of the lead connecting the surge arrester to earth
a_3	(m)	length of the phase conductor between the surge arrester and the protected equipment
a_4	(m)	length of the active part of the surge arrester
B	(-)	factor used when describing the phase-to-phase discharge characteristic
C_e	(nF)	capacitance to earth of transformer primary windings
C_s	(nF)	series capacitance of transformer primary windings
C_2	(nF)	phase-to-earth capacitance of the transformer secondary winding
C_{12}	(nF)	capacitance between primary and secondary windings of transformers
C_{1in}	(nF)	equivalent input capacitance of the terminal 1 of three-phase transformers
C_{2in}	(nF)	equivalent input capacitance of the terminal 2 of three-phase transformers
C_{3in}	(nF)	equivalent input capacitance of the terminal 3 of three-phase transformers
c	(m/µs)	velocity of light
c_f	(p.u.)	coupling factor of voltages between earth wire and phase conductor of overhead lines
d	(m)	air gap length
d_r	(-)	dividing ratio of capacitively transferred surges

E_0	(kV/m)	soil ionization gradient
F		function describing the cumulative distribution of overvoltage amplitudes, where $F(U) = 1 - P(U)$; see Clause B.3
$F_{c\text{-}p}$		function describing the cumulative distribution of overvoltage amplitudes, in case-peak method
f		function describing the probability density of overvoltage amplitudes
H	(m)	altitude above sea-level
h	(-)	power-frequency voltage factor for transferred surges in transformers
H_t	(m)	height above earth
I	(kA)	lightning current amplitude
l_g	(kA)	limit lightning current in tower footing resistance calculation
I_n	(kA)	nominal discharge current of an arrester
J	(-)	winding factor for inductively transferred surges in transformers
K	(-)	gap factor taking into account the influence of the gap configuration on the strength
K_a	(-)	altitude correction factor
K_c	(-)	co-ordination factor
K_s	(-)	safety factor
K_{cd}	(-)	deterministic co-ordination factor
K_{cmp}	(-)	compensation factor, the ratio of reactive power of SR to reactive power of line positive sequence capacitance
K_{co}	(μs/(kVm))	corona damping constant
K_{cs}	(-)	statistical co-ordination factor
$K_{f}{}^{+}{}_{f}$	(-)	gap factor for fast-front impulses of positive polarity
$K_{f}{}^{-}{}_{f}$	(-)	gap factor for fast-front impulses of negative polarity
K_{ev}	(-)	evaluation factor of ratio for lightning overvoltage with respect to standard voltage shape
k	(-)	earth fault factor
k_h	(-)	parameter for humidity correction
L_a	(m)	overhead line length yielding to an outage rate equal to the acceptable one (related to R_a)
L_t	(m)	overhead line length for which the lightning outage rate is equal to the adopted return rate (probability of occurrence, related to R_t)
L_{sp}	(m)	span length
M	(-)	number of insulations in parallel considered to be simultaneously stressed by an overvoltage
m	(-)	exponent in the atmospheric correction factor formula for external insulation withstand
N	(-)	number of conventional deviations between U_{50} and U_{spec} of a self-restoring insulation
n	(-)	number of overhead lines considered connected to a station in the evaluation of the impinging surge amplitude
P	(%)	probability of discharge of a self-restoring insulation

P_w	(%)	probability of withstand of self-restoring insulation
q	(-)	response factor of transformer windings for inductively transferred surges
Q_{rs}	(C)	repetitive charge transfer rating of an arrester
Q_{th}	(C)	thermal charge transfer rating of an arrester
R	(-)	risk of failure (failures per event)
R_a	(1/a)	acceptable failure rate for apparatus; for transmission lines, this parameter is normally expressed in terms of (1/a)/100 km
R_{cs}	(-)	the most critical overvoltage stress
R_f	(Ω)	fault resistance
R_{hc}	(Ω)	high current value of the tower footing resistance
R_{km}	(1/(m.a))	overhead line outage rate per year for a design corresponding to the first kilometre in front of the station
R_{lc}	(Ω)	low current value of the tower footing resistance
R_p	(1/a)	shielding penetration rate of overhead lines
R_{sf}	(1/a)	shielding failure flashover rate of overhead lines
R_t	(1/a)	adopted overvoltage return rate (reference value)
R_u	(kV)	radius of a circle in the U^+/U^- plane describing the phase-phase-earth slow-front overvoltages
R_0	(Ω)	zero sequence resistance
R_1	(Ω)	positive sequence resistance
R_2	(Ω)	negative sequence resistance
S	(kV/μs)	steepness of a lightning surge impinging on a substation
S_e	(kV)	conventional deviation of phase-to-earth overvoltage distribution
S_p	(kV)	conventional deviation of phase-to-phase overvoltage distribution
S_{rp}	(kV/μs)	representative steepness of a lightning impinging surge
s_e	(-)	normalized value of the conventional deviation S_e (S_e referred to U_{e50})
s_p	(-)	normalized value of the conventional deviation S_p (S_p referred to U_{p50})
t_s	(μs)	travel time of a lightning surge
U	(kV)	amplitude of an overvoltage (or of a voltage)
U^+	(kV)	positive switching impulse component in a phase-to-phase insulation test
U^-	(kV)	negative switching impulse component in a phase-to-phase insulation test
U_{spec}	(kV)	truncation value of the discharge probability function $P(U)$ of a self-restoring insulation: $P\ (U \leq U_{spec}) = 0$
U_0^+	(kV)	equivalent positive phase-to-earth component used to represent the most critical phase-to-phase overvoltage
U_{1e}	(kV)	temporary overvoltage to earth at the neutral of the primary winding of a transformer
U_{2e}	(kV)	temporary overvoltage to earth at the neutral of the secondary winding of a transformer

U_{2N}	(kV)	rated voltage of the secondary winding of a transformer
U_{10}	(kV)	value of the 10 % discharge voltage of self-restoring insulation; this value is the statistical withstand voltage of the insulation defined in 3.23 b) of IEC 60071-1:2019
U_{16}	(kV)	value of the 16 % discharge voltage of self-restoring insulation
U_{50}	(kV)	value of the 50 % discharge voltage of self-restoring insulation
U_{50M}	(kV)	value of the 50 % discharge voltage of M parallel self-restoring insulations
U_{50RP}	(kV)	value of the 50 % discharge voltage of a rod-plane gap
U_c	(kV)	continuous operating voltage of an arrester
U_c^+	(kV)	positive component defining the centre of a circle which describes the phase-phase-earth slow-front overvoltages
U_c^-	(kV)	negative component defining the centre of a circle which describes the phase-phase-earth slow-front overvoltages
U_{cw}	(kV)	co-ordination withstand voltage of equipment.
U_e	(kV)	amplitude of a phase-to-earth overvoltage
U_{et}	(kV)	truncation value of the cumulative distribution $F(U_e)$ of the phase-to-earth overvoltages: $F(U_e \geq U_{et}) = 0$ (see Clause B.3)
U_{e2}	(kV)	value of the phase-to-earth overvoltage having a 2 % probability of being exceeded: $F(U_e \geq U_{e2}) = 0,02$ (see Clause B.3)
U_{e50}	(kV)	50 % value of the cumulative distribution $F(U_e)$ of the phase-to-earth overvoltages (see Clause B.3)
U_l	(kV)	amplitude of the impinging lightning overvoltage surge
U_m	(kV)	highest voltage for equipment
U_n	(kV)	nominal voltage
U_p	(kV)	amplitude of a phase-to-phase overvoltage
U_{p2}	(kV)	value of the phase-to-phase overvoltage having a 2 % probability of being exceeded: $F(U_p \geq U_{p2}) = 0,02$ (see Clause B.3)
U_{p50}	(kV)	50 % value of the cumulative distribution $F(U_p)$ of the phase-to-phase overvoltages (see Clause B.3)
U_r	(kV)	rated voltage of an arrester based on temporary overvoltages
U_s	(kV)	highest voltage of a system
U_w	(kV)	standard withstand voltage
U_{pl}	(kV)	lightning impulse protection level of an arrester
U_{ps}	(kV)	switching impulse protection level of an arrester
U_{pt}	(kV)	truncation value of the cumulative distribution $F(U_p)$ of the phase-to-phase overvoltages: $F(U_p \geq U_{pt}) = 0$ (see Clause B.3)
U_{rp}	(kV)	amplitude of the representative overvoltage
U_{rw}	(kV)	required withstand voltage
U_{T1}	(kV)	overvoltage applied at the primary winding of a transformer which produces (by transference) an overvoltage on the secondary winding.
U_{T2}	(kV)	overvoltage at the secondary winding of a transformer produced (by transference) by an overvoltage applied on the primary winding.

u	(p.u.)	per unit value of the amplitude of an overvoltage (or of a voltage) referred to $U_s\ \sqrt{2}/\sqrt{3}$.
w_{21}	(-)	ratio of transformer secondary to primary phase-to-phase voltage.
W	(kJ)	required energy absorption of an arrester.
W_{th}	(kJ/kV)	thermal energy rating of an arrester.
X	(m)	distance between struck point of lightning and substation.
X_p	(km)	limit overhead line distance within which lightning events have to be considered.
X_T	(km)	overhead line length to be used in simplified lightning overvoltage calculations.
X_0	(Ω)	zero sequence reactance of a system.
X_1	(Ω)	positive sequence reactance of a system.
X_2	(Ω)	negative sequence reactance of a system.
x	(-)	normalized variable in a discharge probability function $P(U)$ of a self-restoring insulation.
x_M	(-)	normalized variable in a discharge probability function $P(U)$ of M parallel self-restoring insulations.
Z	(kV)	conventional deviation of the discharge probability function $P(U)$ of a self-restoring insulation.
Z_0	(Ω)	zero sequence impedance.
Z_1	(Ω)	positive sequence impedance.
Z_2	(Ω)	negative sequence impedance.
Z_e	(Ω)	surge impedance of the overhead line earth wire.
Z_L	(Ω)	surge impedance of the overhead line.
Z_M	(kV)	conventional deviation of the discharge probability function $P(U)$ of M parallel self-restoring insulations.
Z_s	(Ω)	surge impedance of the substation phase conductor.
z	(-)	normalized value of the conventional deviation Z referred to U_{50}.
α	(-)	ratio of the negative switching impulse component to the sum of both components (negative + positive) of a phase-to-phase overvoltage.
β	(kV)	scale parameter of a Weibull cumulative function.
$\beta_{c\text{-}p}$	(kV)	scale parameter of a Weibull cumulative function, in case-peak method.
$\beta_{p\text{-}p}$	(kV)	scale parameter of a Weibull cumulative function, in phase-peak method.
U_0	(kV)	truncation value of a Weibull cumulative function.
η	(-)	electric field utilization factor.
Φ		Gaussian integral function.
ϕ	(-)	inclination angle of a phase-to-phase insulation characteristic.
γ	(-)	shape parameter of a Weibull-3 cumulative function.
σ	(p.u.)	per unit value of the conventional deviation (S_e or S_p) of an overvoltage distribution.

$\sigma_{c\text{-}p}$	(p.u.)	per unit value of the conventional deviation (S_e or S_p) of an overvoltage distribution, in case-peak method.
$\sigma_{p\text{-}p}$	(p.u.)	per unit value of the conventional deviation (S_e or S_p) of an overvoltage distribution, in phase-peak method.
ρ	(Ωm)	soil resistivity.
τ	(µs)	tail time constant of a lightning overvoltage due to back-flashovers on overhead lines.

4 Concepts governing the insulation co-ordination

Insulation co-ordination basically helps to determine and dimension the dielectric strength of the equipment and system insulation in such a way that for all expected operating voltages and overvoltages the equipment reliably withstand.

The selection of the dielectric strength of equipment and system should consider economic issues of total costs, such as equipment and system costs, maintenance costs, and costs caused by insulation failure. Insulation coordination is complex task considering technical and economic evaluation criteria.

For those concepts, required withstand voltage is defined as test voltage that the insulation of the equipment shall withstand at the standard withstand voltage test to ensure that the insulation will meet the performance criterion when subjected to a given class of overvoltages in actual service conditions and for the whole service duration.

Figure 1 of IEC 60071-1:2019 shows an overall procedure flow chart as overview for determination of the rated or standard insulation level and gives links for further definitions and descriptions.

Representative overvoltages (Urp) produce the same dielectric effect on the insulation as overvoltages of a given class occurring in service due to various origins. They are first calculated taking surge arrestors as countermeasures to be placed to reduce the overvoltages. Digital simulation is generally used for representative overvoltage determination in the recent procedure of insulation co-ordination. Co-ordination withstand voltages (U_{cw}) are determined by multiplying value of Urp with a coordination factor (K_c) to meet the performance criterion. Besides, simulations of overvoltage events combined with the simultaneous evaluation of the risk of failure, permit the direct determination of the statistical U_{cw} without the intermediate step of determining the Urp. Moreover, because the actual operating conditions of electrical equipment can deviate from the standardized test conditions in the laboratory, the required withstand voltages (Urw) are determined with the aid of altitude correction and safety factors (K_a and K_s).

Overall insulation co-ordination can be summarized in the following four steps:

1) Determination of all representative voltages and overvoltages (U_{rp}) in the network, as described in Clause 5.
2) Determination of the co-ordination withstand voltages (U_{cw}) required for the consideration of the accuracy evaluation of the representative overvoltages and the distribution of the overvoltages and the insulation characteristics, as described in Clause 6.
3) Conversion of the co-ordination withstand voltages into the required withstand voltage (U_{rw}) for the tests taken altitude correction and safety factors into account, as described in Clause 7.
4) Selection of the standard withstand voltages (U_w), as described in Clause 8.

5 Representative voltage stresses in service

5.1 Origin and classification of voltage stresses

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

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

All the preceding overvoltage stresses, except combined overvoltages, are discussed as separate items under 5.3. Combined overvoltages are discussed where appropriate within one or more of these items.

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

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

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

5.2 Characteristics of overvoltage protection devices

5.2.1 General remarks

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

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

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

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

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

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

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

5.2.2 Metal-oxide surge arresters without gaps (MOSA)

5.2.2.1 General

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

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

– determination of continuous operating voltage U_c;

– determination of rated voltage U_r based on temporary overvoltages;

– determination of required energy absorption W and selection of nominal discharge current I_n;

– determination of lightning impulse protection level U_{pl} and switching impulse protection level U_{ps}.

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

The procedure is iterative. If, after the selection procedure, the protection levels of MOSA are too high, a lower continuous voltage, a higher nominal discharge current, a higher energy absorption capability or a reduced distance between the arrester and the protected equipment should be investigated. It has to be regarded, though, that the continuous operating voltage, U_c, shall never be lower than 1,05 times the highest voltage of the system, U_s, divided by $\sqrt{3}$. These measures will result either directly in lower MOSA residual voltages at a given impressed impulse current amplitude or, due to the reduced effects of traveling waves, in reduced overvoltage levels at the protected equipment for a given MOSA residual voltage.

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

5.2.2.2 Protection characteristics related to fast-front overvoltages

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

– lightning impulse protection level U_{pl} (also designated as LIPL);

– maximum residual voltage at steep current impulse.

The lightning impulse protection level is the maximum residual voltage at the nominal discharge current (IEC 60099-4). For the insulation co-ordination of UHV systems, surge arresters with low protection levels are of particular importance. The nominal discharge current for UHV arresters is typically 20 kA.

The resulting protection voltage under the impact of a steep current impulse (with a front time of 1 μs) is typically a few percent higher than U_{pl}. Additionally, inductive voltage drops across the connection leads and the arrester length have to be considered for steep current impulses. For insulation coordination studies, including steep lightning surges, different arrester models considering the increase in protection voltage have been suggested. The background is described in IEC 60099-5.

5.2.2.3 Protection characteristics related to slow-front overvoltages

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

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

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

– controlled switching;

– circuit breakers with closing or closing/opening resistors;

– any combination of the above measures.

5.2.2.4 Energy handling capability

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

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

– For station ("S") arresters, which are further sub-classified as SH, SM, SL arresters:
  - repetitive charge transfer rating, Q_{rs};
  - thermal energy rating, W_{th}.

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

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

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

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

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

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

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

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

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

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

5.3 General approach for the determination of representative voltages and overvoltages

5.3.1 Continuous (power-frequency) voltage

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

5.3.2 Temporary overvoltages

5.3.2.1 General

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

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

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

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

In particular cases, a statistical co-ordination procedure may be adopted describing the representative overvoltage by a distribution frequency of the temporary overvoltages expected in service (see 6.3.2).

5.3.2.2 Earth faults

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

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

The highest voltage at power-frequency which can appear on a sound phase during the occurrence of an earth fault depends not only on the earth fault factor but also on the value of the operating voltage at the time of the fault which can be generally taken as the highest system voltage U_s.

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

5.3.2.3 Load rejection

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

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

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

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

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

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

- In moderately extended systems, a full load rejection can give rise to phase-to-earth overvoltages with amplitude usually below 1,2 p.u. The overvoltage duration depends on the operation of voltage-control equipment and may be up to several minutes;
- In extended systems, after a full load rejection, the phase-to-earth overvoltages may reach 1,5 p.u., or even more when Ferranti or resonance effects occur. Their duration may be in the order of some seconds;
- If only static loads are on the rejected side, the longitudinal temporary overvoltage is normally equal to the phase-to-earth overvoltage. In systems with motors or generators on the rejected side, a network separation can give rise to a longitudinal temporary overvoltage composed of two phase-to-earth overvoltage components in phase opposition, whose maximum amplitude is normally below 2,5 p.u. (greater values can be observed for exceptional cases such as very extended high-voltage systems).

5.3.2.4 Resonance and ferroresonance

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

Temporary overvoltages due to resonance phenomena can reach extremely high values. They shall be prevented or limited by measures recommended in 5.3.2.7. They shall therefore not normally be considered as the basis for the selection of the surge arrester rated voltage or for the insulation design unless these remedial measures are not sufficient (see 5.3.2.8).

5.3.2.5 Longitudinal overvoltages during synchronization

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

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

5.3.2.6 Combinations of temporary overvoltage origins

5.3.2.6.1 General

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

5.3.2.6.2 Earth fault with load rejection

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

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

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

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

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

5.3.2.6.3 Other combinations

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

5.3.2.7 Limitation of temporary overvoltages

5.3.2.7.1 Earth-fault overvoltages

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

5.3.2.7.2 Sudden changes of load

These overvoltages can be controlled by shunt reactors (see Annex K), series capacitors or static compensators.

5.3.2.7.3 Resonance and ferroresonance

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

5.3.2.8 Surge arrester protection against temporary overvoltages

Usually, the selection of the rated voltage of the surge arrester is based upon the envelope of the temporary overvoltage expected, taking into account the energy dissipation capability of the surge arrester. In general, matching the surge arrester rating with the temporary overvoltage stress is more critical in range II according to IEC 60071-1, where the margins are lower, than in range I. Usually, the energy capability of the surge arrester under temporary overvoltage stress is expressed as a characteristic furnished by the manufacturer.

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

5.3.3 Slow-front overvoltages

5.3.3.1 General

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

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

The representative voltage stress is characterized by

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

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

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

The assumed maximum value of the representative overvoltage is equal to the truncation value of the overvoltages (see 5.3.3.2 to 5.3.3.7) or equal to the switching impulse protection level of the surge arrester (see 5.3.3.8), whichever is the lower value.

5.3.3.2 Overvoltages due to line energization and re-energization

5.3.3.2.1 General

A three-phase line energization or re-energization produces switching overvoltages on all three phases of the line. Therefore, each switching operation produces three phase-to-earth and, correspondingly, three phase-to-phase overvoltages [1] - [4].

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

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

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

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

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

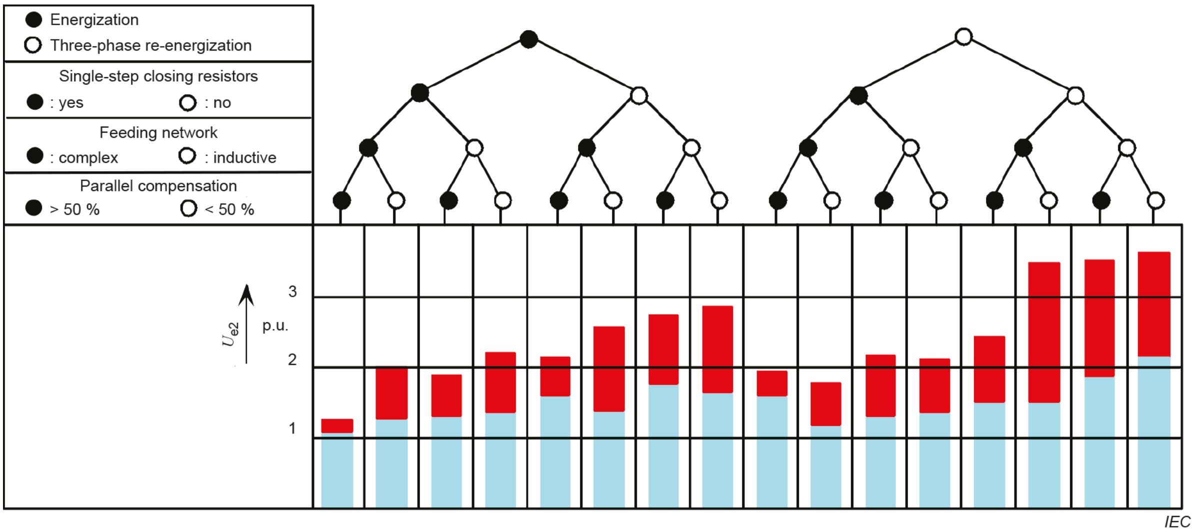
The correct probability distribution of the overvoltage amplitudes can be obtained only from careful simulation of switching operations by digital computation, transient analysers, etc., and typical values such as shown in Figure 1 should be considered only as a rough guide. All considerations relate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

5.3.3.2.2 Phase-to-earth overvoltages

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

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

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



NOTE The red (black) histogram shows the maximum and minimum values of the total overvoltage factors (2% slow-front overvoltages)

Figure 1 – Range of 2 % slow-front overvoltages at the receiving end due to line energization and re-energization [27]

5.3.3.2.3 Phase-to-phase overvoltages

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

– instant of phase-to-phase overvoltage peak: this instant gives the highest phase-to-phase overvoltage value. It represents the highest stress for all insulation configurations, for which the dielectric strength between phases is not sensitive to the subdivision into components. Typical examples are the insulation between windings or short air clearances;

– phase-to-phase overvoltage at the instant of the phase-to-earth overvoltage peak: although this instant gives lower overvoltage values than the instant of the phase-to-phase overvoltage peak, it may be more severe for insulation configurations for which the dielectric strength between phases is influenced by the subdivision into components. Typical examples are large air clearances, for which the instant of the positive phase-to-earth peak is most severe, or gas-insulated substations (three-phase enclosed), for which the negative peak is most severe.

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

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

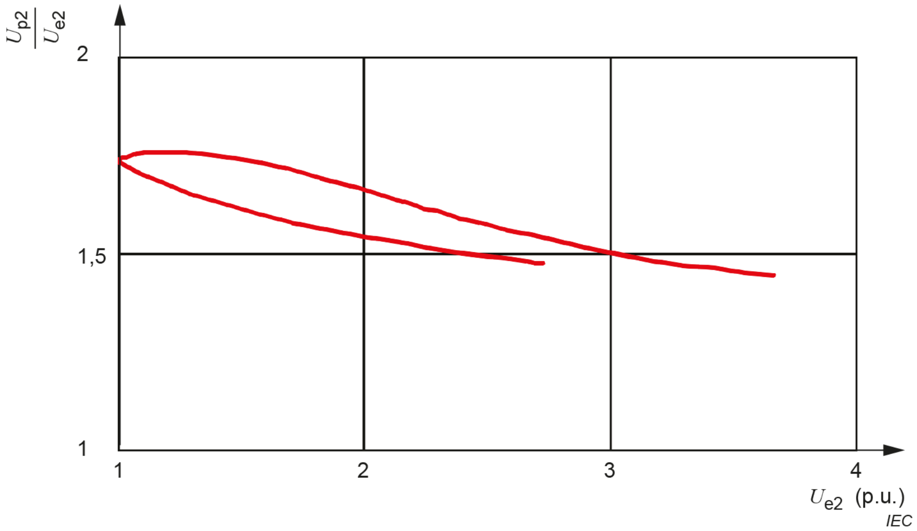


Figure 2 – Ratio between the 2 % values of slow-front overvoltages phase-to-phase and phase-to-earth [28], [29]

5.3.3.2.4 Longitudinal overvoltages

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

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

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

5.3.3.2.5 Assumed maximum overvoltages

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

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

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

5.3.3.3 Fault and fault-clearing overvoltages

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

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

  where k is the earth fault factor.

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

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

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

5.3.3.4 Overvoltages due to load rejection

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

5.3.3.5 Overvoltages due to switching of inductive and capacitive currents

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

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

Restrikes of circuit-breakers occurring while interrupting capacitive currents (switching off unloaded lines, cables or capacitor banks) may generate particularly dangerous overvoltages and the use of restrike-free breakers is necessary. Furthermore, when energizing capacitor banks, in particular ungrounded banks, care should be taken to assess the phase-to-phase overvoltages (see also 5.3.4.3).

5.3.3.6 Slow-front lightning overvoltages

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

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

5.3.3.7 Limitation of slow-front overvoltages

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

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

The saturation effect of the switching impulse strength has a large impact to the air clearances. Closing or opening resistors, surge arresters and/or controlled switching can reduce switching overvoltages. Shunt reactors are also applicable to the reduction of switching overvoltages in overhead transmission lines. However, it is necessary to consider the generation of resonance overvoltages due to slow-front transients when shunt reactors are installed in underground transmission lines (cables) or transmission lines including both overhead line sections and underground line (cable) sections (see Annex K).

5.3.3.8 Surge arrester protection against slow-front overvoltages

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

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

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

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

Surge arresters are usually installed phase-to-earth and it should be observed that, if metal-oxide arresters are used to limit slow-front overvoltages to a level lower than 70 % of the 2 % value of the uncontrolled overvoltage phase-to-earth, the phase-to-phase overvoltages may reach about twice the phase-to-earth protection level of the arrester. The phase-to-phase overvoltage will then consist of two phase-to-earth components with the most frequent subdivision 1:1 [7]. See also 6.3.4.1.

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

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

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

5.3.4 Fast-front overvoltages

5.3.4.1 Lightning overvoltages affecting overhead lines

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

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

5.3.4.2 Lightning overvoltages affecting substations

5.3.4.2.1 General

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

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

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

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

5.3.4.2.2 Direct strokes

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

- calculating the lightning overvoltage return rates for different instantaneous values of the operating voltage,
- evaluating the insulation failure probability for the various subdivisions into components – usually the sum of the two components is the decisive parameter,
- determining the insulation failure rate dependent on the sum of the lightning overvoltage and of the instantaneous value of power-frequency, and
- applying the performance criterion to this expected failure rate to obtain the necessary sum of the two components.

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

5.3.4.2.3 Back flashovers

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

5.3.4.3 Overvoltages due to switching operations and faults

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

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

The maximum peak overvoltages depend on type and behaviour of the switching equipment. It is technically justified to characterize the amplitude of the representative overvoltage by the maximum following values (in p.u. of $U_s\sqrt{2}/\sqrt{3}$):

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

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

- disconnector switching: 3 p.u.

As the overvoltage peak values are usually smaller than those caused by lightning, their importance is restricted to special cases and U_m > 800 kV.

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

5.3.4.4 Limitation of fast-front overvoltage occurrences

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

- for direct lightning strokes to conductors: appropriate earth-wire shielding design;
- for back flashovers: reduction of the tower footing earthing impedance or addition of insulation;
- usage of line surge arresters.

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

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

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

5.3.4.5 Surge arrester protection against fast-front overvoltages

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

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

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

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

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

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

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

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

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

$$U_{rp} = 2\,U_{pl} \quad \text{for } U_{pl} < 2St_s \tag{2}$$

where

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

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

t_s is the travel time of the lightning surge determined as following:

$$t_s = L / c \tag{3}$$

where

c is the velocity of light (300 m/μs for overhead line);

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

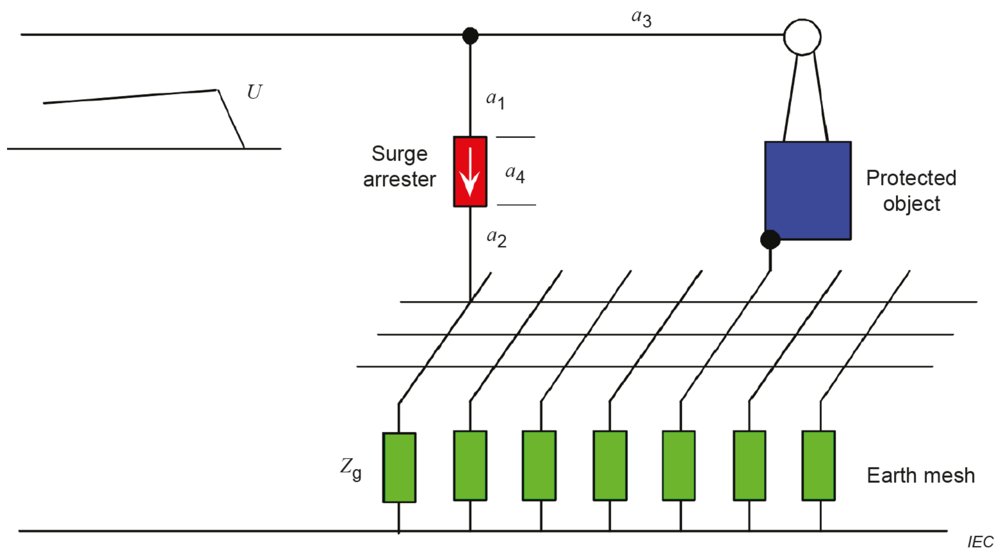
The values of the steepness shall be selected according to the lightning performance of the overhead lines connected to the station and on the adopted risk of failure in the substation. A complete treatment is given in Annex E.

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

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

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

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



Key

a_1 length of the lead connecting the surge arrester to the line

a_2 length of the lead connecting the surge arrester to earth

a_3 length of the phase conductor between the surge arrester and the protected equipment

a_4 length of the active part of the surge arrester

Z_g earthing impedance (Z_g represents the parallel impedance of all green impedances)

U_l amplitude of the impinging lightning overvoltage surge

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

5.3.4.6 Evaluation method of non-standard lightning overvoltage shape

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

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

5.3.5 Very-fast-front overvoltages

Very-fast-front overvoltages (VFFO) [13] originate from disconnector operations or faults within GIS due to the fast breakdown of the gas gap and the nearly undamped surge propagation within the GIS. Their amplitudes are rapidly dampened on leaving the GIS, for example at a bushing, and their front times are usually increased into the range of those of fast-front overvoltages.

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

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

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

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

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

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

5.4 Determination of representative overvoltages by detailed simulations

5.4.1 General overview

Detailed simulations can be used for determination of the representative overvoltages U_{rp}. For determination of the representative overvoltages U_{rp}, detailed simulations can be used which are usually achieved by Electro-Magnetic Transients (EMT) simulation tools. Generally accepted computational methods for determining the representative overvoltages U_{rp} are given in the IEC TR 60071-4.

5.4.2 Temporary overvoltages

5.4.2.1 Overview

As mentioned in 5.3.2, temporary overvoltages (TOV) can originate from faults, switching operations, resonance conditions, non-linearities, or by a combination of these. When designing insulation coordination of power systems, TOVs caused by resonance and ferroresonance are generally not considered, as stated in 5.3.2.4. The representative voltage of TOV caused by the other phenomenon can be determined as follows.

NOTE In this document, the per unit value (p.u.) is used as a unit for evaluation of overvoltages (1,0 p.u.equals $U_s\sqrt{2}/\sqrt{3}$).

5.4.2.2 Earth faults

The per unit value of TOV caused by a phase-to-earth fault can be represented by the earth fault factor k. The earth fault factor k depends on the system neutral earthing and the fault location. Annex A shows how to determine the earth fault factor k in detail. With the earth fault factor k determined, calculate per unit value of TOV for the phase-to-earth and phase-to-phase voltages according to 5.3.2.2.

5.4.2.3 Load rejection

The per unit value of TOV caused by load rejection depends on the rejected load, on the system layout after disconnection and on the characteristics of the sources (power flow at the station, control circuits of the generators, etc.).

In general, when TOV caused by load rejection is calculated by using a computational method, electric power equipment subject to the computational analysis is first modelled and then a circuit is created: electric power equipment subject to the computational analysis includes generators, transformers, overhead transmission lines, underground transmission lines, surge arresters, circuit breakers, and shunt reactors, and is modelled with an EMT-simulation tool by referring to the methods shown in 7.4 and 12.2 of IEC TR 60071-4:2004. To prepare the circuit, it is necessary to be careful about the following points: 1) in modelling of a generator, a control circuit controlling the generator should be incorporated into the generator; 2) the load side bus of the circuit should be prepared by considering the load condition simulating the power flow observed when load rejection occurred; and 3) a circuit breaker should be incorporated into the circuit so that operational scenario of the circuit breaker by protection relay can be simulated.

Using the circuit created with the above-mentioned method, analyse the load rejection and then calculate the per unit value of TOV for the phase-to-earth and phase-to-phase voltages.

5.4.2.4 Earth faults with load rejection

As shown in 5.3.2.6.2, TOV is seldom caused by a combination of earth faults and load rejection. However, it is necessary to evaluate TOV due to a combination of earth faults and load rejection when insulation coordination of power systems is designed. TOV due to the combination of earth faults and load rejection should be evaluated based on the concepts shown in 5.4.2.3: to be more specific, carry out a computational analysis with a circuit and calculate the per unit value of TOV for the phase-to-earth and phase-to-phase voltages.

5.4.2.5 Determination of representative voltages and overvoltages U_{rp} for TOV

Compare the TOVs caused by earth faults, load rejection, and a combination of earth faults and load rejection with each other. Then determine U_{rp} for TOVs based on the comparison results while taking the following factors into consideration:

a) Surge arrester rated voltage and power frequency voltage versus time characteristic
b) Frequency of occurrence

5.4.3 Slow-front overvoltages

5.4.3.1 Overview

For the calculations of SFO, an established EMT-simulation tool shall be utilized. Specialized transient computation modules for power system simulation programs may also be appropriate. The equipment modelling is appropriate to meet the representation of network components given in IEC TR 60071-4:2004, 7.5. Slow-front overvoltages almost always occur during switching operation. Therefore, the implementation of more detailed models (e.g. for the circuit breaker) may be necessary, depending on the scenario. Detailed calculations for insulation co-ordination studies use deterministic, probabilistic and statistical procedures. The calculations are suitable for determining the minimum distances and the electrical strength of the insulation systems. Guidelines for conducting Slow-front overvoltages analyses are given in IEC TR 60071-4:2004, Clause 9. The established electromagnetic transient models of lines and substations are to be verified by load flow and short-circuit current calculations. An independent load flow calculation can confirm that the line load flows, and the busbar voltages are consistent with the results of the electromagnetic transient program. The calculation of symmetrical and asymmetric short-circuit currents can determine whether the positive and zero sequence impedances of the simulated system are correct.

5.4.3.2 Line energization and re-energization

In general, when SFO caused by line energization and re-energization is calculated by using a computational method, electric power equipment subject to a computational analysis is first modelled and then a circuit is created: electric power equipment subject to the computational analysis includes power sources, transformers, overhead transmission lines, underground transmission lines, surge arresters, circuit breakers, and shunt reactors, and is modelled with an EMT-simulation tool by referring to the methods shown in 7.5 and 12.3 of IEC TR 60071-4:2004. The source side bus of the circuit should be prepared by incorporating an inductance element simulating short-circuit impedance.

In analysis estimating SFO caused by line energization and re-energization, it is necessary to simulate the statistical distribution of mechanical operation of circuit breakers and to carry out calculation predetermined times. Note that the statistical distribution of mechanical operation of circuit breakers and the number of calculations may affect the statistical distribution of the SFO to be generated.

When SFO caused by line re-energization is estimated, it is necessary to consider the residual voltage of the line -- voltage remaining in the line or electric charge remaining in the line -- after the line is opened for a certain reason. Therefore, when SFO caused by line re-energization is estimated with an EMT-simulation tool, an overhead transmission line/ underground transmission line should be simulated by using a line model which can simulate the residual voltage of the lines.

5.4.3.3 Determination of representative voltages and overvoltages U_{rp} for SFO

Based on the statistical distribution of SFO obtained through the computational analysis mentioned above, calculate the maximum value of SFO for the phase-to-earth and the phase-to-phase voltages, and the probability that the maximum value of SFO is generated. Based on the results, determine U_{rp} for SFO the phase-to-earth and the phase-to-phase voltages while taking the following factors into consideration:

a) surge arrester rated voltage;

b) frequency of occurrence.

5.4.4 Fast-front overvoltages

5.4.4.1 Overview

In general, fast-front overvoltages are represented by lightning overvoltages.

Lightning overvoltages are generated by direct lightning strokes to the phase conductors of overhead transmission lines (OHTL), by back-flashovers (BFOs) that occur in insulator strings when lightning strikes the transmission tower or the overhead ground wire (OHGW), or by in-direct lightning strokes to the phase conductors. In-direct lightning strokes to the phase conductors, such as lightning strokes on the earth in the vicinity of an OHTL, cause induced lightning overvoltages. The induced lightning overvoltages should only be considered for distribution line insulation design [30] and nominal voltages U_n less than 400 kV, not for power system insulation design.

Based on the matters mentioned above, lightning overvoltages generated by direct lightning strokes to the phase conductors or by BFOs should generally be taken into consideration for power system insulation design.

5.4.4.2 Lightning parameters

5.4.4.2.1 General

In evaluation of lightning overvoltages, it is necessary to consider the lightning parameters including ground flash density (N_g), cumulative frequency distribution of lightning current amplitude ($f_I(i)$), and statistical distributions of lightning current waveshape parameters such as wave front duration time (T_f) and wave tail duration time (T_t). These lightning parameters can be obtained through direct observation or observation with Lightning Location System (LLS).

5.4.4.2.2 Lightning activities

Ground flash density (N_g) is an essential parameter to evaluate the reliability of equipment against lightning. N_g can be obtained by using the LLS which has been used around the world [31]. In general, for power system insulation design, N_g of the target area is estimated by using data obtained through the LLS and then the estimated number of lightnings striking the equipment (Number of Flashes (N_s)) is determined [32].

5.4.4.2.3 Distribution of lightning current amplitudes

The level of lightning overvoltage generated in an OHTL, at a substation, or at a power station varies depending on the lightning current amplitude. High lightning overvoltage is likely to induce massive-scale and extensive lightning failures. Therefore, the cumulative frequency distribution of lightning current amplitude of the target area is indispensable information for power system insulation design. The cumulative frequency distribution of lightning current amplitude can be obtained from direct observation or observation results with LLS [32]-[35]. In general, for power system insulation design, lightning overvoltages should be estimated by using the cumulative frequency distribution of lightning current amplitude of the target area.

5.4.4.2.4 Distribution of lightning waveshape parameters

Lightning current waveshape is an essential parameter which determines the breakdown time of back-flashover (BFO), the waveshape and amplitude of voltage across insulator strings when the BFO occurred, and the waveshape of lightning surge which enters a substation or a power station. Statistical distribution of data obtained for each lightning current waveshape parameter can be directly observed [32]- [35]. Note that the statistical distribution of data for lightning current waveshape parameters varies depending on the region and target. In general, for power system insulation design, lightning overvoltages are analysed by assuming the wave front duration time (Tf) and wave tail duration time (Tt) both of which are the elements that should be considered in insulation design. The lightning current waveshapes applied to analysis includes double ramp shape, double exponential shape, and CIGRE concave shape.

5.4.4.3 Incidence of lightning strike and overhead line shielding

5.4.4.3.1 General

It is important to evaluate the lightning performance of an OHTL for surmising the characteristics of lightning surge entering a substation or a power station. Therefore, the lightning shielding effect of the OHGWs installed on the OHTL should be quantitatively evaluated. Lightning overvoltages caused on an OHTL are generally divided into three types as follows by their causes:

– lightning overvoltage caused by a direct strike to a phase conductor,
– lightning overvoltage caused by BFOs which is generated by a lightning strike to a transmission tower or an OHGW,
– lightning overvoltage caused by an in-direct lightning strike around an OHTL.

Among them, since the induced lightning overvoltage caused by in-direct lightning is smaller than the above-mentioned two other types of lightning overvoltage, it is unnecessary to consider the induced lightning overvoltage caused by in-direct lightning. For power system insulation design, therefore, the lightning shielding effect of OHGWs should be evaluated based on the lightning overvoltage caused by a direct strike to a phase conductor and that caused by BFO.

5.4.4.3.2 Evaluation of lightning performance of overhead lines

For evaluation of the lightning performance of OHTLs, it is necessary to evaluate the lightning shielding effect provided by OHGWs or phase conductors. Various methos such as Electro-Geometric Model (EGM), Rolling Sphere Method (RSM) and Leader Progression Model (LPM) have been used to evaluate the lightning striking distance to OHGWs or phase conductors. When evaluating the lightning shielding effects of these conductors, an EGM is generally applied which was designed by considering the striking distance when a lightning stroke occurred [32], [36]. EGM determines whether the lightning struck OHGWs or phase conductors, and then clarifies the waveshape of lightning surge that would thereafter enter the substation or power station through the transmission line. In recent years, the lightning performance of OHTL has been evaluated through any one of the following analyses: a conventional analysis, an analysis using a model designed by modifying the EGM based on the observation results regarding lightning characteristics, an analysis using an LPM considering the characteristics of lightning discharge path development, or an analysis using a model considering the lightning attachment process [37].

5.4.4.3.3 Estimation of minimum shielding-failure-flashover current and minimum back-flashover current

By evaluating the lightning performance of an OHTL, it is possible to know whether the lightning struck an OHGW/a transmission tower or a phase conductor for each lightning current amplitude of lightning stroke. Lightning strokes to an OHGW/a transmission tower cause BFO, while those to a phase conductor cause shielding failure.

The lightning surge generated by a lightning stroke to a phase conductor varies depending on the current waveshape and current amplitude which enters the phase conductor. When the lightning overvoltage caused by the lightning surge exceeds the insulation level of the line (flashover voltage of insulator strings), a normal flashover occurs thereby chopping the waveshape. As a result, effects of lightning surges entering the substation or power station are suppressed. In general, the critical current at which the lightning surge overvoltage generated by the shielding failure current becomes equivalent to the insulation level of the line (flashover voltage of insulator strings) is called the minimum shielding-failure-flashover (SFFO) current.

Meanwhile, voltage waveshape and its amplitude generated across the insulator strings due to lightning strokes to an OHGW or a transmission tower varies depending on the lightning current waveshape and its peak value. Therefore, when the voltage generated across the insulator strings exceeds the insulation level of the OHTL (flashover voltage of insulator strings), a BFO is observed, and then a lightning current enters a phase conductor from the tower, resulting in generation of lightning surge entering the substation or power station. The minimum current at which a BFO occurs is called the minimum back-flashover current.

Both the minimum SFFO current and the minimum back-flashover current should be considered in the insulation design to protect equipment from lightning overvoltage, because both currents are essential parameters that determine the lightning surge entering substations or power stations.

5.4.4.3.4 Evaluation of limit distance from lightning points to substations

Since lightning occurs randomly, lightning strokes occur everywhere on an OHTL. Therefore, insulation design at substations or power stations should be provided by appropriately evaluating lightning surge entering the substations or power stations from OHTLs.

This document defined a simplified method applicable to evaluation of lightning overvoltages generated at substations or power stations.

Meanwhile, the following three methods (1)-(3) are applicable when lightning overvoltages generated at substations or power stations are evaluated based on a computational analysis:

(1) First determine the minimum SFFO current and minimum back-flashover current for each voltage class, and second set the lightning point which is a spot where the maximum lightning overvoltage is expected to be generated at the substation or power station due to lightning strokes to the transmission line. With the currents determined above, then carry out analysis and evaluate the lightning overvoltages to be generated at the substation or power station.

(2) First randomly generate lightning strokes onto a transmission line connected to the substation or power station and then calculate the lightning overvoltage that enters the substation or power station based on the minimum SFFO current and minimum back-flashover current both of which are estimated beforehand, and statistically evaluate the lightning overvoltages.

(3) First apply lightning strokes with randomly-generated lightning current amplitude onto a transmission line connected to the substation or power station and then evaluate whether shielding failure occurred. Based on the results, calculate the minimum SFFO current and minimum back-flashover current at each stroke point. Calculate the lightning surge overvoltage for each current that enters the substation or power station and statistically evaluate the lightning overvoltages.

The above-mentioned method (3) is difficult for practical use despite being a statistical approach. Therefore, either the above-mentioned method (1) or (2) is applied to actual insulation design.

5.4.4.4 Evaluation of lightning overvoltages entering substations

5.4.4.4.1 General

A method for numerically analysing lightning surge that enters a substation or power station are shown in IEC TR 60071-4. Here, the outline of the method and a method for determining a representative voltage and overvoltage for fast-front overvoltage (FFO) based on the analytical results is described.

5.4.4.4.2 Modelling of transmission lines and substations/power stations

As shown in Figure 4, prepare numerical models of equipment such as OHTL, substation, power station, and lightning arrester by referring to IEC 60071-4 [38]. On this occasion, it is unnecessary to consider the waveshape distortion and deformation caused by corona discharge. Apply the waveshape of the lightning current source having any of the following shapes: double ramp shape, a double exponential shape, and CIGRE concave shape. Connect in parallel the lightning path impedance to the current source when necessary. Simulate BFO by using an equal area model or a leader propagation model [38], [39].

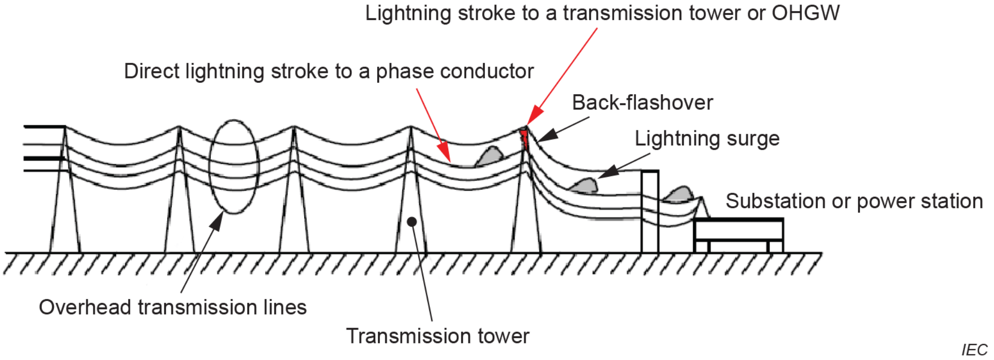


Figure 4 – Modelling of transmission lines and substations/power stations

5.4.4.4.3 Evaluation of lightning overvoltages and their waveshapes entering substations/power stations

For evaluation of the lightning overvoltages and their waveshapes, lightning surge analysis is carried out by using the prepared model shown in Figure 4. Analyse the lightning surges that enter a substation or a power station with an EMT- simulation tool such as Electro-Magnetic Transient Program (EMTP), and then calculate lightning overvoltage and determine its waveshape at each point of the substation/power station (entry point, middle point, transformer point). Next, for each equipment installed in each point, review the maximum overvoltage generated at each point and its waveshape. Also calculate the incidence of lightning overvoltage.

5.4.4.4.4 Determination of representative voltages and overvoltages U_{rp} for FFO

Based on the overvoltage waveshape and its maximum amplitude obtained through the EMT analysis, determine the U_{rp} for FFO while considering the following items a)-d) and the incidence of lightning overvoltage among insulation characteristics of each equipment installed in each point:

a) Breakdown voltage - time characteristics

b) AC voltage superimposed with impulse voltage

c) Frequency of occurrence

The concepts for modelling of the transmission lines and substations/power stations are summarized in the Clause 5 of CIGRE TB 839:2021 [37] and the IEC TR 60071-4. The method shown in the Subclause 4.4 of CIGRE TB 542:2013 [38] is an example of evaluation method for representative voltages and overvoltages U_{rp} for FFO. In addition, the MTBF approach is an effective method for evaluating lightning failure rates of substations or power stations.

5.4.5 Very-fast-front overvoltages

5.4.5.1 Overview

Up to a system voltage of 800 kV the lightning impulse voltage is the dominant dielectric stress.

In UHV systems, VFFO can become the limiting dielectric stress in GIS, and the knowledge of the VFFO amplitude and rise time is a necessary basis for the insulation co-ordination and the evaluation of potential risks and countermeasures.

Because the VFFO are determined by superposition of traveling waves, they depend strongly on the specific GIS configuration and it is not possible to give generally valid voltage values.

In consequence, it is necessary to carry out a system analysis for each specific substation configuration.

A three-step procedure is recommended for VFFO insulation co-ordination. This procedure is outlined in Figure J.1 in Annex J.

5.4.5.2 Modeling aspects

5.4.5.2.1 General

The value of the VFFO depends on the voltage drop at the disconnector contacts just before striking; and on damping measures, if applied.

The voltage drop is dependent on the electric charge on the load side of the disconnector. This charge is remaining “trapped” at the load side after the last striking of an opening operation, and the trapped charge voltage (TCV) is the voltage resulting from this charge.

This TCV is specific for each disconnector design and depends mainly on the contact speed and the field homogeneity of the contact system. More detailed modeling is described in IEC TR 60071-4.

5.4.5.2.2 Disconnector design without integrated damping resistor

For slow acting disconnectors (contact speed < 1 m/s) the maximum trapped charge voltage lies well below 1 p.u. The resulting VFFO is generally in the range of 1,7 p.u.; in specific cases it can reach up to 2,0 p.u. Depending on the LIWL, no measures need to be taken to limit the TCV.

Fast acting disconnectors (contact speed > 1 m/s) exhibit trapped charge levels up to 1 p.u. Consequently, generally higher VFFO could be produced compared to the slow acting disconnector.

5.4.5.2.3 Disconnector design with integrated damping resistor

With the integration of a damping resistor of some hundred ohms inside GIS, VFFO amplitudes in the range of 1,3 p.u. can be reached.

5.4.5.2.4 Evaluation of overvoltages

For the evaluation of the VFFO, the complete switchgear system consisting of GIS and connected equipment is analyzed.

The aim of the analysis is to calculate the maximum peak value U_{max_VFFO}. The temporal course of the voltage is also required, however, for later verification of the applicability of the simulation.

This usually is achieved by means of an approved travelling wave computer simulation program, using adequate models of the components, particularly of disconnectors and damping components.

As input for the simulation the value of the trapped charge voltage TCV is needed:

– For a worst-case assumption TCV = –1 p.u. can be applied; however, this may lead to unrealistic high VFFO values and accordingly extreme efforts for mitigation.
– If the statistics of the trapped charge behavior of the disconnector can be reasonably emulated, the 99 % probability value of the trapped charge voltage distribution shall be taken as TCV for the simulation.
– If the trapped charge behavior of the disconnector can be determined by tests on an appropriate test arrangement, the maximum value of the measured trapped charge voltages shall be taken as TCV for the simulation.

Eventually, the accuracy of the simulation model shall be verified. For this purpose, VFFO measurements are carried out on a representative GIS test pole or on the actual GIS substation arrangement.

5.4.5.2.5 Determination of U_{rp} for very-fast-front overvoltages

Since a general representative voltage for VFFO cannot be specified, the maximum peak value U_{max_VFFO} determined on a case-by-case basis is used instead.

6 Co-ordination withstand voltage

6.1 Insulation strength characteristics

6.1.1 General

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

Breakdown takes place in three main stages:

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

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

– the magnitude, shape, duration and polarity of the applied voltage;
– the electric field distribution in the insulation: homogeneous or non-homogeneous electric field, electrodes adjacent to the considered gap and their potential;

- the type of insulation: gaseous, liquid, solid or a combination of these; the impurity content and the presence of local inhomogeneities;
- the physical state of the insulation: temperature, pressure and other ambient conditions, mechanical stress, etc. The history of the insulation may also have an importance;
- the deformation of the insulation under stress, chemical effects, conductor surface effects, etc.

Breakdown in air is strongly dependent on the gap configuration and on the polarity and wave shape of the applied voltage stress. In addition, relative atmospheric conditions affect the breakdown strength regardless of shape and polarity of applied stress. Since laboratory measurements have been made for non-standard conditions including low air density, high relative humidity, contamination, ice and snow, high temperatures and the presence of combustion particles, the breakdown strength of air derived from laboratory measurements are converted into the standard reference atmospheric conditions defined by IEC 60060-1:

- temperature : 20 °C;
- pressure : 1 013 hPa (1 013 mbar);
- absolute humidity : 11 g/m^3.

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

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

The breakdown process is also statistical in nature and this should be taken into account. Due to the restoring feature of self-restoring insulation, its statistical response to stresses can be obtained by suitable tests. Therefore, self-restoring insulation is typically described by the statistical withstand voltage corresponding to a withstand probability of 90 %. For non-self-restoring insulation, the statistical nature of the strength cannot usually be found by testing and the assumed withstand voltage corresponding to a withstand probability of 100 % is alternatively applied (see definition 3.24 of IEC 60071-1:2019).

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

Subclauses 6.1.2 to 6.1.5 give information on the different factors influencing the insulation response. For more detailed information, reference can be made to the CIGRE technical brochure [4].

6.1.2 Influence of polarity and overvoltage shapes

6.1.2.1 Influence of overvoltage polarity

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

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

6.1.2.2 Influence of overvoltage shape

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

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

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

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

The lightning overvoltage shapes are analysed and the insulating characteristics of SF_6 gas and oil-filled transformer elements for these actual surges are clarified to convert them into the standard voltage shape (see 5.3.4.6).

6.1.3 Phase-to-phase and longitudinal insulation

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

For external insulation in range II, the response of the insulation to phase-to-phase switching overvoltages depends on the value of α which correlates positive and negative voltage stress components (see Annex C); tests to verify the required withstand voltage shall therefore be so designed as to reflect this phenomenon. The representative overvoltage shape standardized in IEC 60071-1 is a combined overvoltage having two synchronous components of opposite polarity; the positive is a standard switching impulse, while the negative is an impulse with time-to-peak and time-to-half value not shorter than those of the positive component. For insulation affected by the relative value of the two components, therefore, the actual overvoltage amplitude shall be converted into the representative amplitude taking into account the insulation response characteristics (see 5.3.3.2 and Annex C where a particular example is given).

For longitudinal insulation structures, the voltage components are specified by the representative overvoltages (see Clause 5).

The values for the conventional deviation for the phase-to-earth insulation strength given in 6.1.5 may also be applied to the strength of the external phase-to-phase or the longitudinal insulation, when the 50 % flashover voltage is taken as the sum of the components applied to the two terminals.

6.1.4 Influence of weather conditions on external insulation

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

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

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

6.1.5 Probability of disruptive discharge of insulation

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

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

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

$$Z = U_{50} - U_{16} \tag{4}$$

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

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

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

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

where

x is the number of conventional deviations corresponding to U;

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

And

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

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

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

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

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

– for lightning impulses: $Z = 0{,}03\ U_{50}$ (kV), and

– for switching impulses: $Z = 0{,}06\ U_{50}$ (kV)

The influence of weather conditions (refer to 6.1.4) is included in the values of derived deviations given above.

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

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

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

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

6.2 Performance criterion

According to entry 3.23 of IEC 60071-1:2019, the performance criterion to be required from the insulation in service is the acceptable failure rate (R_a).

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

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

6.3 Insulation co-ordination procedures

6.3.1 General

6.3.1.1 Overview

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

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

6.3.1.2 Deterministic method

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

With the deterministic method,

– when the insulation is characterized by its conventional assumed withstand voltage (P_W = 100 %), the withstand value is selected equal to the co-ordination withstand voltage obtained by multiplying the representative overvoltage (an assumed maximum) by a co-ordination factor K_c, accounting for the effect of the uncertainties in the assumptions for the two values (the assumed withstand voltage and the representative overvoltage), and
– when, as for external insulation, the insulation is characterized by the statistical withstand voltage (P_W = 90 %), K_c should account also for the difference between this voltage and the assumed withstand voltage.

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

Typical examples are:

– insulation co-ordination of internal insulations against slow-front overvoltages, when the insulation is protected by surge arresters;

– surge arrester protection against lightning overvoltages for equipment connected to overhead lines, for which experience with similar equipment is available.

6.3.1.3 Statistical method

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

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

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

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

6.3.2.1 General

The co-ordination withstand voltage for the continuous (power-frequency) voltage is equal to the highest system voltage for phase-to-phase, and to this voltage divided by $\sqrt{3}$ for phase-to-earth insulations (i.e. equal to the assumed maximum value for the representative voltages given in 5.3.1) with a duration equal to the service life.

With the deterministic method, the co-ordination short-duration withstand voltage is equal to the representative temporary overvoltage. When a statistical procedure is adopted and the representative temporary overvoltage is given by a distribution frequency characteristic (see 5.3.2), the insulation that meets the performance criterion shall be determined, and the amplitude of the co-ordination withstand voltage shall be equal to that corresponding to the duration of 1 min on the withstand characteristic of the insulation.

6.3.2.2 Pollution

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

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

– very light;
– light;
– medium;
– heavy;
– very heavy.

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

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

6.3.3 Insulation co-ordination procedures for slow-front overvoltages

6.3.3.1 Deterministic method

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

For equipment protected by surge arresters, the assumed maximum overvoltage is equal to the switching impulse protection level U_{ps} of the arrester. However, in such cases, a severe skewing in the statistical distribution of overvoltages may take place. This skewing is more pronounced the lower the protection level, as compared to the amplitudes of the prospective slow-front overvoltages, which are calculated without arrester models by Transient Network Analyser (TNA) or digital program simulation, so that small variations of the insulation withstand strength (or in the value of the arrester protection level) can have a large impact on the risk of failure [4]. To cover this effect, it is proposed to evaluate the deterministic co-ordination factor K_{cd} dependent on the relation of the surge arrester switching impulse protection level U_{ps} to the 2 % value of the phase-to-earth prospective overvoltages U_{e2}. Figure 7 establishes this dependence.

For equipment not protected by surge arresters, the assumed maximum overvoltage is equal to the truncation value (U_{et} or U_{pt}) according to 5.3.3.2, and the deterministic co-ordination factor is K_{cd} = 1.

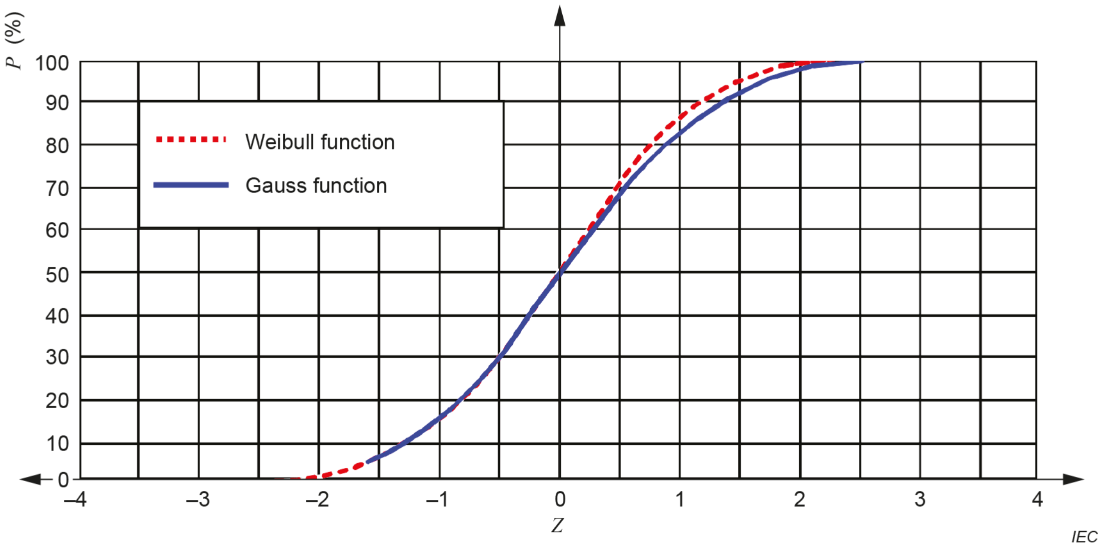


Figure 5 – Distributive discharge probability of self-restoring insulation described on a linear scale

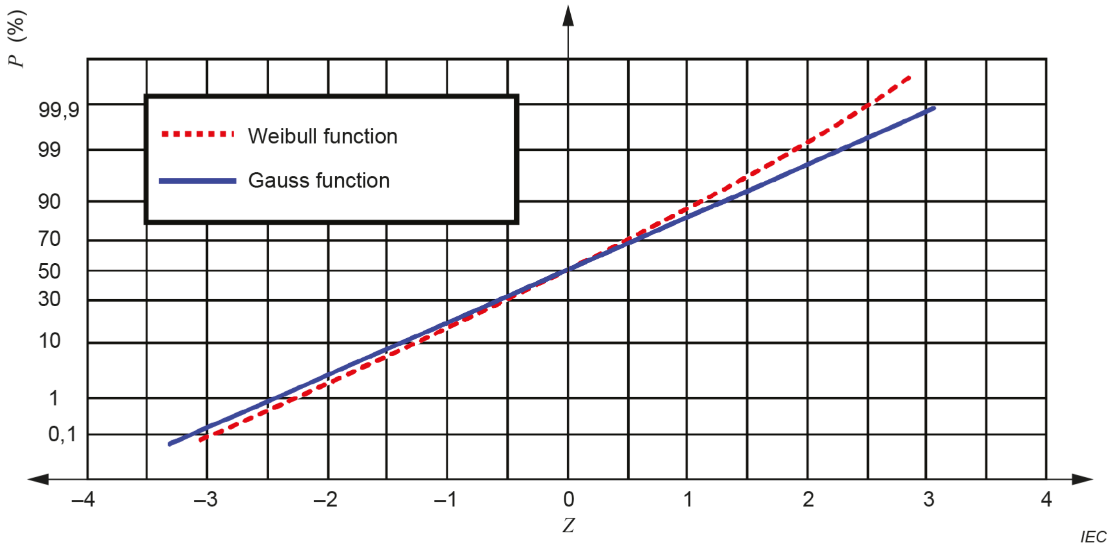
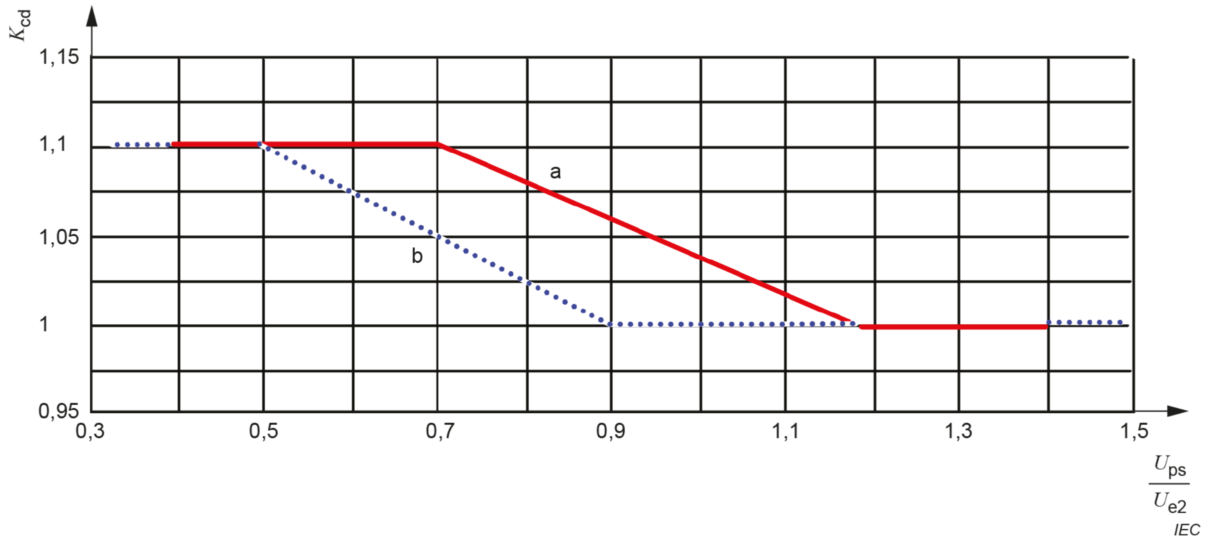


Figure 6 – Disruptive discharge probability of self-restoring insulation described on a Gaussian scale



Key

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

b co-ordination factor applied to twice the surge arrester protection level to obtain the co-ordination withstand voltage phase-to-phase.

Figure 7 – Evaluation of deterministic co-ordination factor K_{cd}

6.3.3.2 Statistical method (and corresponding risk of failure)

In applying the statistical method, it is first necessary to establish an acceptable risk of failure, as described in 6.2, based on technical and economic analysis and service experience.

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

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

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

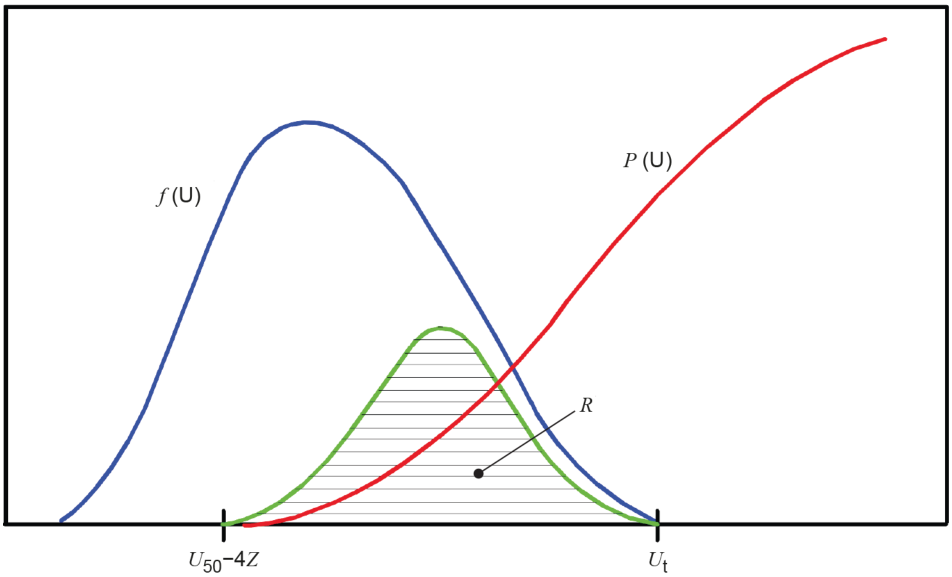
Once the frequency distribution of the overvoltages and the corresponding breakdown probability distribution of the insulation are given, the risk of failure of the insulation between phase and earth can be calculated as follows:

$$R = \int_0^\infty f(U) \times P(U)\, dU \qquad (8)$$

where

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

$P(U)$ is the probability of flashover of the insulation under an impulse of value U (see Figure 8).



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

where

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

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

U_t is the truncation value of the overvoltage probability distribution;

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

Figure 8 – Evaluation of the risk of failure

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

$$R = 1 - (1 - R_1)\,(1 - R_2)\,(1 - R_3) \tag{9}$$

If the overvoltage distribution is based on the phase-peak method (see 5.3.3.2.1), and the insulations in the three phases are the same, the total risk of failure is:

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

If the case-peak method (see 5.3.3.2.1) is used, the total risk is: $R_{\text{total}} = R$.

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

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

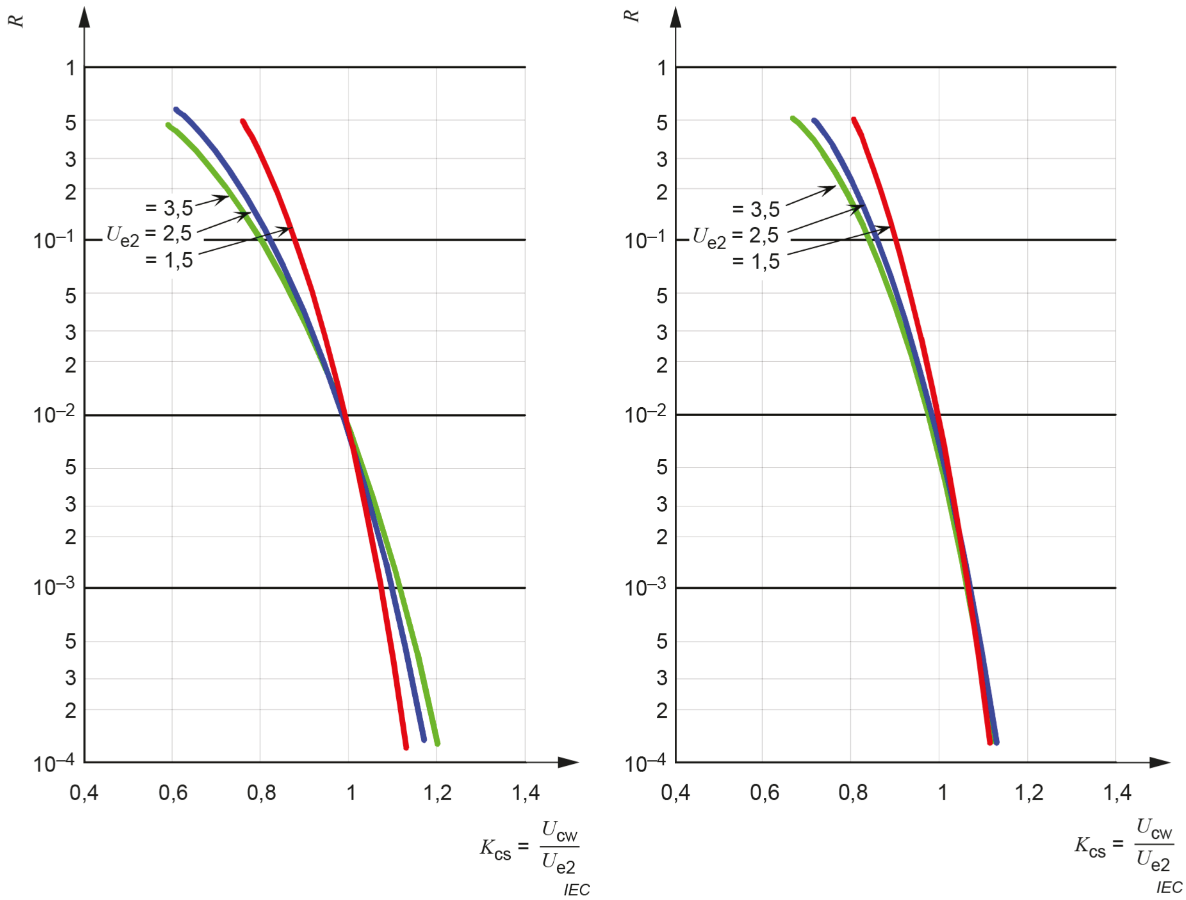
For the important case of the application of the statistical method to many identical parallel insulations, see detailed discussion in Annex B.

Simplified statistical method for slow-front overvoltages:

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

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

Figure 9 shows an example of the relationship between the risk of failure and the statistical co-ordination factor for both the phase-peak and the case-peak methods outlined in Annex C, when the Gaussian distribution is applied for the stress and the modified Weibull distribution is applied for the strength. The curves take into account the fact that the conventional deviation is a function of the 2 % overvoltage value as given in Annex C. Extreme variations in the deviation of the insulation strength, markedly non-Gaussian distribution of overvoltage and, most of all, the shape of the overvoltage may cause the curve to be in error by as much as one order of magnitude. On the other hand, the curves show that a variation of one order of magnitude in the risk corresponds to only a 5 % variation in the electric strength.



Phase-peak method

Case-peak method

Overvoltage parameters: see 5.3.3.2 and Annex C.

Strength parameters: see 6.1.5.

Figure 9 – Risk of failure of external insulation for slow-front overvoltages as a function of the statistical co-ordination factor K_{cs}

6.3.4 Insulation co-ordination procedures for fast-front overvoltages

6.3.4.1 Deterministic method

For fast-front lightning overvoltages, a deterministic co-ordination factor of K_{cd} = 1 is applied to the assumed maximum value of the overvoltages. This is because for lightning, the representative overvoltage includes probability effects. For fast-front switching overvoltages, the same relations are applied as for slow-front overvoltages (see 6.3.3.1).

6.3.4.2 Statistical method

The statistical method recommended in this document is based on the probability distribution of the representative lightning overvoltages (see Annex E). As the frequency distribution of overvoltages is obtained by dividing their return rate by the total number of overvoltages and the probability density $f(U)$ is the derivative of the result, the risk of failure is calculated by the procedures already outlined in 6.3.3.2. The insulation failure rate is equal to the risk of failure multiplied by the total number of lightning overvoltages.

For internal insulation, the assumed withstand voltage has a withstand probability of 100 % (see definition in 3.24 of IEC 60071-1:2019). The withstand probability at higher voltages is assumed to be 0 %. This means that the co-ordination withstand voltage is equal to the representative lightning overvoltage amplitude at a return rate equal to the adopted acceptable failure rate or the reciprocal of the desired MTBF.

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

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

6.3.5 Insulation co-ordination procedures for very-fast-front overvoltages

6.3.5.1 Deterministic method

For very-fast-front overvoltages, a deterministic co-ordination factor of K_{cd} should covers the statistical distribution and frequency of occurrence of VFFO and the inaccuracy of simulation. For UHV GIS, K_{cd} =1,05 is recommended with a proved simulation tool. The co-ordination withstand voltage is obtained by multiplying the assumed maximum value of the corresponding representative overvoltage obtained from VFFO calculation by the deterministic co-ordination factor K_{cd}.

6.3.5.2 Statistical method

In applying the statistical method, the assumed VFTO withstand voltage is equal to the LIWV of GIS divided by safety factor and it has a withstand probability of 100 %. The withstand probability at higher voltages is assumed to be 0 %. The co-ordination withstand voltage is equal to the representative VFFO overvoltage amplitude at the adopted acceptable failure rate or the reciprocal of the desired MTBF. The following statistical factors should be taken into account during the failure rate estimation:

– statistical distribution of trapped charge voltage due to de-energizing GIS pipe of the disconnector;
– statistical closing or opening time distribution of disconnector during a cycle of the power
– statistical operation numbers of disconnector during a year
– statistical magnitude, shape, duration and polarity of the VFTO
– other influence factors, such as the possibility of closing on earth disconnector to discharge the trapped charge voltage before switching on disconnector.

7 Required withstand voltage

7.1 General remarks

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

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

7.2 Atmospheric correction

7.2.1 General remarks

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

The rules for the atmospheric correction of withstand voltages of the external insulation are specified in IEC 60060-1. These rules are based on measurements in altitudes up to 2 000 m, but recent studies show that they are also applicable in the altitude up to 4 000 m with a deviation less than 0,5 %. For insulation co-ordination purposes, the following additional recommendations apply:

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

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

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

7.2.2 Altitude correction

The correction factor K_a is based on the dependence of the atmospheric pressure on the altitude as given in IEC 60721-2-3 [57] and ISO 2533 [56]. The coordination withstand voltage U_{cw} has to be multiplied by K_a for the calculation of the required withstand voltage U_{rw}.

The correction factor can be calculated from:

$$K_a = e^{m \cdot \frac{H}{8\,150}} \tag{11}$$

where

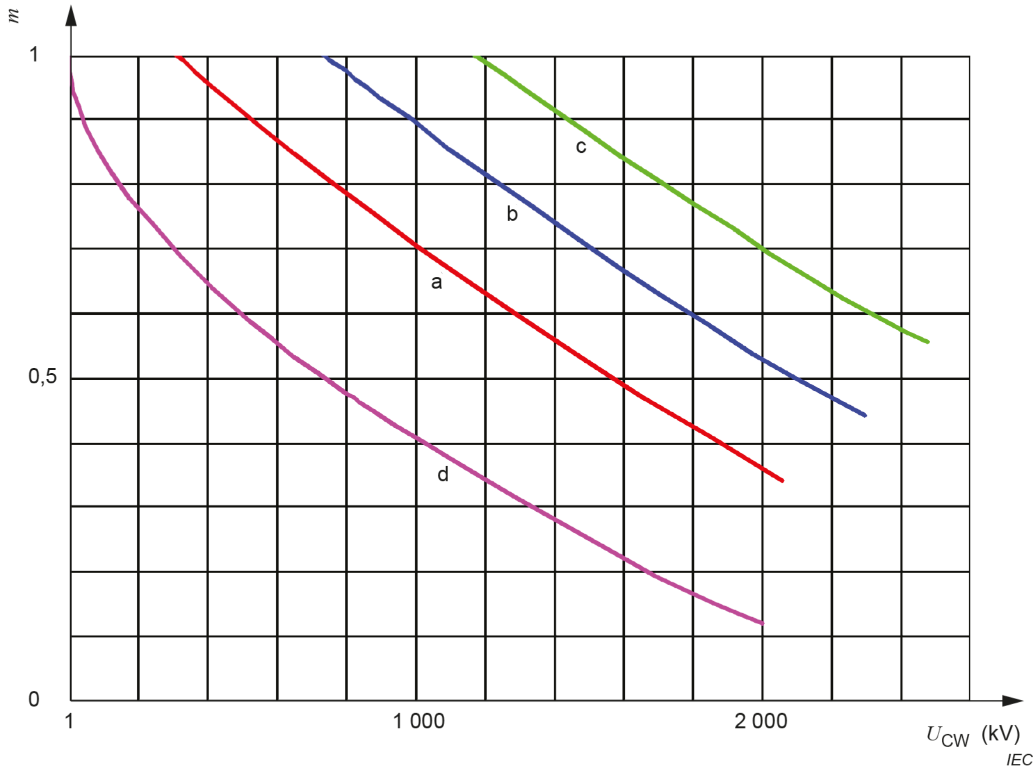
H is the altitude above sea level (in meters);

m is as follows:

- m = 1,0 for co-ordination lightning impulse withstand voltages;
- m is according to Figure 10 for co-ordination switching impulse withstand voltages;
- m = 1,0 for short-duration power-frequency withstand voltages of air-clearances and clean insulators.

NOTE The exponent m depends on various parameters, including minimum discharge path which is generally unknown at the specification stage. However, for insulation co-ordination purposes, the conservative estimates of m shown in Figure 10 could be used for the correction of co-ordination switching impulse withstand voltages. The determination of the exponent m is based on IEC 60060-1 in which the given relations are obtained from measurements at altitudes up to 2 000 m, recent studies show that these values of m are also applicable to the altitude up to 4 000 m with a deviation less than 0,5 % (see Annex H). In addition, for all types of insulation response, conservative gap factor values have been used (refer to Annex G).

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



Key

a phase-to-earth insulation

b longitudinal insulation

c phase-to-phase insulation

d rod-plane gap (reference gap)

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

Figure 10 – Dependence of exponent *m* on the co-ordination switching impulse withstand voltage

7.3 Safety factors

7.3.1 General

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

– thermal stresses;
– electrical stresses;
– environmental stresses;
– mechanical stresses.

The factors to be applied compensate for

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

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

7.3.2 Ageing

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

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

For internal insulations, ageing can be significant and should be covered by the safety factors given in 7.3.5.

7.3.3 Production and assembly dispersion

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

For equipment fully assembled in the factory, this dispersion, for insulation co-ordination purposes, is negligibly small. For equipment assembled on site, the actual withstand voltage may be lower than the required withstand voltage, which shall be taken into account in the safety factors given in 7.3.5.

7.3.4 Inaccuracy of the withstand voltage

For external insulation, possible deviations of the test arrangement from the actual service arrangement and influences of the laboratory surroundings shall be taken into account in addition to the statistical inaccuracy involved in the selected type test procedure. Such deviations shall be covered by the safety factors given in 7.3.5.

For internal insulation for which a withstand probability of 100 % is assumed in 3.23 of IEC 60071-1:2019, an impulse type test with three impulses is usually carried out, and the statistical uncertainty of this test shall be covered by the safety factor as given in 7.3.5 (see also 8.3.2).

7.3.5 Recommended safety factors (K_s)

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

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

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

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

8 Standard withstand voltage and testing procedures

8.1 General remarks

8.1.1 Overview

Tables 2 and 3 of IEC 60071-1:2019 specify standard withstand voltages U_w for range I and range II, respectively. In both tables, the standard withstand voltages are grouped into standard insulation levels associated with standard values of highest voltage for equipment U_m.

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

The standard insulation levels given in Tables 2 and 3 of IEC 60071-1:2019 reflect the experience of the world, taking into account modern protection devices and methods of overvoltage limitation. The selection of a particular standard insulation level should be based on the insulation co-ordination procedure described in this document and should take into account the insulation characteristics of the particular equipment being considered.

8.1.2 Standard switching impulse withstand voltage

In Table 3 of IEC 60071-1:2019, standard switching impulse withstand voltages associated with a particular highest voltage for equipment have been chosen in consideration of the following:

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

8.1.3 Standard lightning impulse withstand voltage

In Table 3 of IEC 60071-1:2019, standard lightning impulse withstand voltages associated with a particular standard switching impulse withstand voltage have been chosen in consideration of the following.

– For equipment protected by surge arresters, the low values of lightning impulse withstand level are applicable. They are chosen by taking into account the ratio of lightning impulse protection level to switching impulse protection level likely to be achieved with surge arresters, and by adding appropriate margins.
– For equipment not protected by surge arresters (or not effectively protected), only the higher values of lightning impulse withstand voltages shall be used. These higher values are based on the typical ratio of the lightning and switching impulse withstand voltages of the external insulation of apparatus (e.g. circuit-breakers, disconnectors, instrument transformers). They are chosen in such a way that the insulation design will be determined mainly by the ability of the external insulation to withstand the switching impulse test voltages.
– In a few extreme cases, provision should be made for a higher value of lightning impulse withstand voltage. This higher value should be chosen from the series of standard values given in 5.6 and 5.7 of IEC 60071-1:2019.

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

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

In order to meet these general requirements, the required withstand voltages should be converted to those voltage shapes for which standard withstand voltages are specified using the test conversion factors given in 8.2. The test conversion factors are determined from existing results to provide a conservative value for the rated withstand voltages. They should, therefore, be used only in the specified direction.

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

8.2 Test conversion factors

8.2.1 Range I

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

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

Insulation	Short-duration power-frequency withstand voltage [a]	Lightning impulse withstand voltage
External insulation		
– air clearances and clean insulators, dry:		
• phase-to-earth	$0,6 + U_{rw} / 8\,500$	$1,05 + U_{rw} / 6\,000$
• phase-to-phase	$0,6 + U_{rw} / 12\,700$	$1,05 + U_{rw} / 9\,000$
– clean insulators, wet	0,6	1,3
Internal insulation		
– GIS	0,7	1,25
– liquid-immersed insulation	0,5	1,10
– solid insulation	0,5	1,00

U_{rw} is the required switching impulse withstand voltage in kV.

[a] The test conversion factors include a factor of $1/\sqrt{2}$ to convert from peak to RMS value.

8.2.2 Range II

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

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

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

8.3 Determination of insulation withstand by type tests

8.3.1 Test procedure dependency upon insulation type

The verification of the electric strength of insulation is achieved through tests. The type of test to be selected for a given equipment shall consider the nature of its insulation(s). Entries 3.4 and 3.5 of IEC 60071-1:2019 distinguish between “self-restoring insulation” and “non-self-restoring insulation”. This constrains the selection of the test procedure to be adopted for a particular equipment from the list provided in 6.3 of IEC 60071-1:2019, and more fully described in IEC 60060-1.

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

8.3.2 Non-self-restoring insulation

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

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

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

8.3.3 Self-restoring insulation

With self-restoring insulation, it is possible to apply a large number of test voltages, the number only being limited by testing constraints and not by the insulation itself, even in the presence of disruptive discharges. The advantage of applying many test voltages is that statistical information may be deduced for the insulation withstand. IEC 60060-1 standardizes three alternative methods leading to an estimation of the 90 % withstand voltage. For insulation co-ordination purposes, the up-and-down withstand method with seven impulses per group and at least eight groups is the preferred method of determining U_{50}. U_{10} can be deduced by assuming a value of conventional deviation (see 6.1.5) or the latter may be determined by a multiple level test. For an evaluation of the statistical significance of the test method, reference could be made to Annex A of IEC 60060-1:2010.

8.3.4 Mixed insulation

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

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

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

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

Thus, an equipment tested using procedure B, which is on the borderline of being acceptable (rated and tested at its U_{10}), has a probability of passing the test of 82 %. A better equipment, having a withstand voltage U_{10} higher than the standard value U_w by 0,32 Z (rated and tested at its $U_{5,5}$), has a 95 % probability of passing the test. A poor equipment, having a withstand voltage lower than the standard value U_w by 0,92 Z (rated and tested at its U_{36}), has a 5 % probability of passing the test. This selectivity of test (1,24 Z) could be further quantified by assuming values for Z as 3 % and 6 % of U_{50} for lightning and switching impulses respectively. (It should be noted that Z cannot be determined from the test.) The selectivity of the 15/2 test is further illustrated in Figure 11 in comparison to the ideal test.

An alternative to the above test procedure is withstand test procedure C, in 7.3.1.3 of IEC 60060-1:2010, which is a modification of USA practice. In this procedure, three test impulses are applied and up to one disruptive discharge is permitted across self-restoring insulation, in which case a further nine impulses are applied and the test requirements are satisfied if no further disruptive discharge occurs. The selectivity of this procedure is compared with that of the 15/2 test in Table 3 and also in Figure 11.

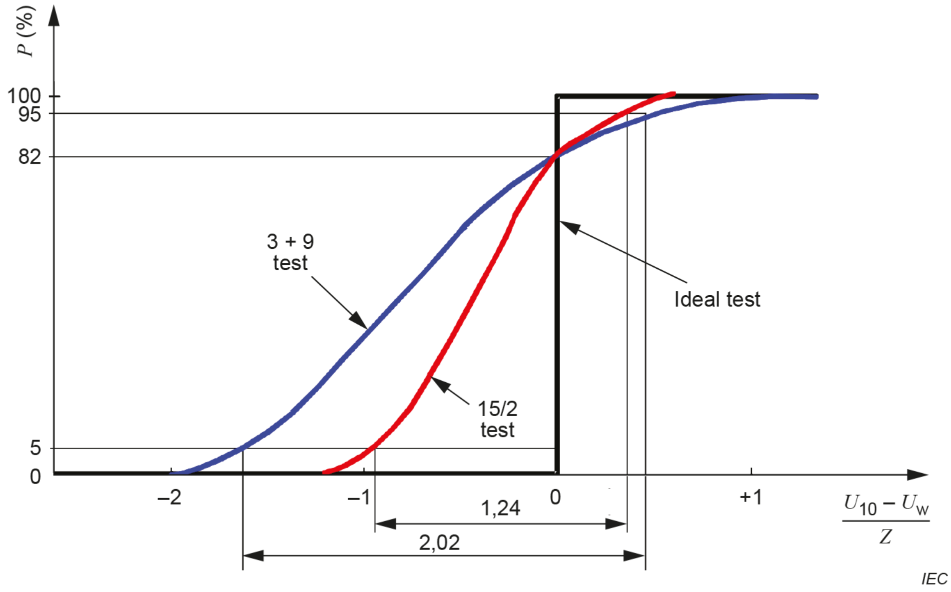


Figure 11 – Probability P of an equipment to pass the test dependent on the difference K between the actual and the rated impulse withstand voltage

8.3.5 Limitations of the test procedures

Since the recovery of insulation from a disruptive discharge is a time-dependent process, an adequate time interval between test voltage applications shall be permitted for the self-restoring insulation to fully recover its electric strength. Apparatus committees should specify the limits of acceptability (if any) of time intervals between test voltage applications which are dependent upon the type of insulation. Considerations should also be given to the possible degradation of the non-self-restoring insulation by the repeated application of test voltages even without the occurrence of a disruptive discharge.

8.3.6 Selection of the type test procedures

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

– self-restoring insulation should be tested with the up-and-down withstand method (one of the methods described in withstand test procedure D, in 7.3.1.4 of IEC 60060-1:2010);

– non-self-restoring insulation should be tested with the three-impulse-withstand test (withstand test procedure A, in 7.3.1.1 of IEC 60060-1:2010);

– in general, equipment which comprises both self-restoring and non-self-restoring insulation (i.e. mixed insulation) should be tested with the 15/2 test (withstand test procedure B, in 7.3.1.2 of IEC 60060-1:2010). When, however, the risk of tree propagation in the non-self-restoring insulation is of prime concern, and the number of voltage applications is considered excessive, the 3 + 9 test (test procedure C, in 7.3.1.3 of IEC 60060-1:2010) is an acceptable alternative;

– also, where power-frequency tests are required for insulation co-ordination purposes, the short-duration power-frequency withstand tests (IEC 60071-1) should be applied to the insulation, whether self-restoring, non-self-restoring, or mixed.

8.3.7 Selection of the type test voltages

8.3.7.1 General

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

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

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

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

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

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

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

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

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

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

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

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

9 Special considerations for apparatus and transmission line

9.1 Overhead line

9.1.1 General

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

- Where the design employs free-swinging insulators, the dielectric strength of air clearances should take into account conductor movement.
- Insulator standards specify the dimensions of insulator units without making reference to a highest voltage for equipment or a highest system voltage. Consequently, the insulation co-

ordination procedure terminates with the determination of the required withstand voltage U_{rw}. The selection of a rated voltage in IEC 60071-1 is not necessary, and Tables 2 and 3 of IEC 60071-1:2019 do not apply.

– The insulation performance of overhead lines has a large impact on the insulation performance of substations. The transmission line outage rate due to lightning primarily determines the frequency of re-energization operations, and the lightning performance rate close to the substation determines the frequency of fast-front overvoltages impinging on the substation.

9.1.2 Insulation co-ordination for operating voltages and temporary overvoltages

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

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

9.1.3 Insulation co-ordination for slow-front overvoltages

9.1.3.1 General

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

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

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

9.1.3.2 Earth-fault overvoltages

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

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

9.1.3.3 Energization and re-energization overvoltages

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

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

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

Slow-front overvoltages are one of the factors determining the air clearances and, for some type of insulators, the insulator fittings. Usually, their importance is restricted to transmission lines in the higher system voltage range of 123 kV and above. Where free-swinging insulators are applied, air clearances for slow-front overvoltages are generally determined assuming moderate (mean) swing conditions. For distribution lines, the clearances are generally determined by the insulator (see 9.1.2) and slow-front overvoltages need not be considered.

9.1.4 Insulation co-ordination for fast-front overvoltages

9.1.4.1 General

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

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

9.1.4.2 Distribution lines

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

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

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

9.1.4.3 Transmission lines

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

9.1.4.4 Lightning failure rate of transmission line

The lightning outage rate of transmission lines is a crucial parameter when studying insulation coordination. As partially referred to in 9.1.1, the lightning outage rate determines the condition and frequency of risks – such as the frequency of single line-to-ground faults, the frequency of transmission line reclosing, the frequency at which lightning surges strike substation apparatuses, and the conditions of overvoltage such as back-flashover lightning surge and direct lightning surge – for wide-ranging power equipment including transmission lines and substation apparatuses, and significantly impacts on the reliability assessment.

Accordingly, evaluation methods on lightning outage rate have been systematized and computer-programmed in IEEE and CIGRE. They are now widely used on a global basis, and further, other organizations have also independently developed evaluation methods. While these methods, namely IEEE's FLASH [40], the CIGRE method [41], and others differ in detail in terms of, for example, parameter values and whether or not corona is taken into consideration, they have common basic principles that the lightning shielding of transmission lines is calculated based on an electro-geometric model (EGM) and the lightning outage rate of transmission lines is calculated adopting on the surge calculation method. Recently, CIGRE WGs under Study Committee C4 have investigated and issued the new Technical Brochures [37], [42], which introduce that the new method has been developed utilizing the results of detailed field observations and large-scale experiments focusing on direct lightning strokes as well [43] and has been put into actual practice, which is included in Annex L as one example for a lightning outage evaluation method. In [42] more advance methods have been also studied, such the so called LPM (Leader progression model), the Fractal approach and so on, however, it is very early to use such methods for standardization.

9.2 Cable line

9.2.1 General

The insulation co-ordination procedure for cable lines is described within this document. The electrical parameters and the structure of the cable insulation lead to special behavior and the following aspects should be considered:

- The insulation of cable systems is non-self-restoring insulation. A breakdown leads to the immediate outage of the line. The reconnection of cables to the power system depends on the repair time and can take several days.
- Single-conductor cables have no phase-to-phase insulation. Therefore, the insulation co-ordination procedure is not necessary for phase-to-phase overvoltages.
- Large overvoltages can occur at the transition between overhead lines and cables due to the refraction and reflection of travelling waves, depending on the respective surge impedances. The transition point between overhead line and cable therefore requires the installation of surge arresters.

9.2.2 Insulation co-ordination for operating voltages and temporary overvoltages

The operating voltage and the temporary overvoltages determine the required phase-to-earth insulation. In directly earthed neutral systems with earth fault factors of 1,4 and below, it is recommended to design the cable insulation to withstand the highest phase-to-earth operating voltage. For earth fault factors 1,4 and above, the consideration of temporary overvoltages could be required.

Concerning long cable lines with system voltage ranges of 123 kV and above, it is nesessary to consider voltage rises due to the Ferranti effect. The Ferranti effect shall be considered for the required phase-to-earth insulation and for the selection of the continuous operating voltage U_c and the rated voltage U_r of the surge arresters and the selection of shunt reactor (see Annex K).

9.2.3 Insulation co-ordination for slow-front overvoltages

9.2.3.1 Earth-fault overvoltages

The magnitude of the earth-fault overvoltages depends on the neutral point treatment. The earth-fault overvoltages should be considered for systems with isolated and resonant earthed neutral points. The crest value of a phase-to-earth overvoltage (in p.u. of $U_s\ \sqrt{2}/\sqrt{3}$) can be expected to be 2,5. In case of re-ignition, the value may reach 3,5 in isolated systems.

9.2.3.2 Energization and re-energization overvoltages

During the energization of cables, transient overvoltages occur as a result of the reflection of travelling waves at the end of the line and as a result of the oscillation of the concentrated elements (capacitances and inductances of the circuit). The crest value of a phase-to-earth overvoltage (in p.u. of $U_s\sqrt{2}/\sqrt{3}$) does not exceed 2,5. Re-energization with a remaining residual charge on the cable line can cause phase-to-earth overvoltages larger than 2,5.

In special configurations with long cable lines, low short circuit impedances and connected compensation devices may lead to large overvoltage factors. Special considerations are necessary.

In specific cases, the single pole re-closing is used for overhead lines with partial cabling. For such cases, detailed investigations are recommended, especially for the occurrence of missing zero crossings in the current.

In principle, no significant overvoltages are effective during the de-energization of cable lines. High overvoltages can be expected in cases with reignitions and restrikes between the open contacts of the circuit breaker. The use of appropriate circuit breakers shall be checked.

9.2.4 Insulation co-ordination for fast-front overvoltages

Direct strokes in cable lines can be excluded. Fast-front (lightning) overvoltages can take effect in direct connections to overhead lines and at substations with connected overhead lines.

Cables have a smaller surge impedance than overhead lines. Therefore, an incoming voltage wave is significantly reduced. The reduced voltage wave travels through the cable and is reflected at the cable end. The reflected wave returns to the cable entrance and is there once more reflected and refracted. In this way, the overvoltage in the cable is built up to a theoretical maximum of two times the incoming voltage wave from the overhead line. Therefore, effects resulting from travelling waves shall be taken into account.

9.2.5 Overvoltage protection of cable lines

A flashover at the cable bushings or the breakdown of the cable insulation lead to damage of the cable. As a result, a lengthy repair or replacement is necessary.

Therefore, at the end of cable lines with a direct connection to overhead lines (partial cabling), an overvoltage protection is required. The protection characteristics are specified by IEC 60099-4. The selection of the surge arresters is recommended in IEC 60099-5. Detailed investigations are necessary for cable lines without direct connection to overhead lines.

The arresters are to be placed near the cable ends. The connecting leads should be as short as possible. The earth connection of the arrester shall be connected in the shortest way possible straight to the cable sheath.

For reduced power losses, the cable sheaths of power cables in high voltage systems are earthed at one end only or may be laid in cross-bonding configurations. The open cable sheaths and the cross-bonding connection points have to be protected against critical switching and lightning voltages. The selection of the sheath voltage limiters shall be made based on the maximum sheath voltage occurring in the steady-state conditions (during short-circuit currents). The EPR (Earth Potential Rising) under fault conditions shall be considered. The continuous operating voltage of these arresters shall be higher than the induced sheath-to-earth voltage at maximum fault current. The nominal charge rating should be the same as that of the phase-to-earth arresters at the cable terminals.

9.3 GIL (gas insulated transmission line) / GIB (Gas-insulated busduct)

9.3.1 General

The insulation co-ordination procedure for Gas insulated transmission lines (GIL) including Gas-insulated busduct (GIB) is described within this document. Overall, a safety factor of 1,15 is recommend for insulation coordination. Technical details are described in [44], [45]. In fact, especially above 220 kV and 100 m length of single-phase line and single phase enclosures, the project-specific boundary conditions shall be taken into account for the insulation coordination and the following aspects should be considered:

Single-conductor GIL/GIB have no phase-to-phase insulation. Therefore, the insulation co-ordination procedure is not necessary for phase-to-phase overvoltages.

Overvoltages can occur at the transition between overhead lines or cables and GIL/GIB due to the refraction and reflection of travelling waves, depending on the respective surge impedances. With the negligible attenuation behaviour of GIL/GIB lines the overvoltage elaboration is more critical than in cables. A detailed overvoltage studies should be considered to optimize the overall system including positioning of the sure arrestors (SA), the SA can be placed externally (AIS SA) or internally (integrated GIS/GIB SA).

Besides the overvoltage consideration also other aspects are of importance for insulation coordination as i) Insulation characteristics (Gas, Gas-Mixture, Design (e.g. particle trap)), ii) Return of Experiences for a given design / manufacturer / processes, iii) presentence of online monitoring and iv) expected (targeted) Major Failure Rate (MFR).

9.3.2 Insulation co-ordination for operating voltages and temporary overvoltages

The operating voltage and the temporary overvoltages determine the required phase-to-earth insulation. In directly earthed neutral systems with earth fault factors of 1,4 and below, it is recommended to design the GIS/GIB insulation to withstand the highest phase-to-earth operating voltage. For earth fault factors 1,4 and above, the consideration of temporary overvoltages could be required.

Special considerations are necessary for long GIL/GIB lines with voltage rises as a result of the Ferranti effect with system voltage ranges of 123 kV and above. The Ferranti effect shall be considered for the required phase-to-earth insulation and for the selection of the continuous operating voltage U_c and the rated voltage U_r of the surge arresters and the selection of shunt reactor (see Annex K).

9.3.3 Insulation co-ordination for slow-front overvoltages

9.3.3.1 Earth-fault overvoltages

The magnitude of the earth-fault overvoltages depends on the neutral point treatment. The earth-fault overvoltages should be considered for systems with isolated and resonant earthed neutral points. The crest value of a phase-to-earth overvoltage (in p.u. of $U_s\sqrt{2}/\sqrt{3}$) can be expected to be 2,5. In case of re-ignition, the value may reach 3,5 in isolated systems.

9.3.3.2 Energization and re-energization overvoltages

During the energization of GIL/GIB, transient overvoltages occur as a result of the reflection of travelling waves at the end of the line and as a result of the oscillation of the concentrated elements (capacitances and inductances of the circuit). The crest value of a phase-to-earth overvoltage (in p.u. of $U_s \sqrt{2} / \sqrt{3}$) can be expected to be 2.5 in system not connected to OHL.

In special configurations with long GIL/GIB lines, low short circuit impedances and connected compensation devices may lead to large overvoltage factors. Special considerations are necessary.

In specific cases, the single pole re-closing is used for overhead lines with partial GIL/GIB. For such cases, detailed investigations are recommended, especially for the occurrence of missing zero crossings in the current.

9.3.4 Insulation co-ordination for fast-front overvoltages

Direct strokes in GIB/GIL or connected cable lines or GIS can be excluded. Fast-front (lightning) overvoltages can take effect in direct connections to overhead lines and at substations with connected overhead lines.

GIL/GIB have a smaller surge impedance than overhead lines. Therefore, an incoming voltage wave is significantly reduced. The surge impedance of the GIL/GIB depend on its dimensions. The reduced voltage wave travels through the GIL/GIB and is reflected at the end. The reflected wave returns to the GIL/GIB entrance and is there once more reflected and refracted. The superposition of forward and backward-travelling waves build up different voltage maxima along the length of the GIL up to a theoretical maximum of two times the incoming voltage wave from the overhead line. Therefore, effects resulting from travelling waves including SA impact shall be taken into account.

9.3.5 Overvoltage protection of GIL/GIB lines

The voltage stress within GIL/GIB can be reduced with SA and especially with integrated SA [46]. Hence the GIL/GIB may be designed more compactly by reducing the standard lightning impulse withstand voltage (LIWV) and/or improve the voltage integrity of the GIL/GIB system.

9.4 Substation

9.4.1 General

9.4.1.1 Overview

The voltage stresses which can arise in a substation as shown in Figure 12 are described in the following subclauses 9.4.1.2 to 9.4.1.5.

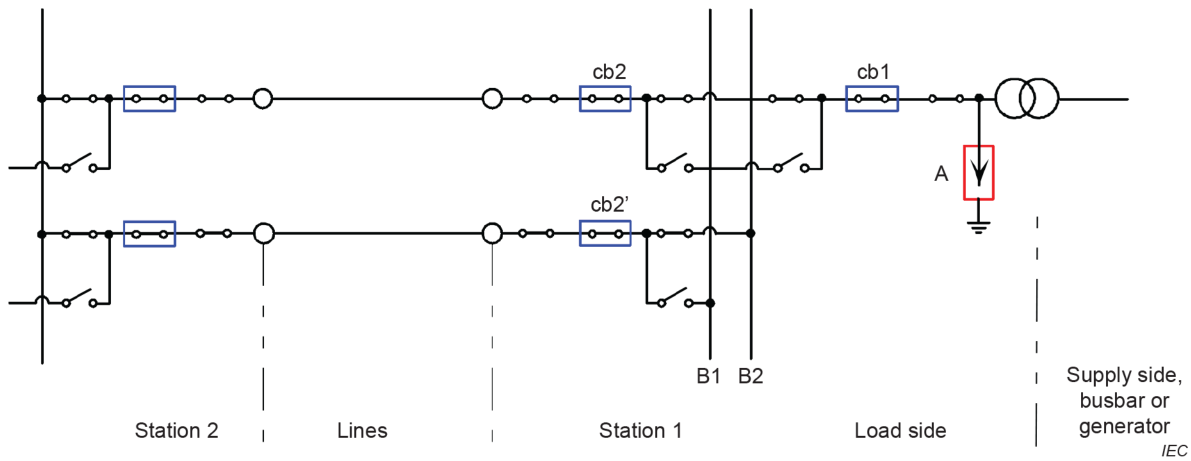


Figure 12 – Example of a schematic substation layout used for the overvoltage stress location

9.4.1.2 Operating voltage

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

9.4.1.3 Temporary overvoltage

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

Load rejection overvoltages often arise in the substation mainly due to a fault in the distant substation (station 2). Depending on the protection scheme, either all or some parts between circuit-breaker cb2 and the transformer will be stressed. For a fault in the substation itself (station 1), only the parts between circuit-breaker cb1 and the transformer are subjected to load rejection overvoltages.

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

9.4.1.4 Slow-front overvoltages

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

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

9.4.1.5 Fast-front overvoltages

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

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

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

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

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

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

In GIS, very-fast-front overvoltages due to disconnector operations should be considered.

9.4.2 Insulation co-ordination for overvoltages

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

9.4.2.1.1 General

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

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

Provided that the slow-front phase-to-phase overvoltages have been accommodated, equipment designed to the lower standard lightning impulse withstand voltage values from IEC 60071-1:2019, Table 2, may be suitable for installations such as the following:

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

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

9.4.2.1.2 Equipment connected to an overhead line through a transformer

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

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

9.4.2.1.3 Equipment connected to an overhead line through a cable

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

When a lightning surge propagating along an overhead line impinges on a cable, it breaks up into a reflected wave and a transmitted wave, where the transmitted wave amplitude is substantially decreased as compared to that of the impinging surge. Subsequent reflections at each end of the cable, however, usually result in a substantial increase in the voltage along the cable above this initial value. In general, the higher standard rated lightning impulse withstand voltages from IEC 60071-1:2019, Table 2, should be selected and surge arresters installed at the line-cable junction. When wood poles are used in the overhead line and when only one line may be connected to the substation, additional arresters could be required at the cable entrance of the substation.

9.4.2.2 Substations in transmission systems with U_m between 52 kV and 245 kV in range I

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

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

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

9.4.2.3 Substations in transmission systems in range II

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

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

Annex A
(informative)

Determination of temporary overvoltages due to earth faults

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

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

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

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

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

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

Figure A.1 shows the overall situation for $R_1 << X_1$ and $R_f = 0$

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

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

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

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

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

________ (solid line)	Maximum voltage occurs on the phase which leads the faulted phase, during a phase-to-earth fault.
.... (dotted line)	Maximum voltage occurs on the phase which lags the faulted phase, during a phase-to-earth fault.
-.-.-.-.-.-.-. (dash-dot line)	Maximum voltage occurs on the unfaulted phases, during a phase-to-earth fault.

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

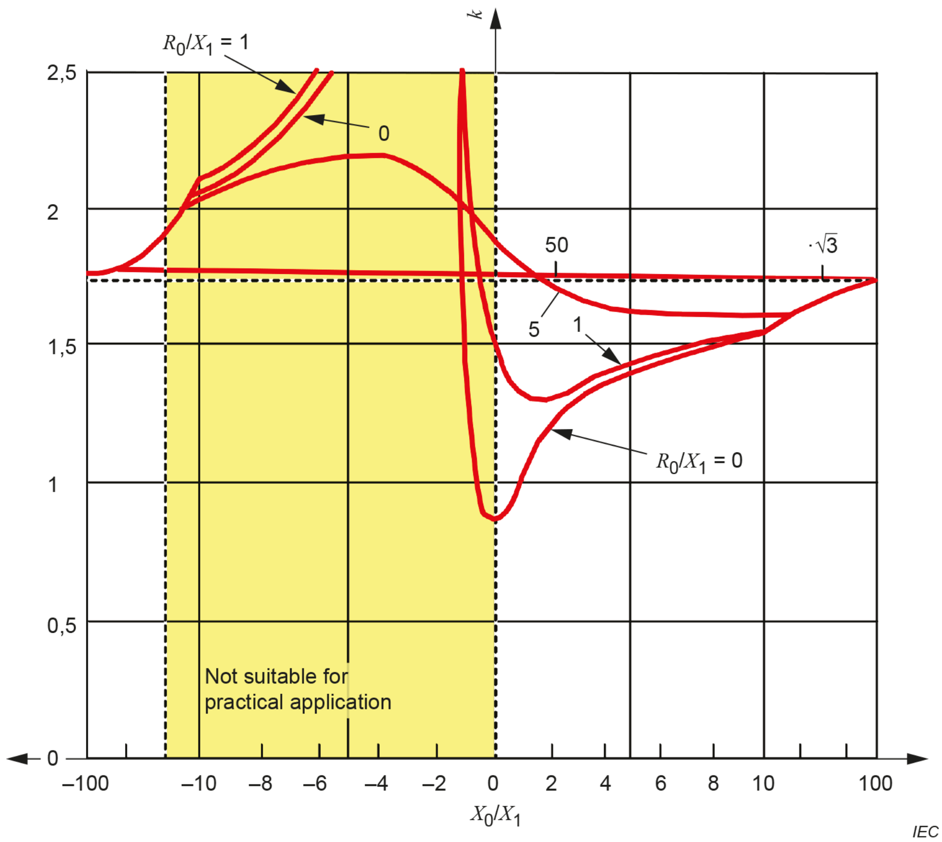


Figure A.1 – Earth fault factor k on a base of X_0/X_1 for $R_1/X_1 = R_f = 0$

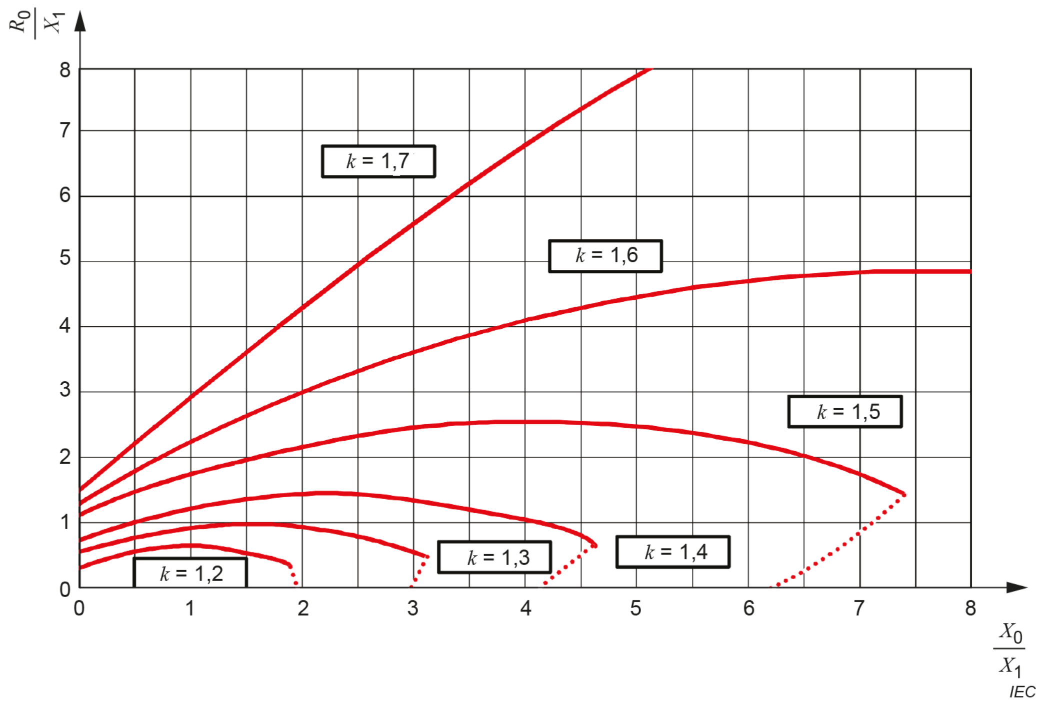


Figure A.2 – Relationship between R_0/X_1 and X_0/X_1 for constant values of earth fault factor k where $R_1 = 0$

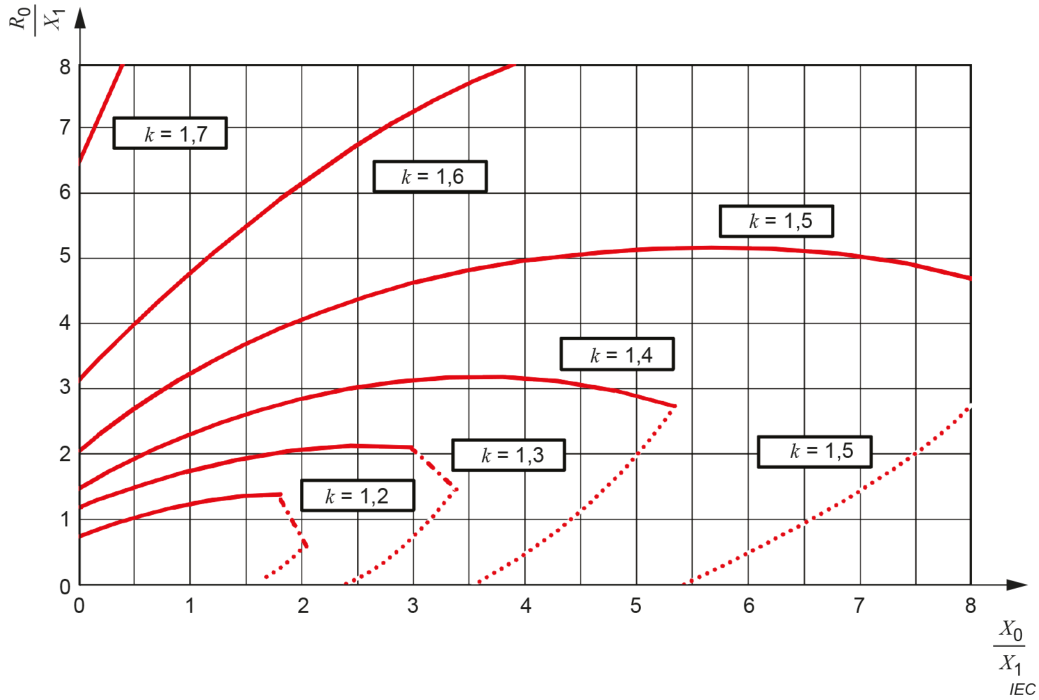


Figure A.3 – Relationship between R_0/X_1 and X_0/X_1 for constant values of earth fault factor k where $R_1 = 0,5\ X_1$

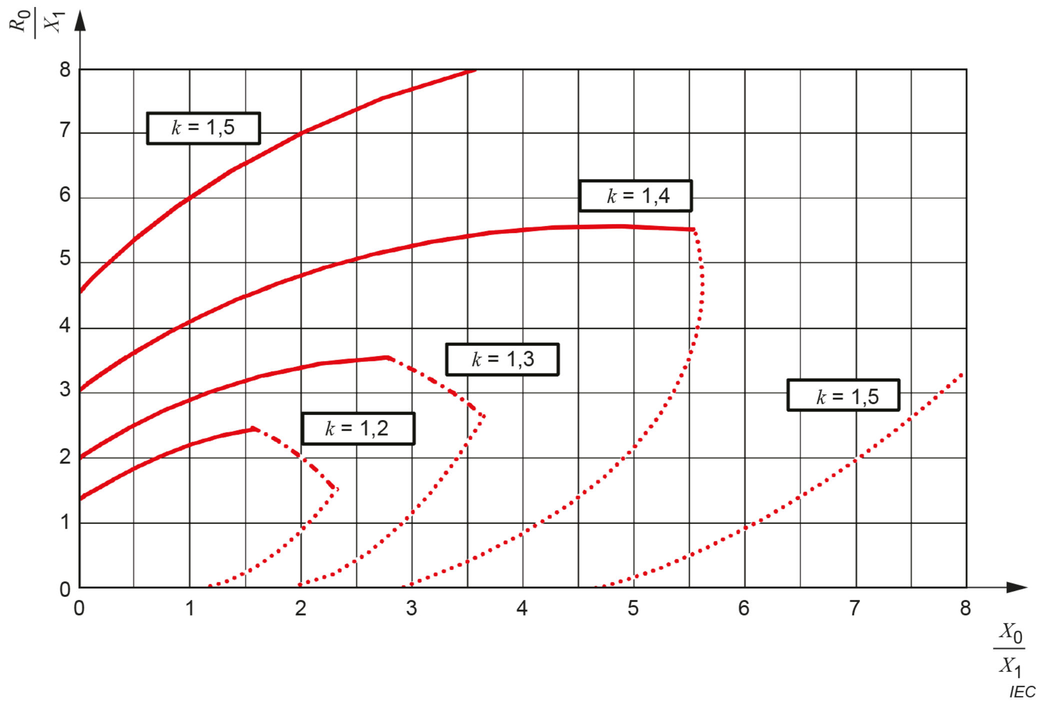


Figure A.4 – Relationship between R_0/X_1 and X_0/X_1 for constant values of earth fault factor k where $R_1 = X_1$

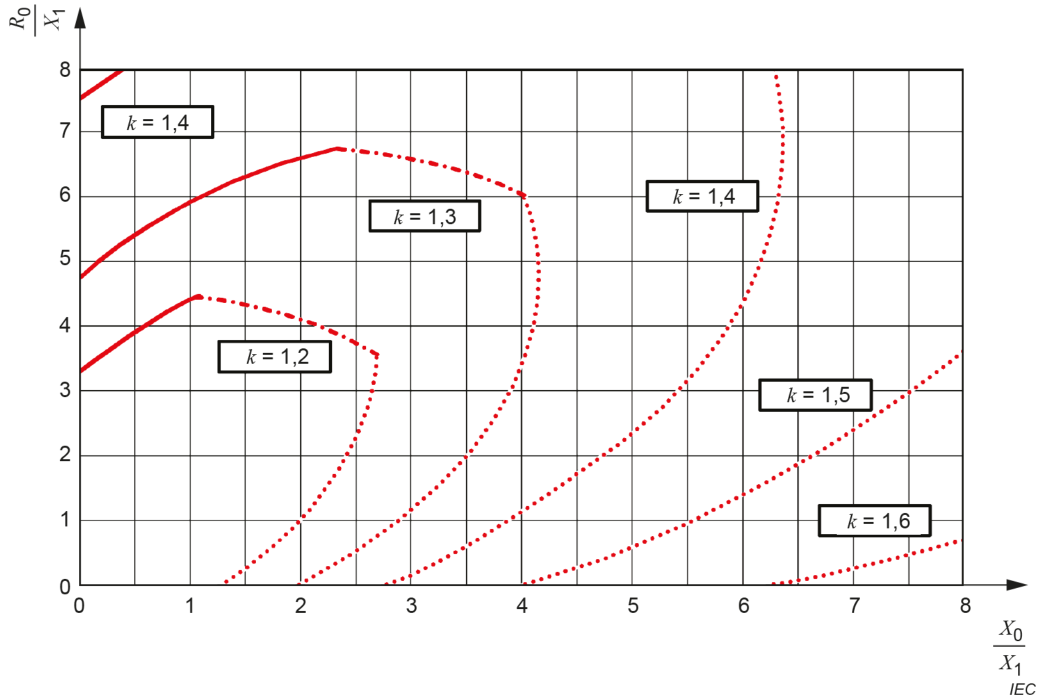


Figure A.5 – Relationship between R_0/X_1 and X_0/X_1 for constant values of earth fault factor k where R_1 = $2X_1$

Annex B
(informative)

Weibull probability distributions

B.1 General remarks

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

$$P(U) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{x} e^{-\frac{1}{2}y^2} \mathrm{d}y \tag{B.1}$$

And

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

where

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

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

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

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

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

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

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

B.2 Disruptive discharge probability of external insulation

The general expression for the Weibull distribution is:

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

where

U_0 is the truncation value;

β is the scale parameter;

γ is the shape parameter.

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

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

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

which leads to the modified Weibull function:

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

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

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

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

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

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

Figure 6 illustrates this modified Weibull distribution together with the Gaussian distribution to which it is matched. Figure 7 shows the same distributions on Gaussian probability scales.

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

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

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

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

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

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

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

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

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

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

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

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

For example, applying preceding formulas for M = 200:

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

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

As another example, for 100 parallel insulations, each one with U_{50} = 1 600 kV and Z = 100 kV, then Z_M = 100 / $(100)^{1/5}$ = 39,8 kV and U_{50M} = 1 359,2 kV. Table B.1 completes this example giving the values of U and U_M for various flashover probabilities $P(U)$.

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

$P(U)$ (%)	50	16	10	2	1,	0,1	0[a]
U (kV)	1 600	1 500	1 475	1 400	1 370	1 310	1 200
U_M (kV)	1 359	1 319	1 308	1 280	1 268	1 244	1 200

[a] The truncation value remains constant.

The calculation of the risk of failure is as follows:

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

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

and $R = 10^{-5}$

For 100 identical parallel insulations:

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

and $R = 10^{-3}$ (to compare to Figure 9)

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

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

where

M is the number of simultaneously stressed insulations;

Φ is the untruncated Gaussian integral function;

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

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

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

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

Then

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

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

B.3 Cumulative frequency distribution of overvoltages

To represent the cumulative frequency of overvoltages with a modified Weibull function, it is sufficient to change the sign of the voltages within the exponent of Equation (B.2) to take into account that the function shall be truncated for high-voltage values. For example, for phase-to-earth overvoltages:

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

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

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

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

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

If the case-peak method and the phase-peak method (for definition see 5.3.3.2.1) are compared, and the overvoltages at the three phases are statistically independent, then the probability distribution is:

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

where c – p and p – p refer to the case-peak and phase-peak method, respectively, and with the parameters γ = 3 et β = 3,5 S_e.

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

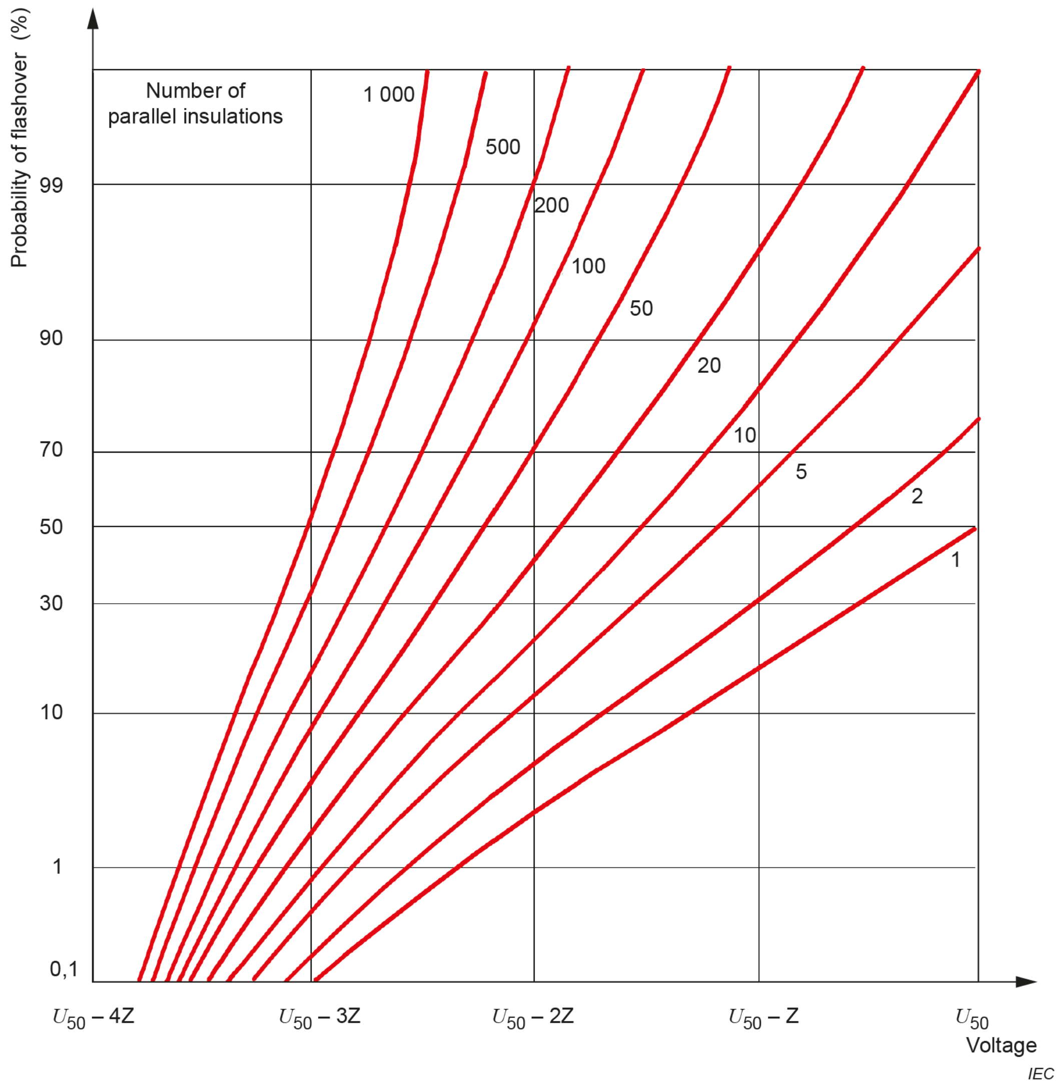
$$\beta_{c-p} = 3^{-1/3}\beta_{p-p} = 0{,}69\ \beta_{p-p} \tag{B.17}$$

and consequently, the relation between the deviations is:

$$S_{c-p} = 0{,}69\ S_{p-p} \tag{B.18}$$

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

$$U_{e2c-p} = 1{,}08\ U_{e2p-p} - 0{,}08 \tag{B.19}$$



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

Z: conventional deviation of a single gap

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

Annex C
(informative)

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

C.1 General remarks

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

The principles are derived for the phase-peak method (defined in 5.3.3.2.1) in the evaluation of the overvoltages. The results and, in particular, the obtained simplifications, however, are also valid when the case-peak method is used

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

Phase-peak method:

From the 2 % overvoltage values phase-to-earth U_{e2} can be estimated from the probability density function of the normal distribution.

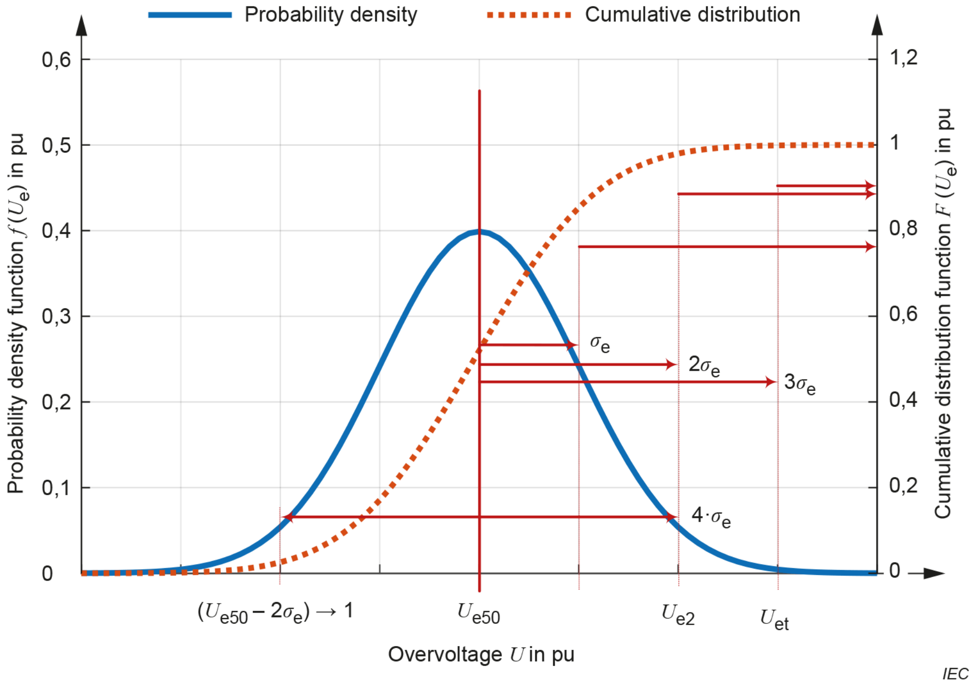


Figure C.1 – Probability density and cumulative distribution for derivation of the representative overvoltage phase-to-earth

If the distribution is symmetric about the expected value U_{e50} and for the lower 2 % overvoltage value is set equal to the reference value 1 pu, it is valid:

$$4\ \sigma_e = U_{e2} - 1$$
$$\sigma_e = 0{,}25\ (U_{e2} - 1) \tag{C.1}$$

With the two-sigma and the three-sigma rule:

$$U_{e2} = U_{e50} + 2\ \sigma_e \approx 98\ \%$$
$$U_{et} = U_{e50} + 3\ \sigma_e > 99\ \% \tag{C.2}$$

can be written for the truncation value:

$$U_{et} = U_{e2} + 0{,}25\ (U_{e2} - 1)$$
$$U_{et} = 1{,}25\ U_{e2} - 0{,}25 \tag{C.3}$$

Case-peak method:

The calculation of the probability distribution for the case-peak method bases on the WEIBULL distribution (see also Clause B.3).

$$P_{weibull}\ (U) = 1 - e^{-\left(\frac{U - U_{et}}{\beta}\right)^{\gamma}} \tag{C.4}$$

The exponent γ (form factor) for the WEIBULL distribution for above assumptions can be assumed to:

$$\gamma = 3{,}07 \approx 3 \tag{C.5}$$

The scale parameter β is:

$$\beta = 3{,}5\ \sigma_e \tag{C.6}$$

The risk R can be calculated with (see 6.3.3.2):

$$R = 1 - (1 - R_1)\ (1 - R_2)\ (1 - R_3) \tag{C.7}$$

For the phase-peak method the total risk of failure can be described to [see Equation (10)]:

$$R_{total} = 1 - (1 - R)^3 \tag{C.8}$$

and for the case-peak method:

$$R_{\text{total}} = R \tag{C.9}$$

The probability distribution is then:

$$F_{\text{c-p}} = 1 - e^{-3\left(\frac{U_{\text{et}} - U}{3{,}5 \cdot \sigma_e}\right)^3} \tag{C.10}$$

This leads with the phase-to-phase scale parameter $\beta_{\text{p-p}}$ to:

$$\beta_{\text{c-p}} = 3^{-\frac{1}{3}}\ \beta_{\text{p-p}} = 0{,}69\ \beta_{\text{p-p}} \tag{C.11}$$

and:

$$\sigma_{\text{c-p}} = 0{,}69\ \sigma_{\text{p-p}} \tag{C.12}$$

and finally, with Equation (C.12):

$$\sigma_{\text{e p-p}} = 0{,}25\ (U_{\text{e2}} - 1) \tag{C.13}$$

to the case-peak standard deviation:

$$\sigma_{\text{e}} = 0{,}69\ 0{,}25\ (U_{\text{e2}} - 1) = 0{,}17\ (U_{\text{e2}} - 1) \tag{C.14}$$

The truncation values should be the same for both methods. Therefore:

$$U_{\text{e2 c-p}} = 1{,}08\ U_{\text{e2 p-p}} - 0{,}8 \tag{C.15}$$

and the truncation value:

$$U_{\text{et}} = 1{,}13\ U_{\text{e2}} - 0{,}13 \tag{C.16}$$

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

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

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

In general, the insulation characteristic should be taken into account in the evaluation of a three-phase overvoltage in order to determine the most critical instant from the overvoltage shape (see Clause C.4). This most critical instant is sufficiently defined by one of the three following instants.

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

   At this instant, the overvoltages are described by

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

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

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

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

   At this instant the overvoltages are described by

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

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

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

In order to simplify and to take into account instants between the three selected ones, it is proposed in [7] to represent the three curves by a circle given in Figure C.3. This circle is fully defined by the positive and the equal negative peak of the phase-to-earth overvoltages and the peak of the phase-to-phase overvoltage. The circle has its centre at:

$$U_{\mathrm{c}}^{+} = U_{\mathrm{c}}^{-} = \frac{U_{\mathrm{p}} - \sqrt{2}U_{\mathrm{e}}}{2-\sqrt{2}} \qquad \text{(C.17)}$$

and a radius:

$$R_{\mathrm{u}} = \frac{2U_{\mathrm{e}} - U_{\mathrm{p}}}{2-\sqrt{2}} \qquad \text{(C.18)}$$

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

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

Phase-peak method:

– 2 % value (in pu): U_{p2};

– deviation: $\sigma_p = 0{,}25\ (U_{p2} - 1{,}73)$; (C.19)

– truncation value: $U_{pt} = 1{,}25\ U_{p2} - 0{,}43$. (C.20)

Case-peak method:

– 2 % value (in pu): U_{p2};

– deviation: $\sigma_p = 0{,}17\ (U_{p2} - 1{,}73)$; (C.21)

– truncation value: $U_{pt} = 1{,}14\ U_{p2} - 0{,}24$. (C.22)

C.4 Insulation characteristic

In the evaluation of three-phase overvoltages, the basic insulation characteristics have to be taken into account in order to determine the instant of the overvoltage transient which is most critical for the insulation (see 6.1.2). Figure C.4 shows two-phase terminals and the earth terminal of a complete insulation configuration in which the third phase is disregarded for simplification reasons. For the description of the dielectric strength of such a configuration two methods have been used.

- The positive component belonging to a given discharge probability is reported dependent on the negative component. With this description, an insulation characteristic is obtained as shown in Figure C.5 a) for the 50 % discharge probability.
- The total discharge voltage equal to the sum of the two components corresponding to a given discharge probability is reported dependent on a ratio α:

$$\alpha = U^- / (U^+ + U^-) = 1 / [1 + (U^+/U^-)] \quad \text{(C.23)}$$

where

U^+ is the positive component;

U^- is the negative component.

The example of Figure C.5 a) then results in the dependency shown in Figure C.5 b).

The insulation characteristic is divided into three ranges (as shown in Figure C.5). Range "a" is the range of discharges from the positive terminal to earth. The negative component has little or no influence on the discharge probability. In range "b" the discharges occur between the terminals and the discharge probability depends on both components (α should be taken into account). Range "c" corresponds to range "a" for the discharges from the negative terminal to earth.

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

– Electrode configurations in which the discharges phase-to-earth and the discharges phase-to-phase occur at different parts of the configuration, for example when the radius of the electrodes is large compared to their clearance. The discharge between phases is exclusively determined by the total voltage between phases. The insulation characteristic in range b decreases at 45° in Figure C.5 a) or is constant in Figure C.5 b). Such configurations exist in three-phase power transformers or in GIS.
– Electrode configurations in which the discharges phase-to-earth and the discharges phase-to-phase occur at the same part of the configuration. For these the insulation characteristic depends on the discharge process.

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

a) Configurations with homogeneous or quasi-homogeneous electric field

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

   In spite of this, as the electrode dimensions are large compared to the clearances, the dielectric field between the phases is little influenced by the earth terminal and, therefore, determined by the total voltage. The insulation characteristic in range "b" is decreasing with about 45° in Figure C.5 a) and constant in Figure C.5 b).

b) Short air clearances with inhomogeneous electric field

   The discharge voltage is substantially higher than the corona inception voltage. This discharge process corresponds to a streamer discharge, as a leader does not develop owing to the short air clearance. The discharge probability is determined by the sum of the two components, which means that the insulation characteristic in range "b" decreases with 45° in Figure C.5 a) or is constant in Figure C.5 b). The air clearances in range I of IEC 60071-1 can be associated with this group;

c) Long air clearances

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

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

– the positive switching impulse withstand voltage phase-to-earth (range "a" in Figure C.5),
– the negative switching impulse withstand voltage phase-to-earth (range "c" in Figure C.5), and
– the insulation characteristic between phases (range "b" in Figure C.5) which can be described, for the representation of Figure C.5 a), by:

$$U^{+} = U_0^{+} - BU^{-} \tag{C.24}$$

or, for the representation in Figure C.5 b), by:

$$U^{+} + U^{-} = \frac{U_0^{+}}{1 - \alpha(1 - B)} \tag{C.25}$$

The value of the constant B is:

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

In range II:

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

Figure C.6 gives the angle ϕ ($B = \tan \phi$) dependent on the ratio of D/H_t.

IEC 60071-1 defines the representative overvoltage between phases as consisting of two components with equal amplitude and opposite polarity. This overvoltage is situated on the line $U^{+} = U^{-}$ or $\alpha = 0{,}5$. The most critical stress on the insulation configuration depends on the insulation characteristic and, in particular, on the inclination B mentioned in Equation (C.16). The most critical stress is given by the voltage component at which the characteristic is tangent to the circle proposed as a simplification to describe the overvoltages. Figure C.3 shows that the most critical stress does not correspond with the representative overvoltage, if the inclination B is smaller than 1. In this case, the representative overvoltage shall be increased in order to test at $\alpha = 0{,}5$. This results in a new value for the phase-to-phase representative overvoltage U_{p2re} given by:

$$U_{p2re} = 2\,(F_1\,U_{p2} + F_2\,U_{e2}) \tag{C.26}$$

The deviation value S_{pre} and the truncation value U_{ptre} are respectively given by Equations (C.19) and (C.20):

$$S_{pre} = 2\,(F_1\,S_p + F_2\,S_e) \tag{C.27}$$

$$U_{ptre} = 2\,(F_1\,U_{pt} + F_2\,U_{et}) \tag{C.28}$$

where:

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

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

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

C.5 Numerical example

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

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

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

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

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

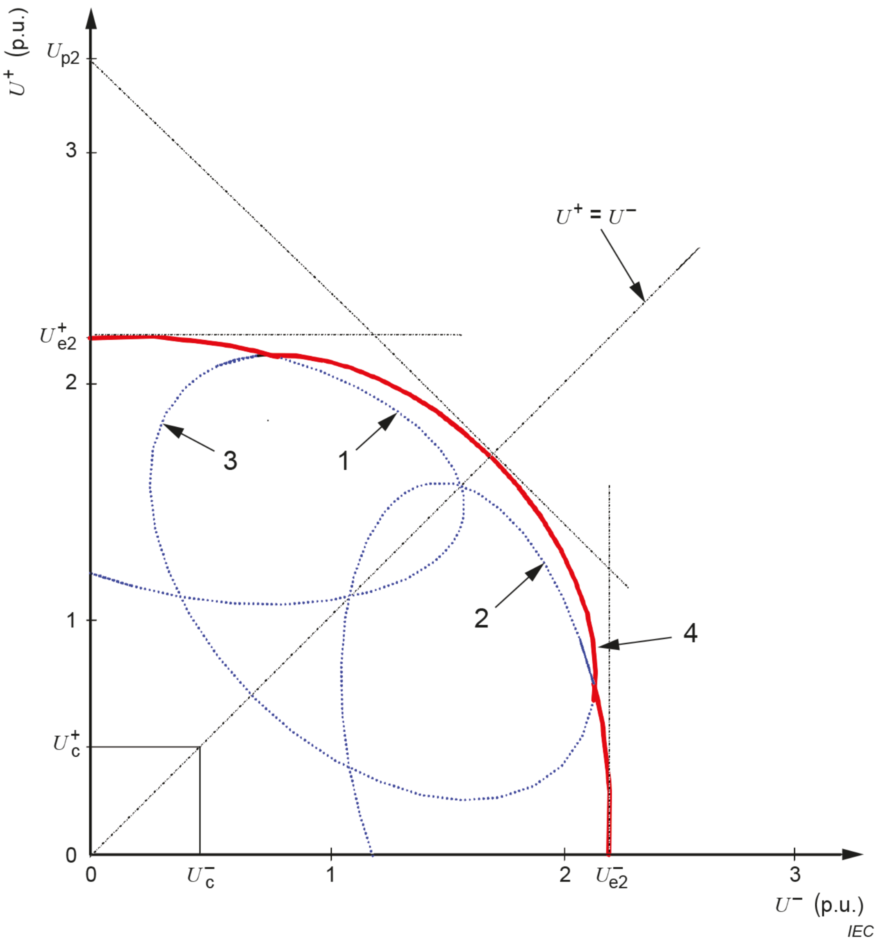
The representative overvoltage amplitude phase-to-earth is equal to the phase-to-earth overvoltage. The representative overvoltage amplitude phase-to-phase is derived from Equations (C.18) to (C.20) with the above-given constants:

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

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

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

In IEC 60071-1:2019, Table 3, provides standard withstand voltages of 1 425 kV phase-to-earth and 2 422 (1 425 × 1,7) kV phase-to-phase. While these values would adequately cover the nominal required withstand voltages, they would not cover the derived phase-to-phase required withstand voltage U_{p2re} of 2 451 kV. Therefore, the next highest standard withstand voltages of 1 550 kV phase-to-earth and 2 480 (1 550 × 1,6) kV phase-to-phase should be selected, and the insulation should be tested with positive and negative switching impulses of equal magnitude.



Key

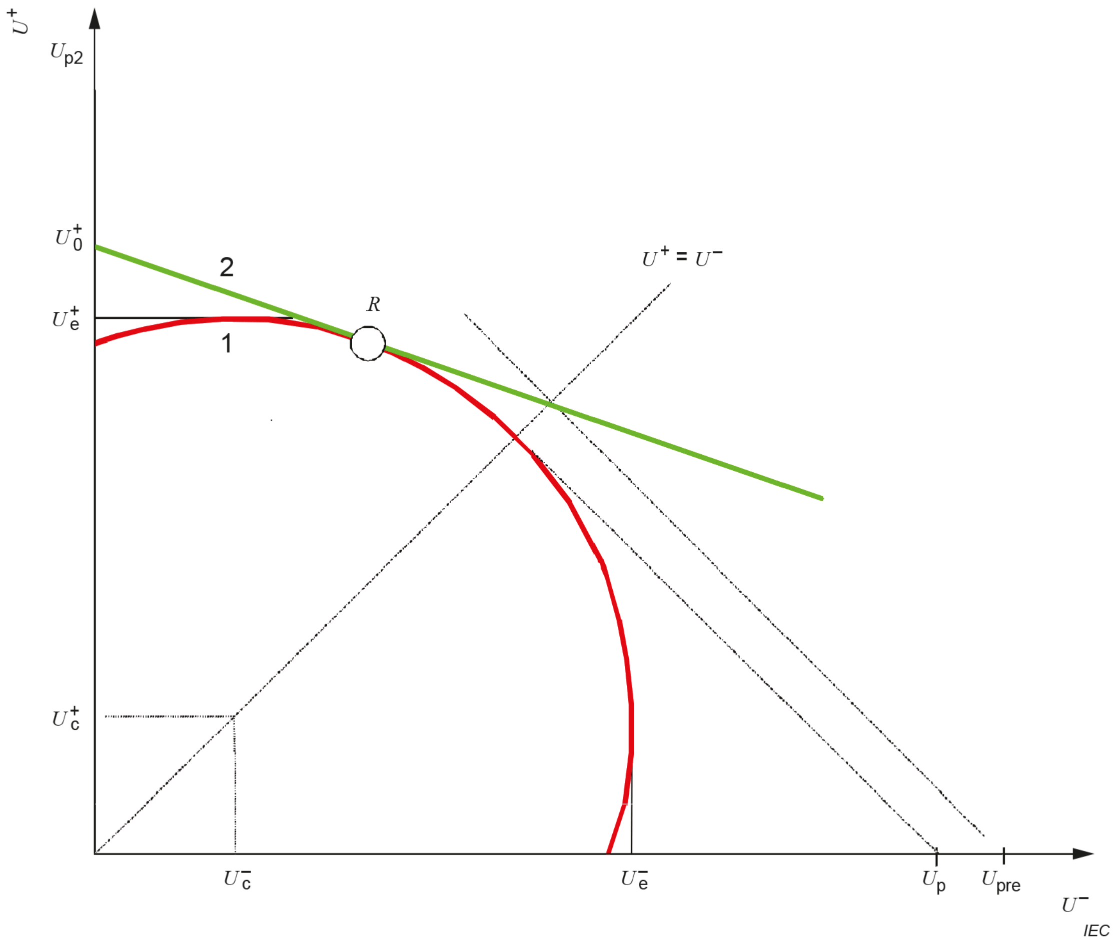
1 overvoltage at the instant of the positive phase-to-earth overvoltage peak

2 overvoltage at the instant of the negative phase-to-earth overvoltage peak

3 overvoltage at the instant of the phase-to-phase overvoltage peak

4 proposed simplification covering all instants

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



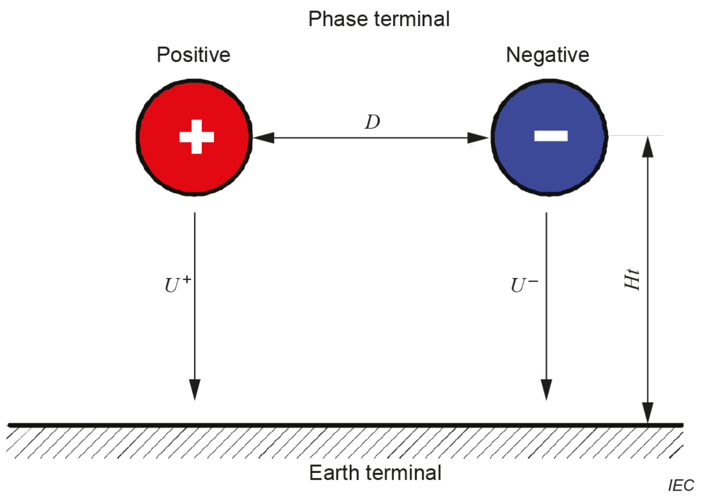
Key

1 simplified overvoltage circle as given by the values for the phase-to-earth overvoltage $U_e^+ = U_e^-$ and for the phase-to-phase for the considered probability

2 50 % flashover characteristic of the insulation

R_{cs} most critical overvoltage stress

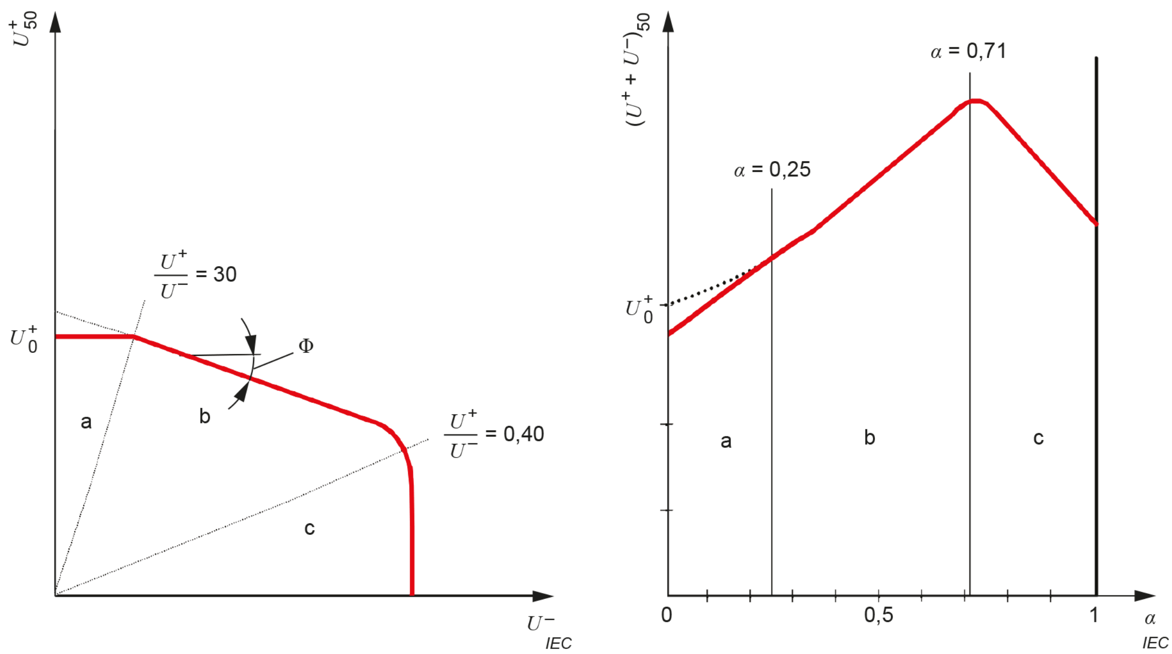
Figure C.3 – Principle of the determination of the representative phase-to-phase overvoltage U_{pre}



U^+: positive voltage component

U^-: negative voltage component

Figure C.4 – Schematic phase-phase-earth insulation configuration



a) 50 % positive component dependent on the negative component

b) 50 % total flashover dependant on *α*

Key

range a: flashover from positive phase terminal to earth

range b: flashover between phase terminals

range c: flashover from negative phase terminal to earth

Figure C.5 – Description of the 50 % switching impulse flashover voltage of a phase-phase-earth insulation

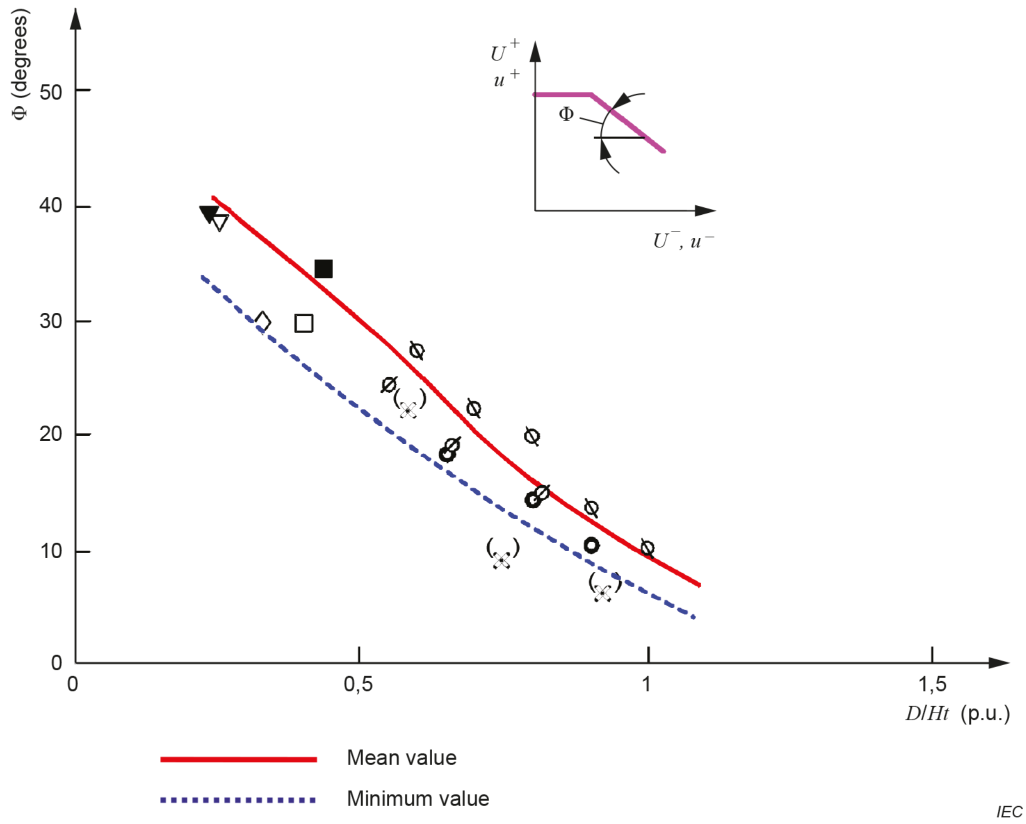


Figure C.6 – Inclination angle of the phase-to-phase insulation characteristic in range "b" dependent on the ratio of the phase-phase clearance D to the height H_t above earth

Annex D
(informative)

Transferred overvoltages in transformers

D.1 General remarks

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

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

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

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

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

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

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

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

Some of the constructional factors influencing the magnitude of transferred surges are difficult to calculate. Therefore, the most practical method to get a quantitative estimate for the magnitude of these surges is to measure them, for example with recurrent surge measurement.

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

D.2 Transferred temporary overvoltages

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

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

$$U_{2e} = \frac{C_{12}}{C_{12} + C_2} U_{1e} + \frac{U_{2N}}{\sqrt{3}} \tag{D.1}$$

where

U_{2e} is the secondary overvoltage caused by the earth fault in the primary;

U_{1e} is the voltage in the neutral point of the primary winding during the earth fault;

$U_{2N} / \sqrt{3}$ is the rated phase-to earth voltage in the secondary side;

C_{12} is the capacitance between primary and secondary windings;

C_2 is the phase-to-earth capacitance of the secondary winding and equipment connected to it.

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

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

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

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

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

D.3 Capacitively transferred surges

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

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

$$C_\mathrm{1in} = \sqrt{C_\mathrm{s} C_\mathrm{e}} \tag{D.2}$$

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

NOTE The validity of the above calculation of C_1in is based on the assumption of a high initial distribution constant of the windings [9]. When high-voltage windings with much higher series capacitances (low distribution constant) are used, this approximation will be less accurate.

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

$$U_\mathrm{T2} = d_\mathrm{r}\, h\, U_\mathrm{T1} \tag{D.3}$$

where

h is the power-frequency voltage factor.

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

$$d_\mathrm{r} = C_\mathrm{1in} / (C_\mathrm{1in} + C_\mathrm{3in})$$

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

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

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

In the case of fast-front overvoltages, the value of U_T1 can be the protection level of the arresters connected on the primary side. In the case of slow-front overvoltages, the value of U_T1 can be the peak value of the phase-to-earth voltage stress (assuming the arresters will not react).

The magnitudes of capacitively transferred surges are damped due to the losses in the windings. This effect, as well as the load connected to the transformer, effectively reduces the magnitude of the capacitive spikes. Usually, these overvoltage spikes are critical only in the case of transformers with large step-down ratios and when only a small capacitance is connected to the secondary. Critical situations can arise if the incoming surge has a great steepness or is chopped. Arresters connected to the secondary effectively limit the magnitudes of the capacitively transferred voltages. The protection can be further improved with additional capacitors, especially in the case of equipment which do not tolerate voltages with fast rising fronts (e.g. generators and motors) or if the capacitive ratio of the transformer is unfavourable, because otherwise the surge arresters on the secondary side might operate too frequently.

D.4 Inductively transferred surges

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

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

The magnitudes of the inductively transferred surges depend on

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

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

$$U_{\mathrm{T2}} = h\, q\, J\, w_{21}\, U_{\mathrm{T1}} \tag{D.4}$$

where

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

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

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

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

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

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

Some typical values for q can be defined as following:

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

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

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

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

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

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

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

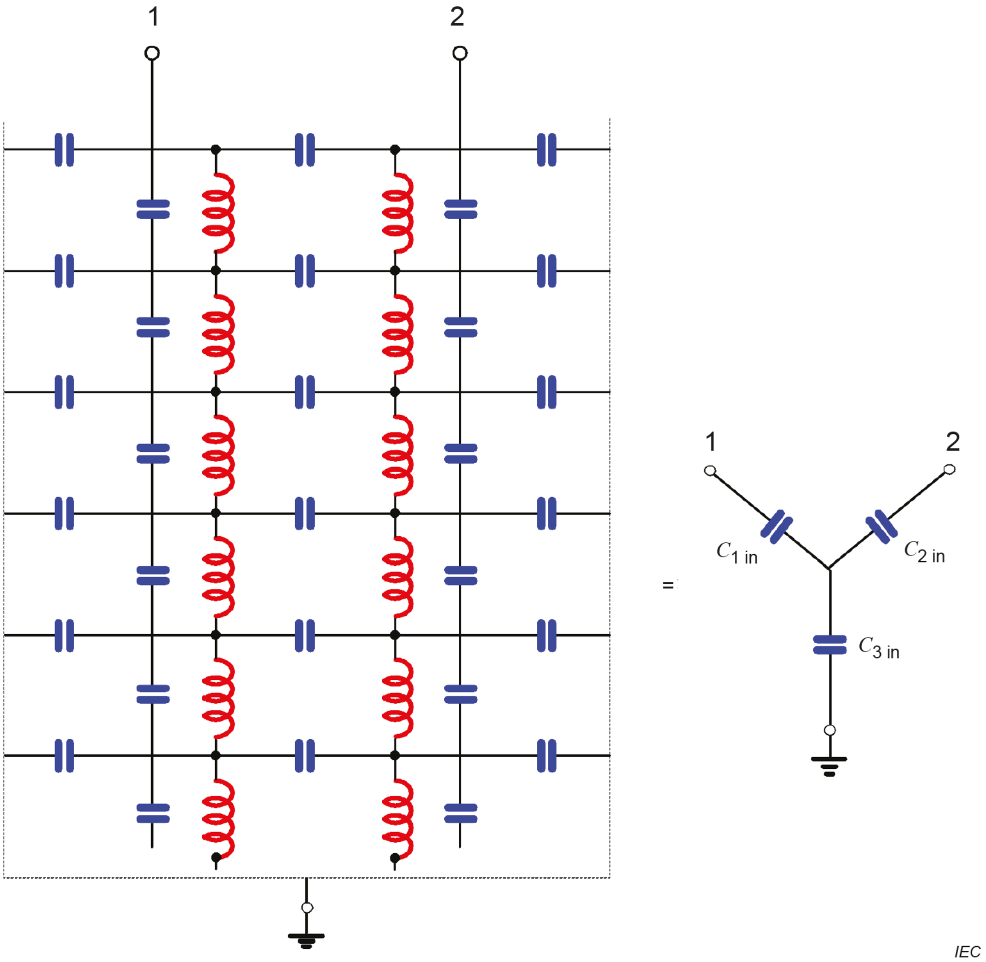
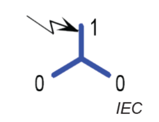
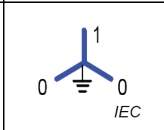
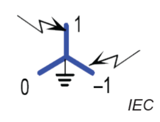
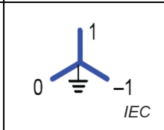
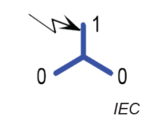
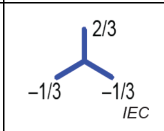
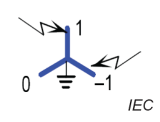
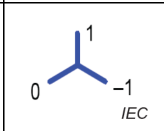
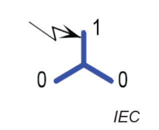
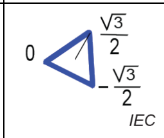
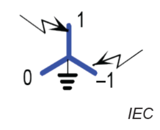
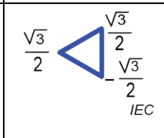
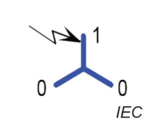
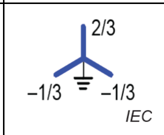
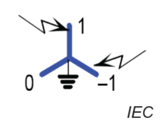
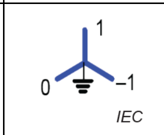
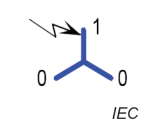
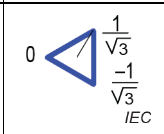
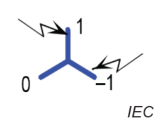
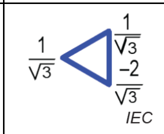
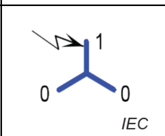
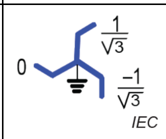
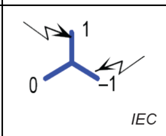
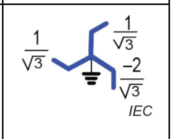
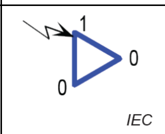
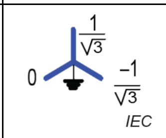
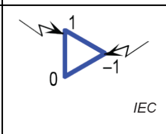
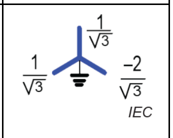
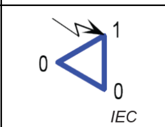
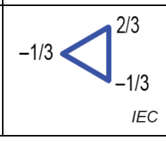
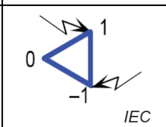
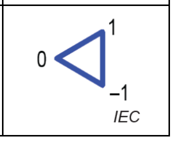


Figure D.1 – Distributed capacitances of the windings of a transformer and the equivalent circuit describing the windings

Case	Transformer connexion			Surge on one phase only $U_A = 1$, $U_B = U_C = 0$		Surges of opposite polarity on 2 phases $U_A = 1$, $U_B = -1$, $U_C = 0$	
No.	Higher-voltage winding	Lower-voltage winding	Tertiary	Higher-voltage winding	Lower-voltage winding	Higher-voltage winding	Lower-voltage winding
1	*Y*(e)	*y*(e)	(–, *y*)				
2	*Y*(e)	*y*(i)	(–, *y*)				
3	*Y*(e)	*d*	(–, *y*, *d*)				
4	*Y*(i)	*y*(e, i)	(–, *y*, *d*)				
5	*Y*(i)	*d*	(–, *y*, *d*)				
6	*Y*(i)	*z*(e, i)	(–, *y*, *d*)				
7	*D*	*y*(e, i)	(–, *y*, *d*)				
8	*D*	*d*	(–, *y*, *d*)				

Key

Y,y	star-connected windings
D,d	delta-connected windings
z	Z-connected windings
U_A, U_B, U_C	overvoltage amplitudes at the high-voltage terminals A, B, C

Figure D.2 – Values of factor *J* describing the effect of the winding connections on the inductive surge transference

Annex E
(informative)

Determination of lightning overvoltages by simplified method

E.1 General remarks

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

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

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

E.2 Determination of the limit distance (X_p)

E.2.1 Protection with arresters in the substation

E.2.1 contains more detailed information on surge arrester protection discussed in 5.3.4.5.

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

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

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

where

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

K_{co} is the corona damping constant according to Table E.1 (μs/(kV·m));

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

NOTE Equation (E.1) has been derived with the assumption that the distances between the protected object and the connection points of the overhead lines result in travel times of less than half the front time of the impinging surge. The lead between object and connection point, therefore, can be neglected in an approximate estimation. This approach is justified for determination of the limit distance in Equation (E.2) because here low steepnesses of the impinging surge are relevant. For the calculation of actual overvoltages resulting from an assumed impinging surge, the simplification could be not conservative.

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

$$X_\mathrm{p} = 2t_\mathrm{s} / [nK_\mathrm{co}\ (U - U_\mathrm{pl})] \qquad \text{(E.2)}$$

where

U is the lowest considered overvoltage amplitude;

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

U_pl is the lightning impulse protection level of the arrester.

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

Table E.1 – Corona damping constant K_co

Conductor configuration	K_co μs/(kV·m)
Single conductor	$1,5 \times 10^{-6}$
Double conductor bundle	$1,0 \times 10^{-6}$
Three or four conductor bundle	$0,6 \times 10^{-6}$
Six or eight conductor bundle	$0,4 \times 10^{-6}$

E.2.2 Self-protection of substation

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

The necessary number of lines can be estimated by:

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

where

n is the number of overhead lines;

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

U is the overvoltage amplitude considered.

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

$$X_p \geq 4\ (t_s / K_{co} U) \tag{E.4}$$

where

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

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

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

where

Z_s is the surge impedance of the substation;

Z_L is the surge impedance of the overhead line.

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

– for shielding failures: X_p = 1 span;

– for back flashovers: X_p = 2 towers.

E.3 Estimation of the representative lightning overvoltage amplitude

E.3.1 General

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

E.3.2 Shielding penetration

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

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

where

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

R_t is the considered return rate;

R_p is the shielding penetration rate withing the limit distance.

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

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

where

R_{sf} is the shielding failure flashover rate;

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

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

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

$$U_I = Z_L I / 2 \tag{E.8}$$

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

where

$X_T = X_P / 4$.

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

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

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

E.3.3 Back flashovers

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

$$F(I) = R_t / R_f \tag{E.10}$$

where

R_t is the considered return rate;

R_f is the flashing rate withing the limit distance.

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

$$R_{hc} = \frac{R_{lc}}{\sqrt{1+\frac{I}{I_g}}} \tag{E.11}$$

where

R_{lc} is the low current resistance;

I_g is the limit current (kA).

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

$$I_g = \frac{1}{2\pi}\frac{E_0 \rho}{R_{lc}^2} \tag{E.12}$$

where

ρ is the soil resistivity (Ω·m);

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

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

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

where

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

Typical values of c_f are:

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

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

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

$$\tau = \frac{Z_e}{R_{lc}}\frac{L_{sp}}{c} \tag{E.14}$$

where

Z_e is the earth-wire surge impedance (typical values are 500 Ω for single earth-wire lines and 270 Ω for double earth-wire lines);

L_{sp} is the span length (m);

c is the light velocity (recommended value: 300 m/μs).

$$S = 1 / (K_{co} X_T) \tag{E.15}$$

where

K_{co} is given by Equation (E.1);

X_T is given by Equation (E.9).

For travelling wave calculations in the considered substation, a single conductor of the length X_T and surge impedance equal to that of the phase conductors is connected to the substation. A voltage source with the internal impedance of the low current footing resistance R_{lc} is placed at the end of the conductor. It produces a voltage with the shape parameters of the impinging surge.

If the impinging surge amplitude is higher than 1,6 times the positive 50 % lightning impulse flashover voltage, the simplifications are no longer applicable and more careful studies may be recommendable. The same applies for tower footing extensions larger than 30 m in radius.

Two dependencies of the representative overvoltage amplitude on the return rate are obtained, one for shielding failures and one for back flashovers. The overall dependency is obtained by adding the return rates for a constant amplitude.

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

E.4 Simplified approach

A further simplification to the procedures described in Clauses E.2 and E.3 is to apply the basic principles given there, but to adopt the following assumptions:

- all lightning events within a certain distance from the substation cause higher overvoltages at the protected equipment than an assumed value, and all events outside this distance lower values;
- the overvoltage at the equipment can be calculated according to Equation (1) and Equation (E.1).

As mentioned already, both assumptions are not strictly valid. Firstly, not all events within a certain distance are equally severe. They depend on the lightning current or on the amplitude of the impinging overvoltage surge. Secondly, the overvoltages could be higher than that calculated with Equations (1) and (E.1). However, current practice of equipment protection by surge arresters has shown that both inaccuracies sufficiently cancel each other.

As regards the distance X to be applied in Equation (E.1), it has been shown that back flashovers do not occur at a tower close to the substation owing to the substation earth. The minimum value of X is one overhead line span length. The representative steepness S_{rp} to be applied in Equation (1), therefore, is equal to:

$$S_{rp} = 1 / [K_{co}(L_{sp} + L_t)] \tag{E.16}$$

And the overhead line section in which the lightning flashover rate is equal to the desired return rate [8] is equal to:

$$L_t = (R_t / R_{km})$$

where

R_t is the adopted overvoltage return rate (1/year);

R_{km} is the overhead line outage rate per year for a design corresponding to the first kilometre in front of the station (see Equation (E.16)) [usual unit: 1/(100 km·year); recommended unit: 1/(m·year)].

NOTE The equation is derived from the observation that back-flashovers do not occur at the tower close to the substation owing to the good substation earthing and that shielding failures do not occur in the first span of the overhead line. Therefore, there is a minimum travel length of the impinging surge which results in a maximum possible steepness. The analytical expression used in Equation (E.16) is an approximation to this observation. Alternatively, instead of the sum, the higher value of the span length or the length L_t can be used.

Thus, introducing S_{rp} in Equation (1) and putting $A = 2 / (K_{co}\ c)$ for transmission lines, the dependence of the representative lightning overvoltage on the return rate is obtained by:

$$U_{rp} = U_{pl} + \frac{A}{n} \frac{L}{L_{sp} + L_t} \quad \text{(E.17)}$$

where

U_{rp} is the representative lightning overvoltage amplitude (kV);

A is a factor given in Table E.2 describing the lightning performance of the overhead line connected to the station;

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

n is the minimum of lines connected to the substation ($n = 1$ or $n = 2$);

L is the separation distance: $L = a_1 + a_2 + a_3 + a_4$ as shown on Figure 3 (m);

L_{sp} is the span length (m);

L_t is the overhead line length with outage rate equal to adopted return rate (m).

The co-ordination withstand voltage is obtained by replacing L_t by the line length L_a which yields an outage rate equal to the acceptable failure rate R_a:

$$L_a = R_a / R_{km} \quad \text{(E.18)}$$

where

L_a is the overhead line section with outage rate equal to acceptable failure rate;

R_a is the acceptable failure rate for equipment.

And the co-ordination lightning impulse withstand voltage (U_{cw}) is equal to:

$$U_{cw} = U_{pl} + \frac{A}{n} \frac{L}{L_{sp} + L_a} \quad \text{(E.19)}$$

For transmission lines, the factors A are obtained from Table E.2 and the corona damping constants K_{co} from Table E.1. For distribution systems, lightning overvoltages are usually multiphase and current sharing of the phase conductors has to be considered. For steel towers, the flashovers of more than one tower during a lightning stroke lead to a further reduction of the lightning overvoltages. For these lines, the factor A has been matched with the service practice.

GIS are, in general, better protected than open-air substations owing to a surge impedance much lower than that of the overhead lines. A generally valid recommendation for the estimation of the amelioration obtained for GIS as compared to open-air substations cannot be made. However, the use of the Equation (E.19) for the open-air substation results in conservative estimates of the co-ordination lightning impulse withstand voltage or of the protection range and a reduction of the ratio A/n to half the value used for outdoor stations is still suitable.

Table E.2 – Factor A for various overhead lines

Type of line	A (kV)
Distribution lines (phase-phase flashovers):	
– with earthed crossarms (flashover to earth at low voltage)	900
– wood-pole lines (flashover to earth at high voltage)	2 700
Transmission lines (single-phase flashover to earth)	
– single conductor	4 500
– double conductor bundle	7 000
– four conductor bundle	11 000
– six and eight conductor bundle	17 000
NOTE Values in this table are applicable in Equations (E.17) and (E.19).	

E.5 Assumed maximum value of the representative lightning overvoltage

For new stations, where lightning insulation performance of existing stations is known, the assumed maximum value of the representative overvoltage may be estimated by:

$$\frac{U_{rp2}}{U_{pl2}} = 1 + \left[\frac{n_1}{n_2}\frac{L_2}{L_1}\frac{U_{pl1}}{U_{pl2}}\left(\frac{U_{rp1}}{U_{pl1}} - 1\right)\right] \qquad (E.20)$$

where

U_{rp} is the assumed maximum representative overvoltage;

U_{pl} is the lightning impulse protection level of the surge arrester;

n is the minimum number of in-service overhead lines connected to the station;

And L is as follows (see Figure 3):

$$L = a_1 + a_2 + a_3 + a_4$$

The index 1 refers to the situation for which service experience has been satisfactory, and the index 2 to the new station situation.

Alternatively, the assumed maximum value can be obtained by assuming the return rate in Equation (E.16) equal to zero, thus leading to L_t = 0, and:

$$U_{rp} = U_{pl} + \frac{A}{n}\frac{L}{L_{sp}} \tag{E.21}$$

Annex F
(informative)

Calculation of air gap breakdown strength from experimental data

F.1 General

The intent of Annex F is not to provide the apparatus committees with a method to calculate air clearances. The purpose is rather to provide help to the user to estimate the size of equipment and the dielectric strength of air gaps for the purpose of determining the atmospheric correction factor.

It shall be noted that the equations provided here are based on experimental data and for the purposes of insulation co-ordination. For distances greater than 1 m, they can be assumed to give an approximate fit to these experimental results.

Discrepancies may be particularly significant for distances less than 1 m where the accuracy of the given equations is questionable.

F.2 Insulation response to power-frequency voltages

For air gap breakdown under power-frequency voltage, the lowest withstand voltage is obtained for the rod-plane gap configuration. The 50 % breakdown voltage for a rod-plane gap may be approximated by the following equation, for air gaps d up to 3 m:

$$U_{50\text{RP}} = 750\sqrt{2}\ \ln\left(1 + 0{,}55\ d^{1{,}2}\right) \quad \text{(kV crest, m)} \qquad \text{(F.1)}$$

The peak value of $U_{50\text{RP}}$ under power-frequency voltage is about 20 % to 30 % higher than the corresponding value under positive switching impulse at critical front time. Withstand can be taken to be 90 % of U_{50}, based on an assumed conventional deviation of 3 % of U_{50}.

The influence of gap configuration on the strength is generally lower under power-frequency than under switching impulse:

– it is quite small for gaps up to about 1 m clearance;
– for gaps larger than 2 m, the strength can be evaluated according to the following equation (applicable to dry conditions):

$$U_{50} = U_{50\text{RP}}\left(1{,}35\ K - 0{,}35\ K^2\right) \qquad \text{(F.2)}$$

where

K is the gap factor (determined from switching impulse tests) as shown in Table F.1;

– for gaps between 1 m and 2 m, Equation (F.1) can be used with the knowledge that the results will be conservative.

When insulators are present, the flashover voltage can substantially decrease with respect to the reference case (the same air gap without insulators), especially in conditions of high humidity.

In general, discharges under power-frequency voltage and normal operating conditions and under temporary overvoltages will be caused by exceptional reductions in insulation withstand strength due to the severe ambient conditions or by aging of the insulation properties of the equipment.

The influence of rain on air gaps is negligible, especially for configurations presenting the lowest strength. However, rain can reduce the external dielectric strength of insulators, especially for post insulators with small distance between sheds. The degree of reduction depends on the rain rate, the insulator configuration and the conductivity of water.

Rain, together with pollution, can drastically reduce the insulation strength. The worst condition is usually caused by fog or light rain together with the polluted insulators (see 6.3.2.2). These conditions could in fact dictate the external insulation design. Comparative insulation contamination levels can be simulated by the equivalent salt deposit density (ESDD) in grams per square metre of NaCl. ESDD relates the steady-state conductivity of dissolved contaminant to an equivalent amount of dissolved NaCl. The determination of the ESDD requires an analysis of either performance of existing insulation in the area or statistical data gathered from on-site investigations.

It would be desirable to analyze performance of existing insulators. However, the results could be inappropriate when existing insulators have never been subjected to pollution flashovers.

Analysis of statistical data requires several years of on-site monitoring as data is gathered by direct measurement of ESDD from washdown of exposed insulators or by other methods, for example leakage current measurement, chemical analysis or conductivity measurements.

NOTE The applicability of the concept of ESDD to non-ceramic insulators is not clear. The present research indicates that the phenomenon of surface hydrophobicity can be more important.

The statistical description of ambient conditions usually requires a greater amount of data. The statistical description of aging is even more difficult. Therefore, statistical procedures are not recommended in this document for estimation of the insulation response at power-frequency voltages.

F.3 Insulation response to slow-front overvoltages

Under stress from slow-front surges, a given self-restoring insulation exhibits an appreciably lower withstand voltage than under fast-front surges of the same polarity. As a result of numerous switching impulse tests, air gaps can be characterized by the minimum strength observed for the critical time-to-crest, as a function of the geometrical characteristics of the air gap which are mainly the gap spacing d and the electrode configuration. Among the different gaps of spacing d, the positively stressed rod-plane gap has the lowest strength and is used as a reference. For rod-plane gaps of length up to 25 m, experimental data for positive-polarity critical-front-time strength can be reasonably approximated by [10] [11]:

$$U_{50\mathrm{RP}} = 1\,080 \ln (0{,}46\, d + 1) \quad \text{(kV crest, m)} \tag{F.3}$$

For standard switching impulses, the following equation provides a better approximation [11] [12]:

$$U_{50\mathrm{RP}} = 500\, d^{\,0{,}6} \quad \text{(kV crest, m)} \tag{F.4}$$

Equations (F.3) and (F.4) are applicable to sea-level (H = 0). Therefore, correction for altitude is required when applying the insulation co-ordination procedure.

Insulators in the air gap generally decrease the breakdown strength, for positive slow-front impulses. For dry cap and pin insulators, the influence is small but can be important for post insulators.

For other gap configurations, a gap factor as described in Table F.1 is applied as follows:

$$U_{50} = K\, U_{50\text{RP}} \quad \text{(F.5)}$$

Note that for $K \geq 1{,}45$, the breakdown voltage under negative polarity could become lower than that for positive polarity.

For phase-to-phase configurations, a similar gap factor may be applied. In this case however, the gap factor is influenced not only by the gap configuration, but also by the ratio α defined as the peak negative component divided by the sum of the peak negative and positive components (see Annex C).

Table F.2 gives typical values of gap factor for usual phase-to-phase gap geometries for $\alpha = 0{,}5$ and $\alpha = 0{,}33$.

NOTE For any given gap configuration, actual gap factors can only be determined accurately by testing.

F.4 Insulation response to fast-front overvoltages

Under fast-front impulse stress, the negative polarity breakdown strength of a rod-plane gap configuration is much higher than that with positive polarity stress. Furthermore, the gap strength when plotted against the gap clearance is non-linear with negative polarity while it is linear with positive polarity. For standard lightning impulses applied to rod-plane gaps from 1 m up to 10 m, the experimental data for positive polarity strength could be approximated by:

$$U_{50\text{RP}} = 530\, d \text{ (kV crest, m)} \quad \text{(F.6)}$$

In general, the gap factors applicable to switching impulse are not directly useable for lightning impulse strength. However, experimental results have shown that for positive polarity the breakdown gradient for a general air gap in per unit of the breakdown gradient for a rod-plane gap increases linearly with switching impulse gap factor for positive impulse stress. The gap factor K_{ff}^{+} for fast-front lightning impulses of positive polarity can be approximated in terms of the switching impulse gap factor as follows:

$$K_{ff}^{+} = 0{,}74 + 0{,}26\, K \quad \text{(F.7)}$$

For the purpose of estimating the breakdown strength of overhead line insulator strings for negative polarity, in order to determine the magnitude of surges impinging on a substation, the following equation may be used:

$$U_{50} = 700\, d \text{ (kV crest, m)} \quad \text{(F.8)}$$

Formulas (F.6) and (F.8) are applicable to sea-level (H = 0). Therefore, correction for altitude is required when applying the insulation co-ordination procedure.

For configurations such as conductor-upper structure and conductor-crossarm, the influence of the insulators on the strength is negligible so that the strength of these configurations is close to that of air gaps.

For other unusual configurations and particularly when large clearances are involved (like in range II), specific testing is advised for accurate results. For these configurations, the presence of insulators between the electrodes can play an important role on the discharge process, thus also heavily affecting the value of U_{50}. The degree of influence depends on insulator type (capacitance between units, distance between metal parts along the insulator set). A lower influence is to be expected for insulators with few metal parts (e.g. post insulators, long rod, composite). The generalization of the results similar to that made for configurations without insulators is not easy when cap and pin insulators are included in the gap. It can be stated however that the influence of cap and pin insulators is reduced when the stress on the first insulator at both extremities of the string is reduced using shielding rings. It is also reduced for more practical configurations with insulators at both extremities less stressed than in the case of rod-plane gaps.

For air gaps, the conventional deviation is about 3 % of U_{50} under positive impulses and about 5 % of U_{50} under negative impulses. When insulators are present, the conventional deviation is increased reaching a maximum of 5 % to 9 % in connection with cases presenting the largest reduction of U_{50}. In other cases, a value close to that of air gaps is applicable.

The influence of rain on a flashover voltage is generally secondary, both in the case of air gaps and insulator strings.

For fast-front overvoltages, the time-to-breakdown is markedly influenced by the amplitude of the applied impulse relative to the breakdown voltage. For impulses close to the value of $U_{50,}$ flashover occurs on the tail of the standard impulse. As amplitude is increased, time to flashover decreases giving rise to the well-known volt-time curve.

Table F.1 – Typical gap factors K for switching impulse breakdown phase-to-earth (according to [1] and [4])

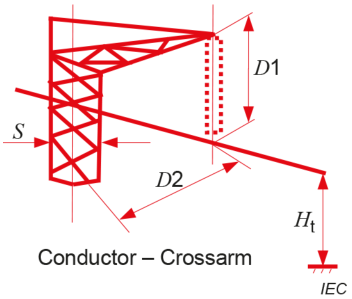
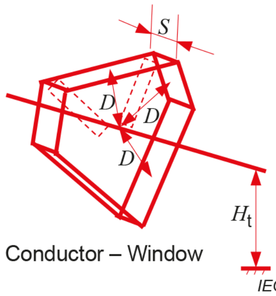
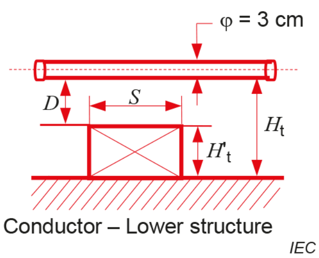
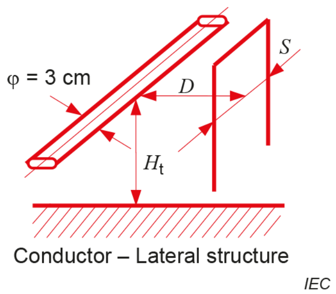
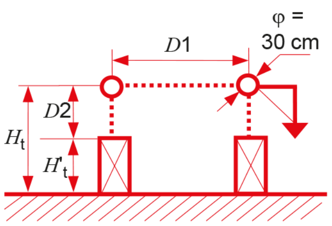
Gap type	Parameters	Typical range	Reference value	
 Conductor – Crossarm	K	1,36 to 1,58	1,45	
	$D2$ / $D1$	1 to 2	1,5	
	H_t / $D1$	3,34 to 10	6	
	S / $D1$	0,167 to 0,2	0,2	
 Conductor – Window	K	1,22 to 1,32	1,25	
	H_t / D	8 to 6,7	6	
	S / D	0,4 to 0,1	0,2	
 Conductor – Lower structure	K	1,18 to 1,35	1,15 Conductor-plane	1,47 Conductor-rod
	H'_t / H_t	0,75 to 0,75	0	0,909
	H'_t / D	3 to 3	0	10
	S / D	1,4 to 0,05	-	0
 Conductor – Lateral structure	K	1,28 to 1,63	1,45	
	H_t / D	2 to 10	6	
	S / D	1 to 0,1	0,2	
 $D1 > D2$ Longitudinal Rod – Rod structure	K	1,03 to 1,66	1,35	
	H'_t / H_t	0,2 to 0,9	0	
	$D1$ / H_t	0,1 to 0,8	0,5	

Table F.2 – Gap factors for typical phase-to-phase geometries

Configuration	α = 0,5	α = 0,33
Ring-ring or large smooth electrodes	1,80	1,70
Crossed conductors	1,65	1,53
Rod-rod or conductor-conductor (along the span)	1,62	1,52
Supported busbars (fittings)	1,50	1,40
Asymmetrical geometries	1,45	1,36
NOTE According to [1] and [4].		

Annex G
(informative)

Examples of insulation co-ordination procedure

G.1 Overview

The insulation co-ordination procedure includes determining the voltage stresses from all origins on equipment and the corresponding electric strength required based on acceptable margins of protection or acceptable levels of performance. These margins (or levels) are mostly empirical.

As described in Figure 1 of IEC 60071-1:2019, there are in fact four main steps in this insulation co-ordination procedure, which can be identified as follows:

– step 1: determination of the representative overvoltages (U_{rp});

– step 2: determination of the co-ordination withstand voltages (U_{cw});

– step 3: determination of the required withstand voltages (U_{rw});

– step 4: determination of the standard withstand voltages (U_{w}).

These main steps, with associated links connecting them, will be illustrated in some examples contained in Annex G. Not only will the required standard withstand voltages be determined but also the calculation related to phase-to-ground and phase-to-phase clearances will be illustrated, as applicable.

The representative overvoltages are not, strictly speaking, the overvoltages that occur in the system but are overvoltages that represent the same electric stress on the equipment as the actual overvoltages. Thus, if the assumed actual overvoltage has a shape different from the test shape, the representative overvoltage may have to be modified accordingly so that the tests truly verify the insulation strength.

In matching the voltage stresses with the electric strength, one has to take into account the various types of voltage stresses and the corresponding response of the insulation. This involves making a distinction between self-restoring (external) insulation and non-self-restoring (internal) insulation. For non-self-restoring insulation, the stress-strength co-ordination is made using deterministic methodology whereas for self-restoring insulation a statistical methodology can be used where this is convenient. The following examples attempt to present all these considerations.

G.2 Numerical example for a system in range I (with nominal voltage of 230 kV)

G.2.1 General

The system analysed corresponds to that shown in Figure 12.

The process of insulation co-ordination is applied to station 1 assumed to be a new station.

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

The evaluation of the required slow-front (switching) withstand voltages is followed by their conversion into equivalent power-frequency and fast-front (lightning) withstand voltages. The example showed in Clause G.2 includes such a conversion procedure.

For normal systems in range I, the insulation co-ordination procedure leads to the general philosophy of specifying one standard insulation level (a set of standard withstand voltages) applicable phase-to-phase and phase-to-earth.

This is illustrated in the first part of the example (G.2.2) where no "abnormal" operating condition is considered.

However, as a second part of the example (G.2.3), to show the importance of considering stresses from all origins and their influence on this general philosophy, such special operating conditions (consisting of capacitor switching at station 2) are considered.

In the third part of this example (G.2.4), flow charts summarize intermediate and final results obtained along the different steps of the insulation co-ordination procedure.

For the purpose of this example, one will assume the following basic data:

– the highest system voltage is U_s = 245 kV;
– the pollution level is heavy (refer to 6.3.2.2);
– the altitude is H = 1 000 m.

G.2.2 Part 1: no special operating conditions

G.2.2.1 Step 1: determination of the representative overvoltages – values of U_{rp}

G.2.2.1.1 Power-frequency voltage

For the insulation co-ordination procedure, the most important reference voltage is the maximum continuous operating voltage U_s. For the system analysed, while the nominal voltage is 230 kV, the value of U_s is confirmed to be 245 kV (RMS, phase-to-phase). The system, including compensation, is designed to operate at or below this limit. Obviously, the installed equipment should have a U_m equal to or greater than U_s.

The new station 1 is to be located adjacent to a major thoroughfare where salt, spread on the road in winter, can be expected to lead to heavy pollution. Because of this environment, the performance requirements of external insulation at power-frequency will be met by specifying an artificial pollution test corresponding to pollution level "heavy" in 6.3.2.2. According to IEC TS 60815-1, the minimum creepage distance recommended for insulators is 25 mm/kV.

G.2.2.1.2 Temporary overvoltages

One source of temporary overvoltages is earth faults (refer to 5.3.2.2) giving rise to phase-to-earth overvoltages. System studies have been made taking into account the system neutral grounding characteristics, and the earth fault factor has been found to be k = 1,5 (such a figure is just for the purpose of the example; in fact, a value of 1,5 is rather unusual at a voltage level of 230 kV where a value not greater than 1,3 is normally expected). The corresponding phase-to-earth representative overvoltage is U_{rp} = 212 kV.

Another source of temporary overvoltages is load rejection (refer to 5.3.2.3) which produces overvoltages affecting both phase-to-phase and phase-to-earth insulation. Analysis and system studies have shown that generator overspeed and regulation combine to produce overvoltages of 1,4 p.u. at station 1 (which is also rather high) which results in phase-to-earth and phase-to-phase representative overvoltages of U_{rp} = 198 kV and U_{rp} = 343 kV.

As mentioned in 5.3.2.6, an earth fault can combine with load rejection to give rise to other overvoltage amplitudes. In this example, such a combination does not occur because after load rejection, the system configuration has changed: circuit-breakers at station 1 have opened, external infeeds are gone, and the earth fault factor (k) at station 1 has been reduced below 1 (with the delta/grounded Y generator step-up transformer).

The representative temporary overvoltages are the highest obtained considering all possible sources:

– phase-to-earth: U_{rp} = 212 kV;

– phase-to-phase: U_{rp} = 343 kV.

G.2.2.1.3 Slow-front overvoltages

System studies have confirmed that slow-front overvoltages from remote lightning strokes (refer to 5.3.3.6) are not a problem in the system under consideration. On the other hand, slow-front overvoltages due to earth faults need to be considered only in systems with resonant neutral earthing (refer to 5.3.3.3), which is not the case in this example.

For the determination of the representative overvoltages, it may be necessary to distinguish between equipment at the line entrance which can be in the open-end condition during energization or re-energization at remote end (station 1), and equipment on the source side at the local end (station 2) which will be affected in a different way and by different stresses.

1) Particular surges affecting line entrance equipment (at station 1)

   System studies using the phase-peak method (refer to Annex C) have shown that line re-energization from station 2 can result in 2 % overvoltages at the open-end line entrance at station 1 of U_{e2} = 3,0 p.u. and U_{p2} = 4,5 p.u. The representative overvoltages for external line entrance equipment, before applying surge arresters, are the truncation values of these overvoltage distributions. As shown in Annex C:

   – $U_{et} = 1,25\ U_{e2} - 0,25 \Rightarrow$ U_{et} = 700 kV;

   – $U_{pt} = 1,25\ U_{p2} - 0,43 \Rightarrow$ U_{pt} = 1 039 kV.

2) Surge affecting all equipment (at station 1)

   All the equipment located in station 1 is subjected to slow-front overvoltages due to local line energization and re-energization. However, these sending end surges are much lower than at the receiving end: for station 1, system studies result in U_{e2} = 1,9 p.u. and U_{p2} = 2,9 p.u. Corresponding values are U_{et} = 425 kV and U_{pt} = 639 kV.

3) Surge arresters at the line entrance (at station 1)

   To control the possible severe overvoltages originating from remote re-energization, metal-oxide surge arresters are installed at the line entrance (refer to 5.3.3.8), identical to those planned for transformer protection. The rating of these arresters is such that they can sustain the worst temporary overvoltage cycle (amplitude and duration). Their protection characteristics are:

   – switching impulse protection level: U_{ps} = 410 kV;

   – lightning impulse protection level: U_{pl} = 500 kV.

As explained in 5.3.3.8, with the use of surge arresters, the slow-front representative overvoltages can be directly given by U_{ps} (phase-to-earth) or 2 U_{ps} (phase-to-phase) if these protection values are lower than the corresponding maximum slow-front overvoltage stresses (U_{et} and U_{pt} values). This is the case for any stress except for line entrance equipment, phase-to-phase, so that the representative slow-front overvoltages are:

– phase-to-earth: U_{rp} = 410 kV for any equipment;

– phase-to-phase:

  • U_{rp} = 639 kV for any equipment except at line entrance;

  • U_{rp} = 820 kV for equipment at line entrance.

G.2.2.1.4 Fast-front overvoltages

In this example, only fast-front overvoltages from lightning have to be considered. A simplified statistical approach will be used which leads directly to the co-ordination withstand voltage (step 2 below), bypassing the need for a representative overvoltage.

G.2.2.2 Step 2: determination of the co-ordination withstand voltages – values of U_{cw}

G.2.2.2.1 General

According to 5.3, different factors have to be applied to the previously determined values of representative overvoltages. These factors, which may vary with the shape of the considered overvoltage, take into account the adopted performance criteria (the economic or operational rate of failure which is acceptable) and the inaccuracies in the input data (e.g. arrester data).

G.2.2.2.2 Temporary overvoltages

For this class of overvoltages, the co-ordination withstand voltage is equal to the representative temporary overvoltage (refer to 6.3.2). In other words, the co-ordination factor K_c is equal to 1. Therefore:

- phase-to-earth: U_{cw} = 212 kV;
- phase-to-phase: U_{cw} = 343 kV.

G.2.2.2.3 Slow-front overvoltages

The deterministic approach is used. With such an approach, one should take into account that surge limitation by an arrester distorts the statistical distribution of these surges, creating a significant bulge in the probability distribution of surges at about the arrester protection level (refer to 6.3.3.1). Therefore, small uncertainties related to the arrester protection characteristic or to equipment strength could lead to an abnormally high increase in the failure rate. Figure 5 takes this into account by applying a deterministic co-ordination factor K_{cd} to the arrester protection level to obtain the U_{cw} values.

For line entrance equipment:

- phase-to-earth: U_{ps}/U_{e2} = 410/600 = 0,68 ⇒ K_{cd} = 1,10;
- phase-to-phase: 2 U_{ps}/U_{p2} = 820/900 = 0,91 ⇒ K_{cd} = 1,00.

For all other equipment:

- phase-to-earth: U_{ps}/U_{e2} = 410/380 = 1,08 ⇒ K_{cd} = 1,03;
- phase-to-phase: 2 U_{ps}/U_{p2} = 820/580 = 1,41 ⇒ K_{cd} = 1,00.

The resulting co-ordination withstand voltages are $K_{cd} \times U_{rp}$:

For line entrance equipment:

- phase-to-earth: U_{cw} = 1,1 × 410 ⇒ U_{cw} = 451 kV;
- phase-to-phase: U_{cw} = 1,0 × 820 ⇒ U_{cw} = 820 kV.

For all other equipment:

- phase-to-earth: U_{cw} = 1,03 × 410 ⇒ U_{cw} = 422 kV;
- phase-to-phase: U_{cw} = 1,0 × 639 ⇒ U_{cw} = 639 kV.

G.2.2.2.4 Fast-front overvoltages

A statistical approach is used (refer to 6.3.4.2), and more specifically, a simplified statistical approach (refer to Clause E.4). Here, the factor to be applied to U_{rp} is based on experience with particular line construction and on the calculated effect due to the separation between the arrester and the protected equipment.

One determines the length L_a of overhead line with an outage rate equal to the acceptable failure rate R_a. Then, taking account of the separation distance L, the number of lines n entering the station, and the span length L_{sp}, one calculates the effective protection level of the arrester, which is the desired value U_{cw}.

For this example, the following data are available: many arresters with a lightning protection level of 500 kV are located at different places (at line entrance and near the transformers). The maximum separation distance for internal insulation is 30 m; for external insulation, it is 60 m. Two steel tower lines characterized by A = 4 500 (refer to Table E.2) and with a span length of 300 m are connected to the station. The lightning performance for such lines is one outage per 100 km per year. For the equipment to be installed in station 1, an acceptable failure rate is defined as 1 in 400 years.

Using Equation (E.18), the value of L_a = 0,25 km is found. Introducing the value of L_a and other parameters in Equation (E.19), the co-ordination withstand voltage is found:

– for internal insulation:

  U_{cw} = 500 +[(4 500 / 2) × 30 / (300 + 250)] ⇒ U_{cw} = 622 kV;

– for external insulation:

  U_{cw} = 500 +[(4 500 / 2) × 60 / (300 + 250)] ⇒ U_{cw} = 745 kV.

Fast-front overvoltages affect the phase-to-phase and the phase-to-earth insulations in the same way.

G.2.2.3 Step 3: determination of the required withstand voltages – values of U_{rw}

G.2.2.3.1 General

The required withstand voltages are obtained by applying to the co-ordination withstand voltages two correction factors (refer to Clause 7): factor K_a which takes into account the altitude of the installation, and a safety factor K_s.

G.2.2.3.2 Safety factor

The recommended values for the safety factor K_s are defined in 7.3.5. The factor K_s is applicable to any type of overvoltage shape (temporary, slow-front, fast-front), phase-to-phase and phase-to-earth:

– for internal insulation: K_s = 1,15;

– for external insulation: K_s = 1,05.

G.2.2.3.3 Atmospheric correction factor

The altitude correction factor K_a is defined in 7.2.2 (Equation (11)). The factor K_a is applicable to external insulation only and its value depends on the overvoltage shape (via parameter m in Equation (11)).

For power-frequency withstand, short-duration tests on polluted insulators are required, and:

$\Rightarrow \quad m$ = 0,5.

For switching impulse withstand, the value of m is a function of the co-ordination withstand voltage according to Figure 10:

- phase-to-earth: U_{cw} = 451 kV $\Rightarrow \quad m$ = 0,94;
- phase-to-phase: U_{cw} = 820 kV $\Rightarrow \quad m$ = 1,00.

For lightning impulse withstand: $\Rightarrow \quad m$ = 1,00.

The installation is at an altitude H = 1 000 m. The corresponding values of K_a are:

- for power-frequency withstand: K_a = 1,063 (phase-to-phase and phase-to-earth);
- for switching impulse withstand: K_a = 1,122 (phase-to-earth),
K_a = 1,130 (phase-to-phase);
- for lightning impulse withstand: K_a = 1,130 (phase-to-phase and phase-to-earth).

G.2.2.3.4 Required withstand voltages

The values for the required withstand voltages are obtained from: $U_{rw} = U_{cw}\ K_s\ K_a$, with U_{cw} values found in step 2 (G.2.2.2) and K_s and K_a values found in step 3 (G.2.2.3).

1) For temporary overvoltages
   - external insulation:
     - phase-to-earth $\Rightarrow$ U_{rw} = 212 × 1,05 × 1,063 $\Rightarrow$ U_{rw} = 237 kV,
     - phase-to-phase $\Rightarrow$ U_{rw} = 343 × 1,05 × 1,063 $\Rightarrow$ U_{rw} = 383 kV;
   - internal insulation:
     - phase-to-earth $\Rightarrow$ U_{rw} = 212 × 1,15 $\Rightarrow$ U_{rw} = 243 kV,
     - phase-to-phase $\Rightarrow$ U_{rw} = 343 × 1,15 $\Rightarrow$ U_{rw} = 395 kV.
2) For slow-front overvoltages

   For line entrance equipment:
   - external insulation:
     - phase-to-earth $\Rightarrow$ U_{rw} = 451 × 1,05 × 1,122 $\Rightarrow$ U_{rw} = 531 kV,
     - phase-to-phase $\Rightarrow$ U_{rw} = 820 × 1,05 × 1,13 $\Rightarrow$ U_{rw} = 973 kV.

   For other equipment:
   - external insulation:
     - phase-to-earth $\Rightarrow$ U_{rw} = 422 × 1,05 × 1,122 $\Rightarrow$ U_{rw} = 497 kV,
     - phase-to-phase $\Rightarrow$ U_{rw} = 639 × 1,05 × 1,13 $\Rightarrow$ U_{rw} = 758 kV.
   - internal insulation:
     - phase-to-earth $\Rightarrow$ U_{rw} = 422 × 1,15 $\Rightarrow$ U_{rw} = 485 kV,
     - phase-to-earth $\Rightarrow$ U_{rw} = 639 × 1,15 $\Rightarrow$ U_{rw} = 735 kV.
3) For fast-front overvoltages:
   - external insulation:
     - phase-to-earth $\Rightarrow$ U_{rw} = 745 × 1,05 × 1,13 $\Rightarrow$ U_{rw} = 884 kV,
     - phase-to-phase $\Rightarrow$ U_{rw} = 745 × 1,05 × 1,13 $\Rightarrow$ U_{rw} = 884 kV.

– internal insulation:
  - phase-to-earth ⇒ U_{rw} = 622 × 1,15 ⇒ U_{rw} = 715 kV,
  - phase-to-phase ⇒ U_{rw} = 622 × 1,15 ⇒ U_{rw} = 715 kV.

G.2.2.4 Step 4: conversion to withstand voltages normalized for range I

G.2.2.4.1 General

In range I, the insulation level is normally described by a set of two values as shown in Table 2 of IEC 60071-1:2019: a short-duration power-frequency withstand voltage and a lightning impulse withstand voltage. Table 3 of IEC 60071-2:2019 gives the test conversion factor to be applied to the required withstand voltage for slow-front overvoltage to get such an equivalent set of values.

G.2.2.4.2 Conversion to short-duration power-frequency withstand voltage (SDWV)

For line entrance equipment:

– external insulation:
  - phase-to-earth ⇒ SDWV = 531 × (0,6 + 531 / 8 500) = 352 kV;
  - phase-to-phase ⇒ SDWV = 973 × (0,6 + 973 / 12 700) = 658 kV.

For other equipment:

– external insulation:
  - phase-to-earth ⇒ SDWV = 497 × (0,6 + 497 / 8 500) = 327 kV;
  - phase-to-phase ⇒ SDWV = 758 × (0,6 + 758 / 12 700) = 500 kV;

– internal insulation:
  - phase-to-earth ⇒ SDWV = 485 × 0,5 = 243 kV;
  - phase-to-phase ⇒ SDWV = 735 × 0,5 = 367 kV.

G.2.2.4.3 Conversion to lightning impulse withstand voltage (LIWV)

For line entrance equipment:

– external insulation:
  - phase-to-earth ⇒ LIWV = 531 × 1,30 = 690 kV;
  - phase-to-phase ⇒ LIWV = 973 × (1,05 + 973 / 9 000) = 1 127 kV.

For other equipment:

– external insulation:
  - phase-to-earth ⇒ LIWV = 497 × 1,30 = 646 kV;
  - phase-to-phase ⇒ LIWV = 758 × (1,05 + 758 / 9 000) = 860 kV;

– internal insulation:
  - phase-to-earth ⇒ LIWV = 485 × 1,10 = 534 kV;
  - phase-to-phase ⇒ LIWV = 735 × 1,10 = 808 kV.

G.2.2.5 Step 5: selection of standard withstand voltage values

Table G.1 summarizes values $U_{rw(s)}$ of minimum required withstand voltages obtained from system studies (results in step 3) which become minimum test values to be applied to verify these withstands in terms of short-duration power-frequency, switching impulse and lightning impulse tests. In range I, the required switching impulse withstand voltage is normally covered by a standard short-duration power-frequency test or by a standard lightning impulse test.

In Table G.1, values obtained after such conversions are indicated under $U_{rw(c)}$ (results from step 4). In this example, converted values for a lightning impulse test are retained so that converted values for a short-duration power-frequency test need no more consideration.

Table G.1 – Summary of minimum required withstand voltages obtained for the example shown in G.2.2

Values of U_{rw} kV		External insulation				Internal insulation	
		Line entrance equipment		Other equipment			
		$U_{rw(s)}$	$U_{rw(c)}$	$U_{rw(s)}$	$U_{rw(c)}$	$U_{rw(s)}$	$U_{rw(c)}$
Short-duration power-frequency (RMS)	phase-earth	**237**	352	**237**	327	**243**	243
	phase-phase	**383**	658	**383**	500	**395**	367
Switching impulse (peak)	phase-earth	531		497	–	485	–
	phase-phase	973	–	758	–	735	–
Lightning impulse (peak)	phase-earth	**884**	690	**884**	646	715	534
	phase-phase	884	1127	**884**	860	715	**808**
NOTE The figures are obtained from part 1 (G.2.2), without capacitor switching at remote station (station 2).							

Standard voltages to be defined for the purpose of the short-duration power-frequency and lightning impulse tests have to be selected taking into account results shown in bold characters in Table G.1 (highest value of minimum withstand required $U_{rw(s)}$ or converted value $U_{rw(c)}$) and standard values proposed in IEC 60071-1:2019, 5.6 and 5.7. Normally, specified voltages are chosen in such a way as to correspond to a standard insulation level as defined in 3.36 of IEC 60071-1:2019 and shown in Table 2 of IEC 60071-1:2019.

Standardized values of 395 kV (for short-duration power-frequency) and 950 kV (for lightning impulse) correspond to such a standard insulation level for a system with U_m = 245 kV; these values will cover any insulation, phase-to-earth and phase-to-phase, except the phase-to-phase external insulation at line entrance for which a 1 127 kV minimum withstand value is required. However, in this example, three-phase equipment is not installed at line entrance so that a minimum phase-to-phase clearance can be specified instead of testing. According to IEC 60071-1, a clearance of 2,35 m between phases would be required for line entrance equipment, corresponding to a standard lightning impulse withstand voltage of 1 175 kV. A minimum phase-to-earth and phase-to-phase clearance of 1,9 m is required for any other external insulation not located at line entrance. These clearances are solely based on insulation co-ordination requirements.

It will be noted that, for external phase-to-earth insulation, the high value specified for the short-duration power-frequency test (395 kV) is well above minimum requirement related to temporary overvoltages (237 kV). However, a 395 kV value corresponds to the standard insulation level having the required lightning withstand level of 950 kV. Refinements in studies could lead to lower requirements by one step for the phase-to-earth external insulation (360 kV/850 kV).

For the internal insulation, the selection of the same standard insulation level as for external insulation could be considered as leading to too much margin with respect to required lightning withstand voltages (715 kV phase-to-earth and 808 kV phase-to-phase). Other choices, considering the economic issue, are possible (refer to 5.10 of IEC 60071-1:2019): specification of a lightning impulse withstand voltage of 850 kV, phase-to-phase and phase-to-earth; or 750 kV phase-to-earth with a special phase-to-phase test at 850 kV. However, the short-duration power-frequency test at a minimum value of 395 kV should be kept. Even if acceptable, the final issue related to these other choices would lead to a rated insulation level not corresponding to a standard insulation level as defined in IEC 60071-1.

G.2.3 Part 2: influence of capacitor switching at station 2

This second part of the example exposed in Clause G.2 deals with an additional slow-front overvoltage possibility originating from capacitor bank switching done at station 2 (remote station). All the other stresses considered in G.2.2 (part 1) are present at their same values, with the same arrester implementation at station 1.

Results from system studies show that all equipment at station 1 (including line entrance equipment in normal operating closed condition) is subjected to severe voltage surges due to capacitor bank energization at station 2. These surges propagate and, due to amplification phenomenon (resonance at given frequencies), show the following maximum amplitudes at station 1:

– phase-to-earth:
  - U_{e2} = 500 kV;
  - U_{et} = 575 kV;
– phase-to-phase:
  - U_{p2} = 750 kV;
  - U_{pt} = 852 kV.

For the open-end line entrance equipment, the highest slow-front surges are those related to line re-energization described in G.2.2 (part 1). But for all other equipment, the slow-front surges governing the insulation co-ordination procedure are now related to capacitor bank switching in station 2, which are higher than surges originating from local energization and re-energization (described in part 1). Hereafter, only this type of stress (new slow-front surges) is dealt with, conclusions for the other types of stress (temporary and fast-front overvoltages) remaining the same as discussed in part 1.

Values of representative slow-front overvoltages U_{rp} are now controlled by the surge arrester protection characteristic because $U_{ps} < U_{et}$ and 2 $U_{ps} < U_{pt}$, so that:

– phase-to-earth: U_{rp} = 410 kV;
– phase-to-phase: U_{rp} = 820 kV.

To obtain the slow-front co-ordination withstand voltages U_{cw}, a deterministic co-ordination factor K_{cd} is applied to U_{rp} values by following the same procedure described in part 1:

– phase-to-earth: U_{ps} / U_{e2} = 410 / 500 = 0,82 ⇒ K_{cd} = 1,10 ⇒ U_{cw} = 451 kV;
– phase-to-phase: 2 U_{ps} / U_{p2} = 820 / 750 = 1,09 ⇒ K_{cd} = 1,00 ⇒ U_{cw} = 820 kV.

The values for the safety factor K_s and for the atmospheric correction factor K_a keep approximately the same values as in part 1 so that the resulting required withstand voltages U_{rw} are:

– external insulation:
  - phase-to-earth ⇒ U_{rw} = 451 × 1,05 × 1,122 ⇒ U_{rw} = 531 kV;
  - phase-to-phase ⇒ U_{rw} = 820 × 1,05 × 1,13 ⇒ U_{rw} = 973 kV;
– internal insulation:
  - phase-to-earth ⇒ U_{rw} = 451 × 1,15 ⇒ U_{rw} = 518 kV;
  - phase-to-phase ⇒ U_{rw} = 820 × 1,15 ⇒ U_{rw} = 943 kV.

The required withstand voltages for slow-front surges are converted into short-duration power-frequency and lightning impulse withstand voltages (refer to part 1 for detailed information).

Conversion to short-duration power-frequency withstand voltage (SDWV):

– external insulation:
  - phase-to-earth ⇒ SDWV = 531 × (0,6 + 531 / 8 500) = 352 kV;
  - phase-to-phase ⇒ SDWV = 973 × (0,6 + 973 / 12 700) = 658 kV;

– internal insulation:
  - phase-to-earth ⇒ SDWV = 518 × 0,5 = 259 kV;
  - phase-to-phase ⇒ SDWV = 943 × 0,5 = 472 kV.

Conversion to lightning impulse withstand voltage (LIWV):

– external insulation:
  - phase-to-earth ⇒ LIWV = 531 × 1,30 = 690 kV;
  - phase-to-phase ⇒ LIWV = 973 × (1,05 + 973 / 9 000) = 1 127 kV;

– internal insulation:
  - phase-to-earth ⇒ LIWV = 518 × 1,10 = 570 kV;
  - phase-to-phase ⇒ LIWV = 943 × 1,10 = 1 037 kV.

Table G.2 reflects the minimum withstand (or test) values required to take into account the different overvoltage stresses related to part 2 of the example exposed in Clause G.2.

Table G.2 – Summary of required withstand voltages obtained for the example shown in G.2.3

Values of U_{rw} kV		**External insulation**				Internal insulation	
		Line entrance equipment		Other equipment			
		$U_{rw(s)}$	$U_{rw(c)}$	$U_{rw(s)}$	$U_{rw(c)}$	$U_{rw(s)}$	$U_{rw(c)}$
Short-duration power-frequency (RMS)	phase-earth	**237**	352	**237**	352	**243**	259
	phase-phase	**383**	658	**383**	658	**395**	472
Switching impulse (peak)	phase-earth	531	–	531	–	518	–
	phase-phase	973	–	973	–	943	–
Lightning impulse (peak)	phase-earth	**884**	690	**884**	690	**715**	570
	phase-phase	884	**1127**	884	**1127**	715	**1037**

Minimum values required for the short-duration power-frequency and lightning impulse withstand tests are shown in bold characters.

NOTE The figures are obtained from part 2, with capacitor switching at remote station (station 2).

A comparison between Table G.2 and Table G.1 shows the impact of slow-front overvoltages due to capacitor switching at station 2, mainly on phase-to-phase switching impulse requirements and on the resulting equivalent minimum testing values.

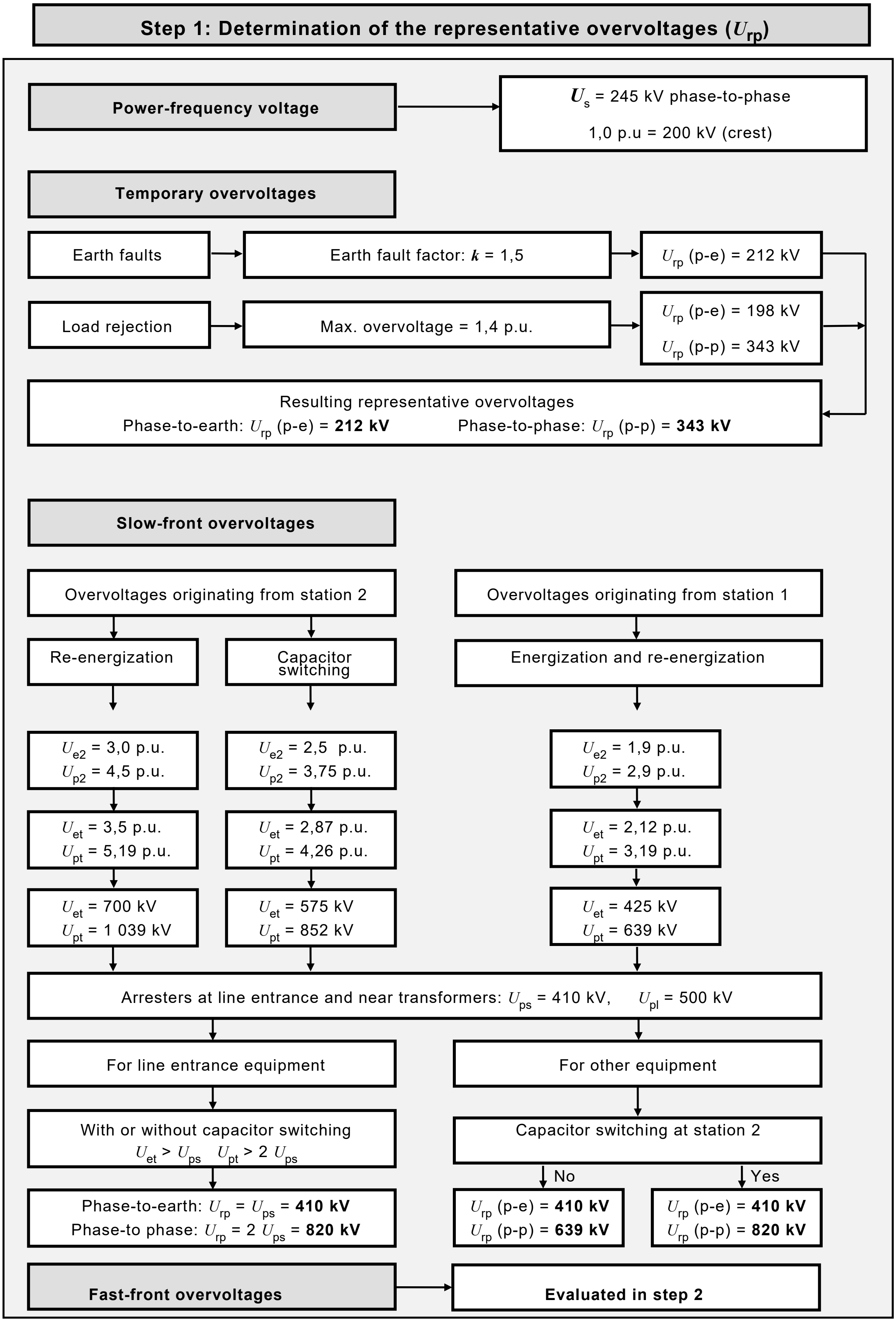
For external insulation, including longitudinal insulation, the same standard insulation level defined in part 1 (395 kV/950 kV) is also applicable here, no phase-to-phase test being required if a 2,35 m phase-to-phase clearance (corresponding to a standard lightning impulse withstand voltage of 1 175 kV) is adopted for all external equipment (not only at line entrance as for part 1).

For internal insulation, a standard insulation level applicable phase-to-phase and phase-to-earth of 460 kV/1 050 kV, corresponding to U_m = 245 kV, can be chosen (refer to Table 2 of IEC 60071-1:2019). This corresponds to one standard insulation level higher than in part 1 of this example, and is due to the switching of a capacitor at the remote station. Lower, phase-to-earth insulation levels, as discussed in part 1, could be retained but, in any case, a special phase-to-phase test at 1 050 kV would be required.

G.2.4 Part 3: flow charts related to the example of Clause G.2

The following flow charts summarize the insulation co-ordination procedure and the results obtained along the different steps. The flow charts include results obtained without (part 1) or with (part 2) capacitor switching at station 2.

It should be noted that this example does not consider any means of mitigation to reduce the severe slow-front overvoltage surges from capacitor switching. As mentioned in 5.3.3.7, such measures could be considered, such as the use of closing resistors at the remote station to obtain a substantial reduction of slow-front stresses with a consequent reduction of withstand levels to be selected. This implies the necessity for additional system studies taking into account the presence of the means of mitigation and, on the basis of the new representative stresses found, to restart the insulation co-ordination procedure. For the particular example discussed here, this would lead to a reduction of some of the requirements obtained (inscribed under the flow chart of step 5 below), such as the phase-to-phase lightning impulse withstand voltage for internal insulation and the phase-to-phase clearance for external insulation.


Step 1: Determination of the representative overvoltages (U_{rp})
Power-frequency voltage
U_s = 245 kV phase-to-phase
1,0 p.u = 200 kV (crest)
Temporary overvoltages
Earth faults
Earth fault factor: k = 1,5
U_{rp} (p-e) = 212 kV
Load rejection
Max. overvoltage = 1,4 p.u.
U_{rp} (p-e) = 198 kV
U_{rp} (p-p) = 343 kV
Resulting representative overvoltages
Phase-to-earth: U_{rp} (p-e) = **212 kV**
Phase-to-phase: U_{rp} (p-p) = **343 kV**
Slow-front overvoltages
Overvoltages originating from station 2
Overvoltages originating from station 1
Re-energization
Capacitor switching
Energization and re-energization
U_{e2} = 3,0 p.u.
U_{p2} = 4,5 p.u.
U_{e2} = 2,5 p.u.
U_{p2} = 3,75 p.u.
U_{e2} = 1,9 p.u.
U_{p2} = 2,9 p.u.
U_{et} = 3,5 p.u.
U_{pt} = 5,19 p.u.
U_{et} = 2,87 p.u.
U_{pt} = 4,26 p.u.
U_{et} = 2,12 p.u.
U_{pt} = 3,19 p.u.
U_{et} = 700 kV
U_{pt} = 1 039 kV
U_{et} = 575 kV
U_{pt} = 852 kV
U_{et} = 425 kV
U_{pt} = 639 kV
Arresters at line entrance and near transformers: U_{ps} = 410 kV, U_{pl} = 500 kV
For line entrance equipment
For other equipment
With or without capacitor switching
$U_{et} > U_{ps}$ $U_{pt} > 2\ U_{ps}$
Capacitor switching at station 2
No
Yes
Phase-to-earth: $U_{rp} = U_{ps}$ = **410 kV**
Phase-to phase: $U_{rp} = 2\ U_{ps}$ = **820 kV**
U_{rp} (p-e) = **410 kV**
U_{rp} (p-p) = **639 kV**
U_{rp} (p-e) = **410 kV**
U_{rp} (p-p) = **820 kV**
Fast-front overvoltages
Evaluated in step 2

Step 2: Determination of the co-ordination withstand voltages (U_{cw})

Temporary overvoltages → K_c factor = 1,0

Phase-to-earth: $U_{cw} = K_c \times U_{rp}$ = 1,0 × 212 = 212 kV
Phase-to-phase: $U_{cw} = K_c \times U_{rp}$ = 1,0 × 343 = 343 kV

Slow-front overvoltages → Deterministic method used = K_{cd} factor

Line entrance equipment (external insulation only)		Other equipment	
Phase-to-earth	**Phase-to-phase**	**Phase-to-earth**	**Phase-to-phase**
a) U_{ps}/U_{e2} = 0,68 b) U_{ps}/U_{e2} = 0,82	a) 2 U_{ps}/U_{e2} = 0,91 b) 2 U_{ps}/U_{e2} = 1,09	1) U_{ps}/U_{e2} = 0,82 2) U_{ps}/U_{e2} = 1,08	1) U_{ps}/U_{e2} = 1,09 2) U_{ps}/U_{e2} = 1,41
a) K_{cd} = 1,10 b) K_{cd} = 1,08	a) K_{cd} = 1,00 b) K_{cd} = 1,00	1) K_{cd} = 1,08 2) K_{cd} = 1,03	1) K_{cd} = 1,00 2) K_{cd} = 1,00
Retained value: K_{cd} = 1,10		Retained values: 1) K_{cd} = 1,10 2) K_{cd} = 1,03	
$U_{cw} = K_{cd} \times U_{rp}$ U_{cw} = **451 kV**	$U_{cw} = K_{cd} \times U_{rp}$ U_{cw} = **820 kV**	1) U_{cw} = **451 kV** 2) U_{cw} = **422 kV**	1) U_{cw} = **820 kV** 2) U_{cw} = **639 kV**

a) From re-energization at station 2.
b) From capacitor switching at station 2.

1) With capacitor switching at station 2.
2) Without capacitor switching at station 2.

Fast-front overvoltages → Simplified statistical method used

Data from experience
Performance required

→

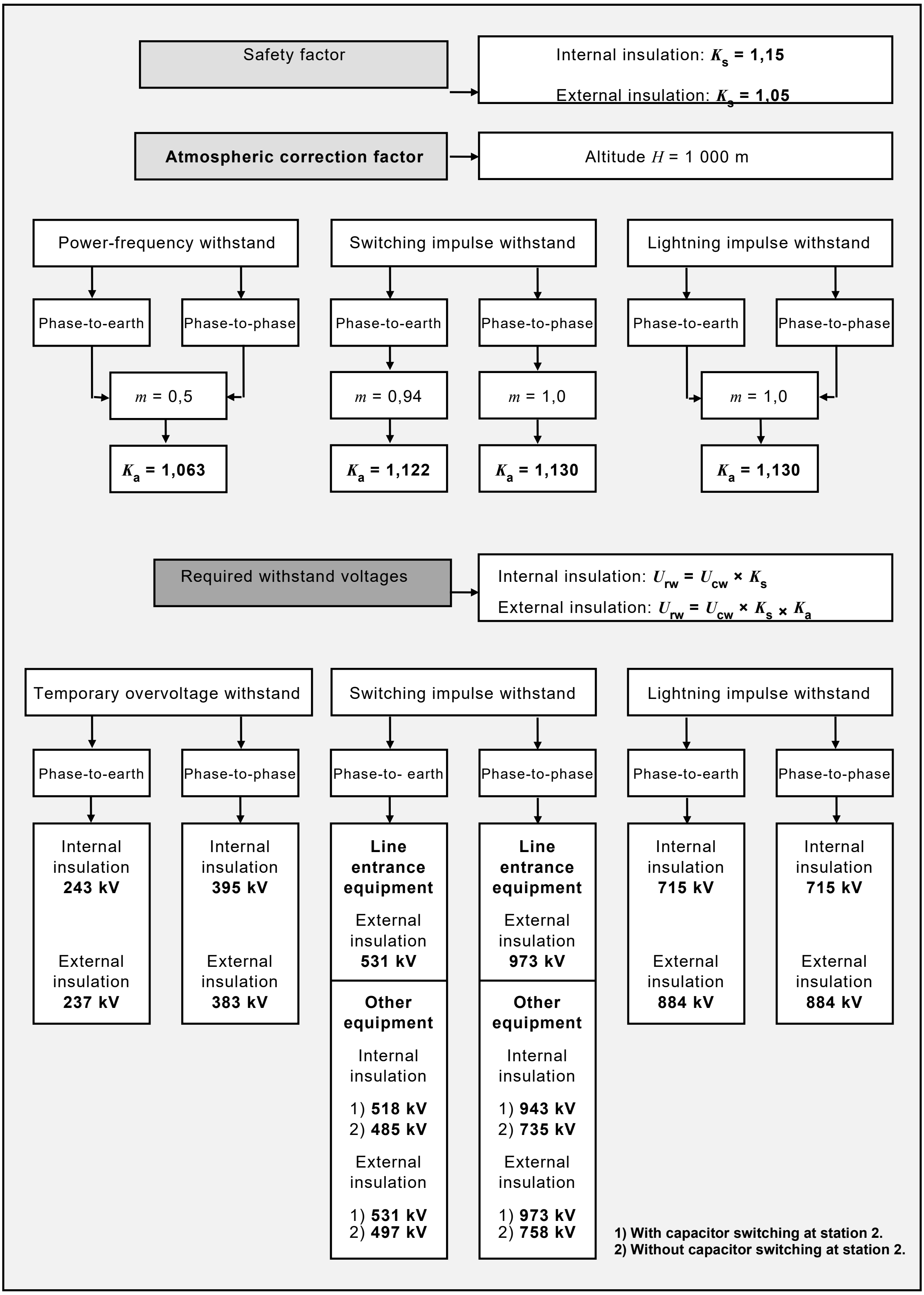
Parameter « A »:	A = 4 500
Span length:	L_{sp} = 300 m
Outage rate:	1/100 km·year
Acceptable failure rate:	1/400 years

→ L_a = 250 m

Arrester lightning protection level: U_{pl} = 500 kV
Max. separation from internal insulation: L = 30 m
Max. separation from external insulation: L = 60 m

Internal insulation:	U_{cw} = **622 kV**
External insulation:	U_{cw} = **745 kV**

Step 3: Determination of the required withstand voltages (U_{rw})



Step 4: Conversion to withstand voltages normalized for range I

Conversion of switching impulse withstand voltages to short-duration power-frequency withstand voltages

Conversion factors

External insulation:
- phase-to-earth: $0,6 + U_{rw}/8500$
- phase-to-phase: $0,6 + U_{rw}/12\,700$

Internal insulation:
- phase-to-earth: 0,5
- phase-to-phase: 0,5

Line entrance equipment

External insulation
- phase-to-earth: **352 kV**
- phase-to-phase: **658 kV**

Other equipment

External insulation
- phase-to-earth: 1) **352 kV**; 2) **327 kV**
- phase-to-phase: 1) **658 kV**; 2) **500 kV**

Internal insulation
- phase-to-earth: 1) **259 kV**; 2) **243 kV**
- phase-to-phase: 1) **472 kV**; 2) **367 kV**

Conversion of switching impulse withstand voltages to lightning impulse withstand voltages

Conversion factors

External insulation:
- phase-to-earth: 1,3
- phase-to-phase: $1,05 + U_{rw}/9000$

Internal insulation:
- phase-to-earth: 1,1
- phase-to-phase: 1,1

Line entrance equipment

External insulation
- phase-to-earth: **690kV**
- phase-to-phase: **1 127 kV**

Other equipment

External insulation
- phase-to-earth: 1) **690 kV**; 2) **646 kV**
- phase-to-phase: 1) **1 127 kV**; 2) **860 kV**

Internal insulation
- phase-to-earth: 1) **570 kV**; 2) **534 kV**
- phase-to-phase: 1) **1 037 kV**; 2) **808 kV**

1) With capacitor switching at station 2.
2) Without capacitor switching at station 2.

Step 5: Selection of standard withstand voltage values

	Without capacitor switching at remote station. Refer to explanations related with Table G.1	**With** capacitor switching at remote station. Refer to explanations related with Table G.2
Standard insulation level:	395 kV/950 kV Applicable to any insulation	395 kV/950 kV External insulation 460 kV/1 050 kV Internal insulation
External insulation No phase-to-phase test required if clearances are:		
- for line entrance equipment:	2,35 m	2,35 m
- for other equipment:	1,90 m	2,35 m
Internal insulation Minimum standard lightning impulse level:		
- phase-to-earth:	750 kV	750 kV
- phase-to-phase:	850 kV	1 050 kV

G.3 Numerical example for a system in range II (with nominal voltage of 735 kV)

G.3.1 General

For the purpose of this example, one will assume the following basic data:

- the highest system voltage is: U_s = 765 kV;
- the pollution level is low to medium (refer to 6.3.2.2);
- the altitude is: H = 1 000 m.

The altitude level is here assumed so as to cover all possible locations. The pollution level is assumed sufficiently mild that the standard insulation levels (and clearances) can be determined by the voltage stresses (usually the slow-front overvoltages for systems in range II).

Considerations of tower design such as conductor size and phase-to-phase spacing do not fall into the category of insulation co-ordination procedure. Only the phase-to-earth clearance results from the insulation co-ordination procedure since it depends on the slow-front overvoltages (in range II). Lightning considerations may dictate the type of overhead ground wires and counterpoise wires but this is generally the result of a separate study based on keraunic levels. Thus the transmission line design is not usually specified in terms of standard insulation levels but rather in terms of tower dimensions.

G.3.2 Step 1: determination of the representative overvoltages – values of U_{rp}

G.3.2.1 General

The representative temporary and slow-front overvoltages are usually determined from system studies (transient network analyser or digital simulation or a combination of both). For this example, results from such studies confirmed the following values:

- temporary overvoltages: U_{rp} = 660 kV (RMS, phase-to-earth);
- slow-front overvoltages: U_{e2} = 1 200 kV (peak, phase-to-earth; phase-peak method).

G.3.2.2 Power-frequency and temporary overvoltages

The high level of temporary overvoltage (1,5 p.u.) is associated with situations involving long lines radially fed after a major load rejection. For systems in range II, the two standard withstand voltages normally specified are the lightning and the switching impulse levels. The conversion of the required short-duration power-frequency withstand voltage into an equivalent required switching impulse withstand voltage is discussed under step 4 (G.3.5) of this example.

G.3.2.3 Slow-front overvoltages

The slow-front overvoltage is related to line reclosing and is limited to about 2,0 p.u. by the use of closing resistors implemented on line circuit breakers.

The surge arrester rating is also determined from these same system studies (normally from the temporary overvoltage characteristics: amplitude and duration) and, for the particular case of this example, the following protection levels were determined:

- switching impulse protection level: U_{ps} = 1 300 kV (peak value);
- lightning impulse protection level: U_{pl} = 1 500 kV (peak value).

G.3.2.4 Fast-front overvoltages

The simplified statistical method for fast-front overvoltages will be used, leading directly to the co-ordination withstand voltage.

In this step and those that follow, only the phase-to-earth insulation is considered. Phase-to-phase insulation co-ordination will be treated at the end of the example as a separate item (see G.3.7).

G.3.3 Step 2: determination of the co-ordination withstand voltages – values of U_{cw}

G.3.3.1 General

The co-ordination withstand voltage is obtained by applying a co-ordination factor (K_c) to the representative overvoltages, this factor being either K_{cd} for the deterministic method or K_{cs} for the statistical method. Thus the determination of the co-ordination withstand voltages should be carried out for internal insulation (such as transformers) and external insulation separately.

G.3.3.2 U_{cw} for internal insulation

G.3.3.2.1 General

In this step, the determination of U_{cw} for internal insulation is carried out for power-frequency, slow-front and fast-front overvoltages.

G.3.3.2.2 U_{cw} for temporary overvoltages

For this class of overvoltages, the co-ordination withstand voltage is equal to the representative temporary overvoltage (refer to 6.3.2). In other words, the co-ordination factor K_c = 1. Therefore:

– phase-to-earth: U_{cw} = 660 kV.

G.3.3.2.3 U_{cw} for slow-front overvoltages

For equipment protected by surge arresters, the maximum slow-front overvoltage (and thus the slow-front representative overvoltage) is equal to the switching-impulse protection level of the surge arrester, namely 1 300 kV.

This value of 1 300 kV should be adjusted by the co-ordination factor K_{cd} to account for the skewing of the statistical distribution of the slow-front overvoltages as discussed in 6.3.3.1. It can be seen from Figure 5 that for a ratio of U_{ps} / U_{e2} = 1,08 (1 300 / 1 200) the value of K_{cd} is 1,03. Hence, the co-cordination withstand voltage for slow-front surges is 1 340 kV:

– representative slow-front overvoltage: U_{rp} = 1 300 kV;

– deterministic co-ordination factor: K_{cd} = 1,03;

– co-ordination withstand voltage: U_{cw} = 1 340 kV.

G.3.3.2.4 U_{cw} for fast-front overvoltages

For equipment protected by surge arresters, the maximum fast-front overvoltage (and thus the fast-front representative overvoltage) is equal to the lightning-impulse protection level of the surge arrester, namely 1 500 kV.

However, to this value of 1 500 kV, one should add a voltage equal to $AL/(n\ (L_{sp} + L_a))$ according to Equation (E.19) to take into account the separation distance L between the surge arrester and the protected equipment, as explained in 5.3.4.5.

The parameters are obtained as follows:

– A: from Table E.2 (for an assumed four conductor bundle) is 11 000;

– n: the minimum number of connected overhead lines is assumed equal to two for this example;
– L: is equal to $a_1 + a_2 + a_3 + a_4$ according to Figure 3; is assumed equal to 40 m for this example;
– L_{sp}: length of the first line span is assumed equal to 400 m for this example;
– L_a: length of overhead line section with flashover rate equal to the acceptable failure rate. If the acceptable failure rate is assumed to be 1/(500 year) or 0,002/year and the line lightning flashover rate is 0,15/(100 km·year), then L_a is 1,3 km.

Then, the separation term $AL/(n(L_{sp} + L_a))$ is 130 kV.

– Representative fast-front overvoltage: U_{rp} = 1 500 kV.
– Correction value for separation: 130 kV.
– Co-ordination withstand voltage: U_{cw} = 1 630 kV.

G.3.3.3 U_{cw} for external insulation

G.3.3.3.1 General

Determination of the co-ordination withstand voltage for external insulation is carried out for slow-front overvoltages using the statistical method because of the nature of the insulation. A statistical method could also be applied to fast-front overvoltages but this is generally not necessary for voltages in range II; refer to G.3.3.3.3 below.

G.3.3.3.2 U_{cw} for temporary overvoltages

These are the same as for the internal insulation (G.3.3.2.2).

G.3.3.3.3 U_{cw} for slow-front overvoltages

The value of the statistical co-ordination factor K_{cs} comes from choosing a risk of failure of the insulation that has been proven from experience to be acceptable. The relation between the risk of failure R and K_{cs} is shown in Figure 9 and, for a usually acceptable value of R in the range of 10^{-4}, the value of K_{cs} is 1,15. Hence the co-ordination withstand voltage is U_{cw} = 1 200 kV × 1,15 = 1 380 kV:

– statistical overvoltage: U_{e2} = 1 200 kV;
– statistical co-ordination factor: K_{cs} = 1,15;
– co-ordination withstand voltage: U_{cw} = 1 380 kV.

G.3.3.3.4 U_{cw} for fast-front overvoltages

The determination of the co-ordination withstand voltage for fast-front overvoltage is not necessary since the lightning impulse withstand voltage of the minimum clearances that result from the switching impulse withstand voltage will be far in excess of those that should be determined solely by the lightning impulse withstand voltage required for the non-self-restoring insulation.

G.3.4 Step 3: determination of the required withstand voltages – values of U_{rw}

G.3.4.1 General

The required withstand voltage is obtained by applying a safety factor K_s to the co-ordination withstand voltage as explained in 7.3.5. The values of K_s are given as:

– for internal insulation: K_s = 1,15;

– for external insulation: K_s = 1,05.

For external insulation, an atmospheric correction factor K_a is also applied (refer to G.3.4.3 below).

G.3.4.2 U_{rw} for internal insulation

The values of U_{rw} for internal insulation are as follows:

– U_{cw} for temporary overvoltages: U_{cw} = 660 kV;
– safety factor: K_s = 1,15;
– U_{rw} for temporary overvoltages: U_{rw} = 759 kV;
– U_{cw} for slow-front overvoltages: U_{cw} = 1 340 kV;
– safety factor: K_s = 1,15;
– U_{rw} for slow-front overvoltages: U_{rw} = 1 540 kV;
– U_{cw} for fast-front overvoltages: U_{cw} = 1 630 kV;
– safety factor: K_s = 1,15;
– U_{rw} for fast-front overvoltages: U_{rw} = 1 875 kV.

G.3.4.3 U_{rw} for external insulation

For power-frequency, the atmospheric correction factor is determined assuming a short-duration power-frequency test on polluted insulators is required, for which m = 0,5 and assuming H = 1 000 m, K_a = 1,063.

Hence, U_{rw} = 660 × 1,063 × 1,05 = 737 kV:

– U_{cw} for temporary overvoltages: U_{cw} = 660 kV;
– atmospheric correction factor: K_a = 1,063;
– safety factor: K_s = 1,05;
– U_{rw} for temporary overvoltage: U_{rw} = 737 kV.

The atmospheric correction factor K_a for slow-front overvoltages is based on the assumed altitude as explained in 7.2.2 and Equation (11). For H = 1 000 m and m = 0,6 (from Figure 10), then $K_a = e^{0,07}$ = 1,07. Hence U_{rw} = 1 380 kV × 1,07 × 1,05 = 1 550 kV:

– U_{cw} for slow-front overvoltages: U_{cw} = 1 380 kV;
– atmospheric correction factor: K_a = 1,07;
– safety factor: K_s = 1,05;
– U_{rw} for slow-front overvoltages: U_{rw} = 1 550 kV.

G.3.5 Step 4: conversion to switching impulse withstand voltages (SIWV)

Referring to Clause 8, the required short-duration power-frequency withstand voltages are converted to an equivalent switching impulse withstand voltage (SIWV), according to Table 2.

– For internal insulation: SIWV = 759 × 2,3 = 1 746 kV.
– For external insulation: SIWV = 737 × 1,7 = 1 253 kV.

G.3.6 Step 5: selection of standard insulation levels

G.3.6.1 General

The standard withstand voltages U_w are obtained from the required withstand voltages by choosing the next highest value from the standard values listed in IEC 60071-1.

G.3.6.2 U_w for internal insulation

For the temporary overvoltage stresses, a switching withstand voltage of 1 750 kV would be required according to step 4. Considering this last requirement, many options are available. At first, a value of 1 750 kV is not standardized in IEC 60071-1, the highest one being 1 550 kV, so that a switching test at such a value would be considered as a special one. Another option is to realize an alternative test, as mentioned in 5.4 of IEC 60071-1:2019, to verify the withstand of internal insulation to power-frequency. For this example, an applied voltage test at a minimum value of 660 kV (1,5 p.u.) for a minimum duration of 1 min is required. It is recommended to refer to standards issued by the relevant apparatus committee (as for power transformers) which give more detailed information relative to such a test. For instance, to avoid saturation, such a test is performed with a source whose frequency is three or four times the nominal frequency. Also, fixed values are recommended for voltages and durations associated with the different cycles involved in such a test (such as 1,7 p.u. during 7 200 periods followed by 1,5 p.u. for 1 h).

- U_{rw} for slow-front overvoltages: U_{rw} = 1 540 kV.
- Standard switching-impulse withstand voltage: U_w = 1 550 kV.
- U_{rw} for fast-front overvoltages: U_{rw} = 1 875 kV.
- Standard lightning impulse withstand voltage: U_w = 1 950 kV.

G.3.6.3 U_w for external insulation

The lightning impulse withstand voltage of 1 950 kV would apply to the external insulation of equipment protected by arresters, such as transformers and shunt reactors.

In the case of equipment remotely located from the surge arresters such as current transformers, circuit-breakers, disconnectors and busbar, the separation distance (see 5.3.4.5) has a greater impact and for this example it is decided to choose one step higher in the lightning impulse withstand voltage. Hence, for this equipment the standard lightning-impulse withstand voltage is U_w = 2 100 kV.

- U_{rw} for slow-front overvoltages: U_{rw} = 1 550 kV.
- Standard switching impulse withstand voltage: U_w = 1 550 kV.
- Standard lightning impulse withstand voltage (protected equipment): U_w = 1 950 kV.
- Standard lightning impulse withstand voltage (unprotected equipment): U_w = 2 100 kV.

The standard switching impulse withstand voltage of 1 550 kV is more than sufficient to cover the required switching impulse withstand voltage of 1 253 kV converted from the power-frequency requirements (external insulation).

G.3.7 Considerations relative to phase-to-phase insulation co-ordination

The phase-to-phase dielectric strength of the external insulation of three-phase equipment is usually tested with equal impulses of positive and negative polarity. The actual test values are determined from a consideration of the positive and negative slow-front overvoltages (which are the most critical) as explained in Clause C.4. Based on this G.3.7, the assumption is made that B = 0,6 from which F_1 = 0,463 and F_2 = 0,074. In this example, the value of B (B = tan ϕ) comes from Figure C.6 which gives an inclination angle $\phi \cong 30°$ for the considered three-phase equipment (height above earth ≅ 16 m and phase-to-phase distance ≅ 8 m). The required test voltages are obtained as follows:

– phase-to-earth slow-front overvoltage: U_{e2} = 1 200 kV;
– phase-to-phase slow-front overvoltage: U_{p2} = 2 040 kV.

The phase-to-earth slow-front overvoltage was determined in G.3.2. The phase-to-phase slow-front overvoltage is found from Figure 2: at U_{e2} = 1,92 p.u., the ratio of U_{p2}/U_{e2} is 1,7 which gives U_{p2} = 2 040 kV. Equation (C.18) gives the phase-to-phase representative overvoltage:

$$U_{p2\text{-re}} = 2\ (F_1\ U_{p2} + F_2\ U_{e2}) = 2\ 067\ \text{kV}.$$

The co-ordination phase-to-phase withstand voltage is obtained applying a co-ordination factor K_{cs} = 1,15:

$$U_{p\text{-cw}} = K_{cs}\ U_{p2\text{-re}} = 2\ 377\ \text{kV}.$$

The required phase-to-phase withstand voltage is based on an altitude correction factor K_a = 1,07 and a safety factor K_s = 1,05 (the same procedure as for phase-to-earth insulation, see G.3.4):

$$U_{p\text{-rw}} = K_a\ K_s\ U_{p\text{-cw}} = 2\ 670\ \text{kV}.$$

Test values are thus specified as ±1 335 kV but, as these are not standard values, the test itself is not a standard test since there is very little three-phase equipment at the 735 kV level.

For the temporary overvoltage, we have a representative overvoltage of 660 kV phase-to-earth from step 1 yielding a phase-to-phase voltage of 1 143 kV. This results in the same value for the co-ordination withstand voltage since K_c = 1,0 as in step 2. Applying the safety factors and atmospheric correction factors, we obtain the required withstand voltages:

– internal insulation: U_{rw} = 1 143 × 1,15 = 1 314 kV;
– external insulation: U_{rw} = 1 143 × 1,063 × 1,05 = 1 276 kV.

These are converted into phase-to-phase switching impulse withstand voltages (SIWV):

– internal insulation: SIWV = 1 314 × 2,3 = 3 022 kV;
– external insulation: SIWV = 1 276 × 1,7 = 2 169 kV.

The previously determined switching impulse test voltage of 2 670 kV is adequate to cover the external insulation power-frequency requirement but not the internal insulation. Special measures as described in G.3.6.2 would be required.

G.3.8 Phase-to-earth clearances

The required phase-to-earth clearance for switching impulses can be obtained from IEC 60071-1 and a standard switching impulse withstand voltage of 1 550 kV.

For the conductor-structure configuration (slow-front gap factor K = 1,35), the minimum clearance is 4 900 mm. For the rod-structure configuration (slow-front gap factor K < 1,15), the minimum clearance is 6 400 mm. The lightning impulse withstand voltage of such clearances can be estimated from the equations given in Annex F. Using Equation (F.7) to obtain the equivalent fast-front gap factors, we obtain:

– conductor-structure: K_{ff}^{+} = 0,74 + 0,26 × 1,35 = 1,05;

– rod-structure: K_{ff}^{+} = 0,74 + 0,26 × 1,15 = 1,04.

Using K_{ff}^{+} = 1,04 to be conservative, we obtain from Equations (F.6) and (F.7):

– U_{50RP} = K_{ff}^{+} 530 d = 1,04 × 530 × 4,9 = 2 700 kV; and

– LIWV = U_{50RP} – 1,3 Z = U_{50RP} (1 – 1,3 z) = 2 700 (1 – 1,3 × 0,03) = 2 595 kV,

which is well above the standard lightning impulse withstand voltage of 2 100 kV from G.3.6.3.

G.3.9 Phase-to-phase clearances

The required phase-to-phase clearance can be obtained from Equation (C.16) which states that $U_0^+ = U^+ + BU^-$ where U_0^+ is an equivalent phase-to-earth voltage that represents the effect of a positive voltage on one phase (U^+) and a negative voltage on the other phase (U^-). From the work carried out in G.3.7, with the values of $U^+ = U^-$ = 1 335 kV and with B = 0,6, one can find U_0^+ as:

$$U_0^+ = 1\,335 \times 1{,}6 = 2\,136 \text{ kV}$$

The corresponding value of U_{50} is given by $U_{50} = U_{10}$ / 0,922 = 2 317 kV; d is obtained from Equations (F.3) and (F.5), and for gap factors K = 1,62 (parallel conductor configuration) and K = 1,45 (rod-conductor configuration):

$$2\,317 = K\ 1\,080 \ln (0{,}46\ d + 1)$$

from which phase-to-phase clearances are:

– conductor-conductor: d = 6,0 m;

– rod-conductor: d = 7,4 m.

From IEC 60071-1, a standard phase-to-earth switching impulse withstand voltage of 1 550 kV leads to standard phase-to-phase minimum clearances of 7,6 m (conductor-conductor) and 9,4 m (rod-conductor). Therefore, use of the above-calculated clearances would require a special test.

G.4 Numerical example for substations in distribution systems with U_m up to 36 kV in range I

G.4.1 General

For equipment in this voltage range, IEC 60071-1 specifies standard rated short-duration power-frequency and lightning impulse withstand voltages. The selection of these values is illustrated in Table G.3 for U_m = 24 kV, where the values are examples and not valid for general application.

For the purpose of this example, one will assume the following basic data:

– the highest system voltage is: U_s = 24 kV;

– the pollution level is: light;

– the altitude is: H = 1 000 m.

The altitude level here is assumed to cover all possible locations.

G.4.2 Step 1: determination of the representative overvoltages – values of U_{rp}

G.4.2.1 Power-frequency and temporary overvoltages

Owing to the neutral earthing practice, the highest overvoltages phase-to-earth originate from earth faults. Values up to the highest system voltage are frequent. In this example, the representative temporary overvoltage is the assumed maximum value equal to the highest system voltage 24 kV.

Overvoltages phase-to-phase originate from load rejections. A full load rejection in the distribution system itself does not cause substantial high overvoltages. However, a load rejection in the transmission system, to which the distribution system is connected, may have to be considered. In this example it is assumed that the load rejection temporary overvoltage reaches 1,15 times the highest system voltage, which is 1,15 × U_s = 27,6 kV or approximately 28 kV. This value is assumed to be the highest possible voltage stress and thus is the representative temporary phase-to-phase overvoltage: U_{rp} = 28 kV.

G.4.2.2 Slow-front overvoltages

Slow-front overvoltages may originate from earth faults or line energization or re-energization. As distribution transformers usually remain connected during a re-energization of lines, and as the reclosing is not fast, the presence of trapped charges is improbable. The re-energization overvoltages, therefore, have the same probability distribution as those due to energization. The 2 % values in Table G.3 are selected according to Annex C for the phase-peak method taking into account the usual operation conditions, no closing resistors, complex feeding network and no parallel compensation. The 2 % values are assumed to be U_{e2} = 2,6 p.u. (phase-to-earth) and U_{p2} = 3,86 p.u (phase-to-phase).

As the deterministic insulation co-ordination procedure is sufficient for distribution systems and as surge arresters do not usually limit slow-front overvoltages in this voltage range, the representative slow-front overvoltages U_{rp} are considered to correspond to the truncation values U_{et} and U_{pt} of the overvoltage probability distributions. With the equations of Annex C, the truncation values are obtained: U_{et} = 3,0 p.u. which leads to U_{rp} = 59 kV phase-to-earth and u_{pt} = 4,4 p.u. which leads to U_{pt} = 86 kV phase-to-phase.

G.4.2.3 Fast-front overvoltages

With the exception of motor switching by some type of circuit-breakers, fast-front overvoltages due to switching operations can be neglected.

Fast-front lightning overvoltages are transmitted on the lines connected to the substation. The simplified method described in Clause E.4 is applied to estimate the return periods of the representative lightning overvoltage amplitudes. No reference value is specified and, therefore, no value can be given in Table G.3.

G.4.3 Step 2: determination of the co-ordination withstand voltages – values of U_{cw}

G.4.3.1 Temporary overvoltages

As the previously defined representative temporary overvoltages correspond to the maximum assumed voltage stresses, the deterministic insulation co-ordination procedure is applicable (see 5.3). The deterministic co-ordination factor is K_c = 1 and the resulting co-ordination power-frequency withstand voltages U_{cw} correspond to the representative overvoltage values U_{rp} ($U_{cw} = K_c \quad U_{rp} = U_{rp}$).

G.4.3.2 Slow-front overvoltages

The co-ordination withstand voltages U_{cw} are obtained as: $U_{cw} = K_{cd}\ U_{rp}$. The deterministic co-ordination factor is $K_{cd} = 1$ because the insulation co-ordination procedure is applied to the truncation values of the overvoltage distributions (no skewing effect as discussed in 6.3.3.1). Therefore, in this example, values of the co-ordination withstand voltages are the same as those for representative slow-front overvoltages: U_{cw} = 59 kV phase-to-earth and U_{cw} = 86 kV phase-to-phase.

G.4.3.3 Fast-front overvoltages

For the determination of the co-ordination lightning impulse withstand voltages, the following values are assumed:

– the arrester lightning impulse protection level is U_{pl} = 80 kV;

– four wood-pole lines (n = 4) are connected to the station. Referring to Table E.2, the corresponding value for the factor A is 2 700;

– the observed overhead line outage rate is R_{km} = 6/(100 km·year) or, in the recommended units, $R_{km} = 6 \times 10^{-5}$/(m·year);

– the span length is L_{sp} = 100 m;

– the acceptable failure rate is R_a = 1/400 year.

As it is common practice to install arresters close to the power transformers, the separation distance may be different for internal insulation (example: 3 m) and external insulation (example: 5 m). Therefore, the co-ordination withstand voltages values U_{cw} may be different for different equipment.

With these values, the overhead line section, in which the outage rate will be equal to the acceptable failure rate, will be in accordance with Equation (E.18):

$$L_a = 42 \text{ m}$$

This means that protection is required for lightning strokes to the first span of the overhead line.

The co-ordination lightning impulse withstand voltages are obtained according to Equation (E.19) as U_{cw} = 94 kV for internal insulation (power transformer, distance to the arrester = 3 m) and U_{cw} = 104 kV for the more distant external insulation.

G.4.4 Step 3: determination of required withstand voltages – values of U_{rw}

G.4.4.1 General

The required withstand voltages are obtained by applying the recommended safety factors (see 7.3.5) and the altitude correction (see 7.2.2). For the example given, it is assumed that substations of the same design shall be used up to altitudes of 1 000 m.

G.4.4.2 Safety factors

The recommended safety factors from 7.3.5 are:

– for internal insulation: K_s = 1,15;

– for external insulation: K_s = 1,05.

G.4.4.3 Altitude correction factor

The altitude correction factor is defined in 7.2.2. It is applicable to the external insulation only and its value depends on the overvoltage shape (parameter m in Equation (11)).

- For power-frequency (clean insulators), m = 1,0.
- For slow-front overvoltages, the value of m depends on the value of U_{cw}. For values of U_{cw} less than 300 kV phase-to-earth or 1 200 kV phase-to-phase, m = 1,0.
- For lightning impulse withstand, m = 1,0 and K_a = 1,13.

G.4.4.4 Temporary overvoltage

The temporary overvoltage values are as follows:

- Phase-to-earth:
  - internal insulation ⇒ $U_{rw} = U_{cw}$ × 1,15 = 24 × 1,15 = 28 kV;
  - external insulation ⇒ $U_{rw} = U_{cw}$ × 1,05 × 1,13 = 24 × 1,05 × 1,13 = 28 kV.
- Phase-to-phase:
  - internal insulation ⇒ $U_{rw} = U_{cw}$ × 1,15 = 28 × 1,15 = 32 kV;
  - external insulation ⇒ $U_{rw} = U_{cw}$ × 1,05 × 1,13 = 28 × 1,05 × 1,13 = 33 kV.

G.4.4.5 Slow-front overvoltage

The slow-front overvoltage values are as follows:

- Phase-to-earth:
  - internal insulation ⇒ $U_{rw} = U_{cw}$ × 1,15 = 59 × 1,15 = 68 kV;
  - external insulation ⇒ $U_{rw} = U_{cw}$ × 1,05 × 1,13 = 59 × 1,05 × 1,13 = 70 kV.
- Phase-to-phase:
  - internal insulation ⇒ $U_{rw} = U_{cw}$ × 1,15 = 86 × 1,15 = 99 kV;
  - external insulation ⇒ $U_{rw} = U_{cw}$ × 1,05 × 1,13 = 86 × 1,05 × 1,13 = 102 kV.

G.4.4.6 Fast-front overvoltage

The fast-front overvoltage values are as follows:

- internal insulation: ⇒ $U_{rw} = U_{cw}$ × 1,15 = 95 × 1,15 = 109 kV;
- external insulation: ⇒ $U_{rw} = U_{cw}$ × 1,05 × 1,13 = 95 × 1,05 × 1,13 = 125 kV.

G.4.5 Step 4: conversion to standard short-duration power-frequency and lightning impulse withstand voltages

G.4.5.1 General

For the selection of the standard withstand voltages in Table 2 of IEC 60071-1:2019, the required switching impulse withstand voltages are converted into short-duration power-frequency withstand voltages and into lightning impulse withstand voltages by applying the test conversion factors of Table 2 (for internal insulation, factors corresponding to liquid-immersed insulation are selected).

G.4.5.2 Conversion to short-duration power-frequency withstand voltage (SDWV)

The conversion values to SDWV are as follows:

– Phase-to-earth:
  - internal insulation ⇒ SDWV = U_{rw} × 0,5 = 68 × 0,5 = 34 kV;
  - external insulation ⇒ SDWV = U_{rw} × 0,6 = 70 × 0,6 = 42 kV.

– Phase-to-phase:
  - internal insulation ⇒ SDWV = U_{rw} × 0,5 = 99 × 0,5 = 50 kV;
  - external insulation ⇒ SDWV = U_{rw} × 0,6 = 102 x 0,6 = 61 kV.

G.4.5.3 Conversion to lightning impulse withstand voltage (LIWV)

The conversion values to LIWV are as follows:

– Phase-to-earth:
  - internal insulation ⇒ LIWV = U_{rw} × 1,10 = 68 × 1,1 = 75 kV;
  - external insulation ⇒ LIWV = U_{rw} × 1,06 = 70 × 1,06 = 74 kV.

– Phase-to-phase:
  - internal insulation ⇒ LIWV = U_{rw} × 1,10 = 99 × 1,1 = 109 kV;
  - external insulation ⇒ LIWV = U_{rw} × 1,06 = 102 × 1,06 = 108 kV.

G.4.6 Step 5: selection of standard withstand voltages

Table 2 of IEC 60071-1:2019 gives, for U_m = 24 kV, a standard short-duration power-frequency withstand voltage of 50 kV. This is adequate to cover the requirements for temporary overvoltage and all slow-front overvoltages except the phase-to-phase requirement for external insulation which can be accommodated by adequate air clearances. Table 2 of IEC 60071-1:2019 provides three possible values for the standard lightning impulse withstand voltage for U_m = 24 kV. Selection of a value of 125 kV covers the lightning impulse requirement as well as the switching impulse withstand voltage for external phase-to-phase insulation.

G.4.7 Summary of insulation co-ordination procedure for the example of Clause G.4

Table G.3 summarizes values obtained while completing the insulation co-ordination procedure for this example, for a considered maximum operating voltage U_s = 24 kV.

Table G.3 – Values related to the insulation co-ordination procedure for the example in G.4

Type of overvoltage		Temporary				Slow-front				Fast-front	
		Phase-to-earth		Phase-to-phase		Phase-to-earth		Phase-to-phase		Phase-to-earth and phase-to-phase	
Insulation		**Internal**	**External**	**Internal**	**External**	**Internal**	**External**	**Internal**	**External**	**Internal**	**External**
Step 1 Representative voltage stresses in service	Values of U_{rp}	24 kV	24 kV	28 kV	28 kV	59 kV	59 kV	86 kV	86 kV	—	—
Step 2 Co-ordination withstand voltages	Values of K_c or K_{cd}	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	—	—
	Values of U_{cw}	24 kV	24 kV	28 kV	28 kV	59 kV	59 kV	86 kV	86 kV	95 kV	105 kV
Step 3 Required withstand voltages	Safety factor K_s	1,15	1,05	1,15	1,05	1,15	1,05	1,15	1,05	1,15	1,05
	Altitude correction K_a	—	1,13	—	1,13	—	1,13	—	1,13	—	1,13
	Values of U_{rw}	28 kV	28 kV	32 kV	33 kV	68 kV	70 kV	99 kV	102 kV	109 kV	125 kV
Step 4 Standard withstand voltages	1) Test conversion factors	To short-duration power-frequency				0,5	0,6	0,5	0,6		
		To lightning impulse				1,10	1,06	1,10	1,06		
	2) Resulting required withstand voltages	Short duration power-frequency				34 kV	42 kV	50 kV	61 kV		
		Lightning impulse				75 kV	74 kV	109 kV	108 kV		
Step 5	Selection of standard withstand voltages	Short-duration power-frequency 50 KV								Lightning impulse 125 kV	

Annex H
(informative)

Atmospheric correction – Altitude correction application example

H.1 General principles

H.1.1 Atmospheric correction in standard tests

IEC 60060-1 specifies the atmospheric correction factors for testing of air clearances and insulators with the standardized

- short-duration power-frequency voltage,
- switching impulse voltage,
- lightning impulse withstand voltage, and
- direct voltage.

Direct test voltages are disregarded here, because such tests are not required for systems within the scope of IEC 60071-1.

The standard insulation levels of external insulation refer to the standard reference atmosphere as given in IEC 60071-1:2006, 5.9.2, and IEC 60060-1:2010, 4.3.1.

The standard reference atmosphere is:

- ambient air temperature ϑ_0: 20 °C
- absolute air pressure p_0: 1 013 hPa (1 013 mbar)
- absolute air humidity h_0: 11 g/m^3

NOTE Deviating from the standards mentioned above, the letter symbol ϑ is used here for ambient air temperature to be in line with the common usage in scientific literature.

Any deviation of air temperature, pressure or humidity from these reference values will affect the dielectric strength of the external insulation. These deviations have to be corrected in the test to verify a certain standard insulation as required in IEC 60060-1:2010, 4.3. In accordance with this document, the atmospheric correction factor is defined as

$$K_t\,(t) = k_1 \times k_2 \tag{H.1}$$

where

k_1 is the air density correction factor;

k_2 is the humidity correction factor.

$K_t(t)$ is time dependent according to the varying conditions in the considered time period (seasons or years) and corresponds with the correction factor K_t of IEC 60060-1 for the moment of test.

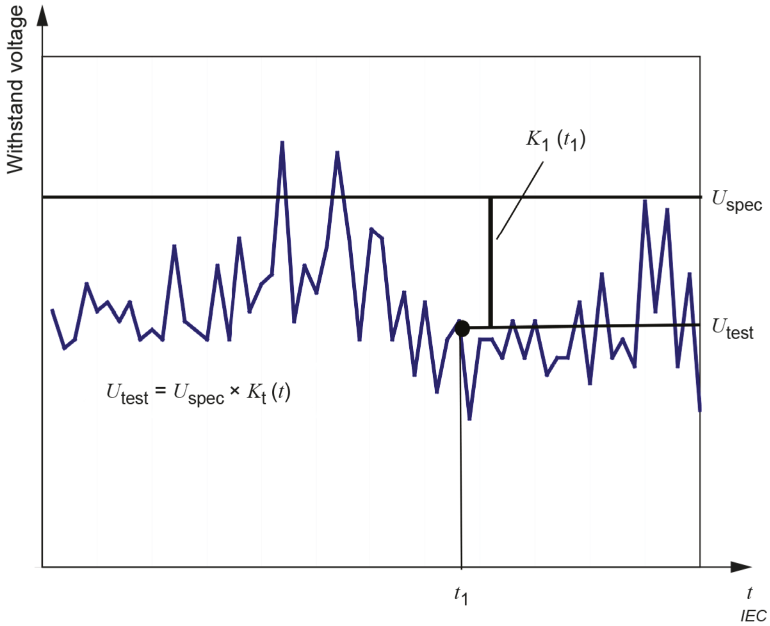


Figure H.1 – Principle of the atmospheric correction during test of a specified insulation level according to the procedure of IEC 60060-1

The principles of the atmospheric correction during tests are outlined in Figure H.1. The atmospheric conditions at the test location vary throughout for example the year. Therefore, the atmospheric correction factor $K_t(t)$ at the time of testing and the voltage U_{test} to be applied to the test object vary accordingly to prove the specified voltage U_{spec}, which is related to the standard reference atmosphere and normally in line with the standard withstand voltages according to IEC 60071-1 and applicable product standards.

$$U_{spec} = \frac{U_{test}}{K_t(t)} \tag{H.2}$$

During testing, by considering the atmospheric condition, the altitude of the test location is covered by the atmospheric correction of IEC 60060-1. The altitude correction of standard insulation levels has no relation to testing in a certain location at a certain time.

H.1.2 Task of atmospheric correction in insulation co-ordination

The actual withstand voltage of external insulation of equipment in service $U_{10}(t)$ varies over the year in the same way as during testing according to IEC 60060-1. The atmospheric correction factor and the safety correction factor used in insulation co-ordination have to cover these variations in order to achieve the specified insulation when stressing external insulation with these atmospheric conditions.

The task of insulation co-ordination is to determine one required withstand voltage value that results in an acceptable risk-of-flashover taking into account the varying withstand voltage over the lifetime of the equipment.

Based on the co-ordination withstand voltage, the correction has to be chosen in the way that the required withstand voltage covers sufficiently the actual withstand voltages in service:

$$U_{rw} = \frac{K_s \times U_{cw}}{K_t} \qquad \text{(H.3)}$$

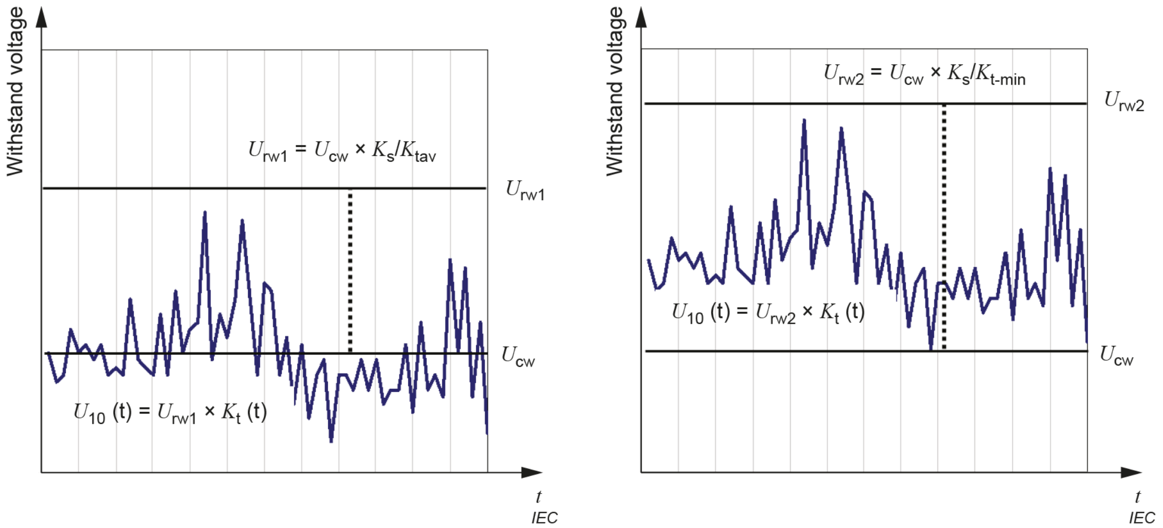
where

U_{rw} is the required withstand voltage;

U_{cw} is the co-ordination withstand voltage;

K_s is the safety factor;

K_t is the atmospheric correction factor (selected value out of $K_t(t)$).



a) Considering an average value of atmospheric conditions with a higher risk

b) Considering the worst atmospheric conditions with a lower risk

Figure H.2 – Principal task of the atmospheric correction in insulation co-ordination according to IEC 60071-1

Figure H.2 shows this procedure in principle. In Figure H.2 a), the correction is based on an average value of atmospheric correction K_{tav} resulting in a required withstand voltage U_{rw1}, which covers the actual time dependent withstand voltage of equipment $U_{10}(t)$. Considering the worst atmospheric condition with $K_{t\text{-min}}$ will lead to a higher required withstand voltage U_{rw2} as shown in Figure H.2 b). This includes a lower risk of failure in comparison to Figure H.2 a).

The safety factor K_s is increasing the required withstand voltage by a constant factor and has to be considered in the process of insulation co-ordination. For convenient reading, it is neglected in the following.

From the required withstand voltage U_{rw} results a standard rated withstand voltage U_w according to IEC 60071-1, which normally is the voltage U_{spec} applied during a withstand test after atmospheric correction with $K_t(t)$ according to IEC 60060-1.

The atmospheric correction according to IEC 60060-1 can only be performed when all necessary data for the atmospheric conditions, the required insulation level of the equipment and the dimensions of the equipment are known. For the specification of the required withstand voltages in the insulation co-ordination process of IEC 60071-1, these data are frequently not fully available, and simplifications have to be adopted to determine the required withstand voltages. The application of atmospheric correction can be simplified in most cases by using an altitude correction factor only. The validation of this simplification and the limits of its application are shown in the following Clauses H.2 to H.4.

H.2 Atmospheric correction in insulation co-ordination

H.2.1 Factors for atmospheric correction

For air clearances and dry insulators, the atmospheric correction factor K_t is given in IEC 60060-1 as

$$K_t = k_1 \times k_2 = \delta^m \times k_h^w \quad \text{(H.4)}$$

where

δ is the relative air density;

k_h is the parameter for humidity depending on air density and test voltage;

m, w are the exponents depending on parameter g (each parameter is defined in IEC 60060-1).

For configurations with inhomogeneous electric field distributions under impulse voltages, as they are usually present in the higher voltage ranges, the parameter g is always below 1,2. In this range of g the exponents are equal:

$$m = w \quad \text{(H.5)}$$

With this simplification, for $g \leq 1{,}2$, the atmospheric correction factor to be applied to the voltages stressing the air clearances of equipment is given by

$$K_t = (\delta \times k_h)^m \quad \text{(H.6)}$$

With δ and k_h as defined in IEC 60060-1, a detailed equation for the atmospheric correction K_t with the three atmospheric parameters pressure, temperature and humidity and exponent m is given.

H.2.2 General characteristics for moderate climates

To find an overall valid atmospheric correction for the location of installation, the variations of the weather conditions over the year have to be investigated.

Generally, the relative air density δ is high in winter time due to the low temperature and low in summer due to the high temperature. The humidity, described by correction factor k_h, shows the opposite trend. For the overall correction $\delta \times k_h$ the values of relative air density and humidity compensate each other. The variation of the overall correction $\delta \times k_h$ over the year is much smaller than the variation of the air density alone owing to the compensating influence of the humidity.

This situation is valid also for high altitudes. Although the relative air density δ is low due to the high altitude, and humidity correction factor k_h is low due to low temperature, both are following the same trend as at the stations on sea level.

Owing to the strong correlation between temperature and absolute humidity, it is appropriate to separate the atmospheric correction into two parts (Equation (H.7)), which seem to be independent one from each other: One factor being the air pressure related to the reference pressure (p/p_0), the second factor being the inverted relative temperature multiplied by the humidity correction factor ($T_0/T \times k_h$).

$$K_t = [\delta \times k_h]^m = \left[\frac{p}{p_0} \times \frac{T_0}{T} \times k_h\right]^m \quad \text{(H.7)}$$

Due to the compensation effect, the term ($T_0/T \times k_h$) is nearly equal to 1 for all altitudes. The given relation is valid for regions with moderate climate which provide sufficient air humidity at increasing temperature.

The term (p/p_0) fits very well to the average overall atmospheric correction $\delta \times k_h$. Therefore, the best estimation for the average atmospheric correction $\delta \times k_h$ is the related average pressure p/p_0.

With these considerations of the compensating effect and with Equation (H.7) follows that, for insulation co-ordination purpose, the atmospheric correction factor K_t can be simply used by taking only the air pressure p into account:

$$K_t = \left[\frac{p}{p_0}\right]^m \quad \text{(H.8)}$$

H.2.3 Special atmospheric conditions

For regions with special atmospheric conditions, different considerations may apply. Figure H.3 shows the summary of data from various weather stations around the world, comparing the overall atmospheric correction $\delta \times k_h$ with the pressure related correction p/p_0. For most locations, the difference is within the standard deviation of the values justifying the considerations for moderate climates above.

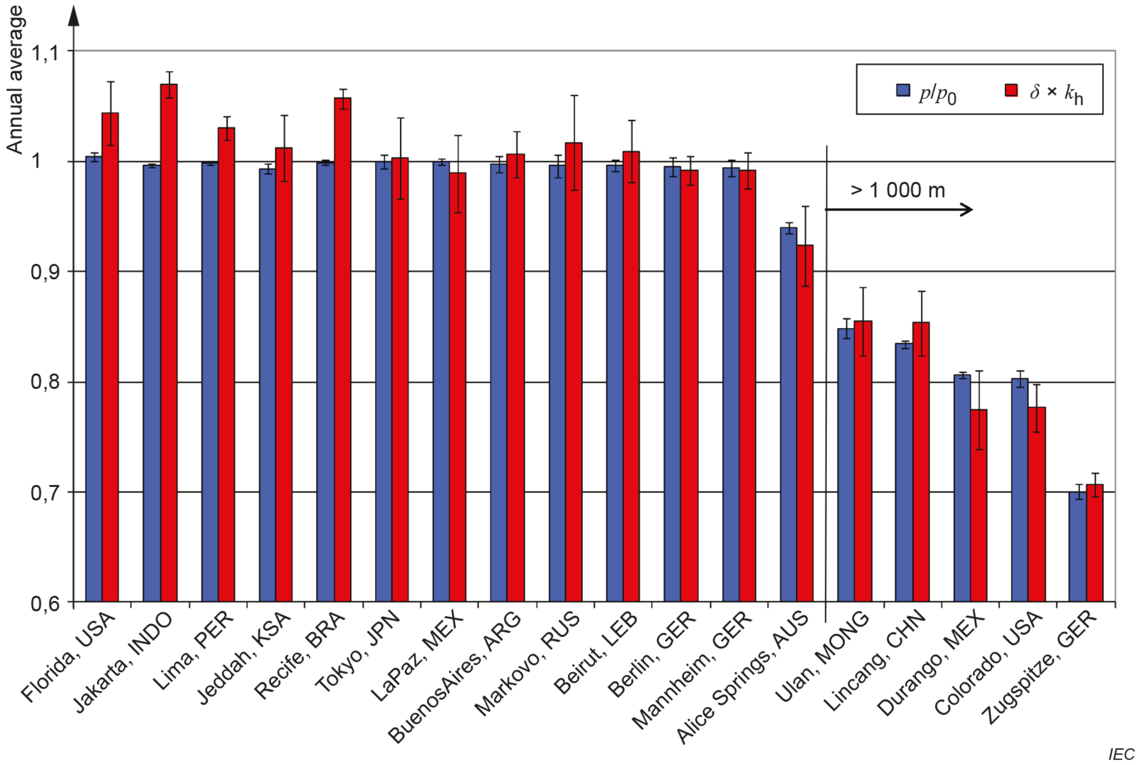


Figure H.3 – Comparison of atmospheric correction $\delta \times k_h$ with relative air pressure p/p_0 for various weather stations around the world

Higher differences show special atmospheric conditions which may need special consideration. There is no compensation and the application of the complete atmospheric correction may become necessary instead of the simplification by taking in account the pressure only. For example, for tropical climate with high temperature and very high humidity (like Jakarta, Indonesia and Recife, Brazil), factor $(T_0/T \times k_h)$ dominates the correction $\delta \times k_h$.

For such special atmospheric conditions at sea level it should be noted that this difference is covered by the insulation co-ordination procedure for normal environmental conditions which includes the altitude of 1 000 m. This leads to a pressure related correction with p/p_0 (correction factor 1,13) covering the overall correction $\delta \times k_h$, and no further consideration is needed.

For areas at high altitude with a large difference it is recommended to consider the complete atmospheric correction $\delta \times k_h$ to cover the effects of pressure, temperature and humidity.

H.2.4 Altitude dependency of air pressure

As shown above, the atmospheric correction can be reduced in most cases to a correction considering the air pressure only. The dependency of air pressure and altitude will be described in the following.

According to ISO 2533:1975, the simultaneous solution of the equations of static atmosphere and the perfect gas law gives a dependency of air pressure p on altitude H (ISO 2533:1975, Equation (12)). A linear reduction of temperature with altitude is included by a temperature gradient. By using a constant average temperature the dependency of p versus H can be simplified to the exponential function:

$$p = p_0 e^{-\frac{H}{8\,150}} \qquad \text{(H.9)}$$

The deviation of this simplified way of pressure calculation to the pressure calculation including the temperature gradient of ISO 2533 is shown in Figure H.4. The maximum deviation up to nearly 4 000 m altitude is less than 0,5 %. The difference is small and the simplified equation can be applied with sufficient accuracy.

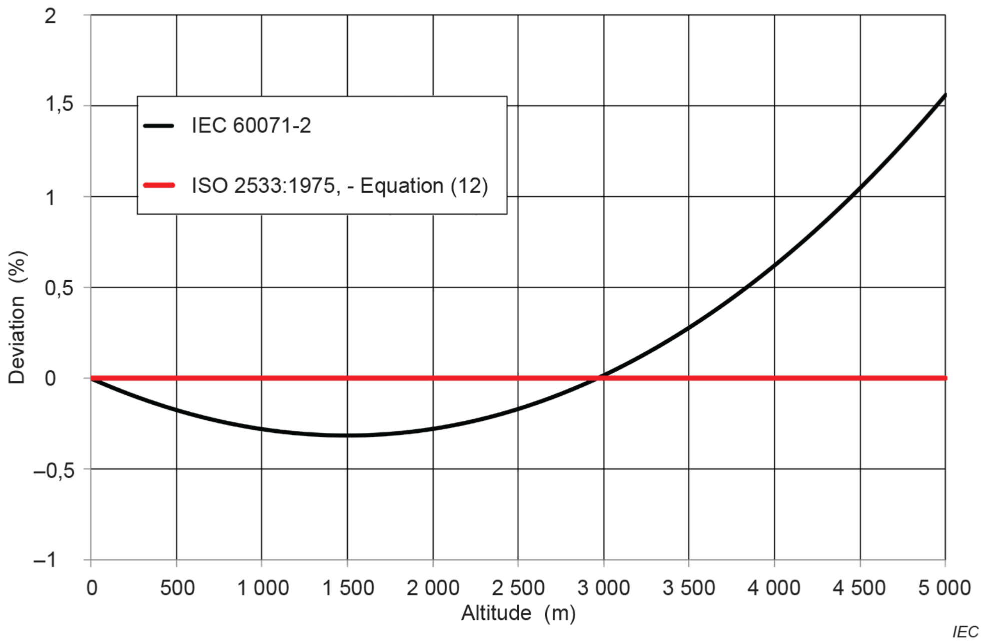


Figure H.4 – Deviation of simplified pressure calculation by exponential function in this document from the temperature dependent pressure calculation of ISO 2533

H.3 Altitude correction

H.3.1 Definition of the altitude correction factor

With the basic idea of atmospheric correction for insulation co-ordination to simplify it to a pure pressure dependent correction the correction factor K_t can be written in exponential form by combining Equations (H.8) and (H.9).

$$K_t = \left(\frac{p}{p_0}\right)^m = e^{-m\frac{H}{8\,150}} \qquad \text{(H.10)}$$

It describes the reduction of the withstand voltage at elevated altitude.

The altitude correction factor has to compensate the reduction. It is defined as a factor, by which the rated withstand voltage has to be increased to a higher value at standard reference atmosphere in order to assure a withstand voltage equal to the required value at certain altitude.

The altitude correction factor is given by

$$K_a = \frac{1}{K_t} = e^{m\frac{H}{8\,150}} \qquad \text{(H.11)}$$

The altitude correction is a simplification of the atmospheric correction. It implies that the differences in the atmospheric conditions at an elevated altitude can be described by one single parameter, namely the installation altitude H of the equipment.

H.3.2 Principle of altitude correction

In insulation co-ordination, the co-ordination withstand voltage U_{cw} has to be applied with the safety factor K_s and the altitude correction factor K_a to achieve the required withstand voltage U_{rw}.

$$U_{rw} = K_s \times K_a \times U_{cw} \tag{H.12}$$

Figure H.5 shows the principle of altitude correction for an example of U_m = 420 kV and a rated lightning impulse withstand voltage of 1 425 kV, the highest voltage of equipment U_m and its corresponding standard rated lightning impulse withstand voltage are taken from IEC 60071-1 Table 3. The figure shows that the actual withstand voltage of the equipment decreases from the rated value at sea level with the installation altitude according to the decreasing air pressure.

The value 1 425 kV [IEC 60071-1 Table 3] has been derived from the co-ordination withstand voltage U_{cw} = 1 200 kV multiplied by the safety factor K_s = 1,05 recommended in this document for external insulation. As this example relates to a standardized equipment, an altitude correction factor K_a = 1,13 (according to the pressure at 1 000 m) has been applied. The design meets the requirements for the withstand voltage to be equal to 1 260 kV (1,05 U_{cw}) exactly up to 1 000 m.

In order to meet the design requirement for the external insulation at altitudes above 1 000 m (e.g. 3 000 m in Figure H.5), the withstand voltage of the external insulation at standard reference atmosphere has to be increased by altitude correction according to the altitude of installation. An altitude correction according to Equation (H.11) has to be applied to cover the requirements at installation altitude. With K_a = 1,45, a withstand voltage of 1 822 kV at sea level is necessary to meet the requirements at 3 000 m.

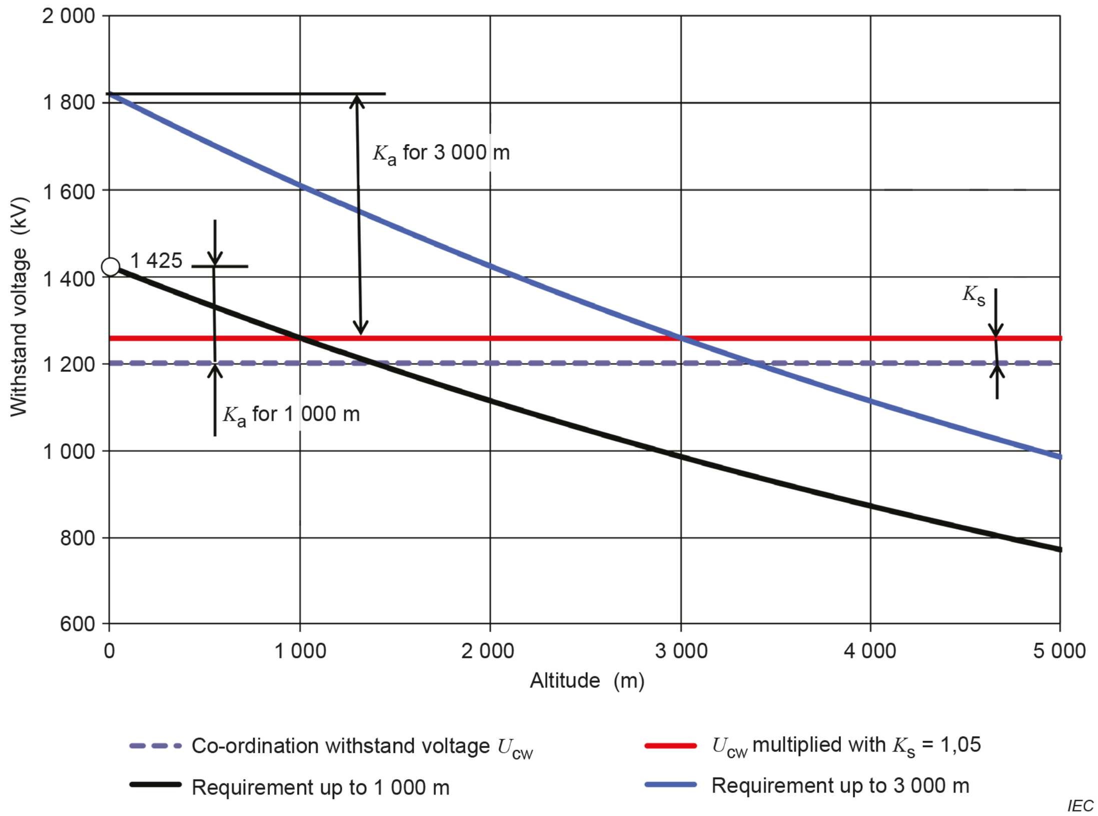


Figure H.5 – Principle of altitude correction: decreasing withstand voltage U_{10} of equipment with increasing altitude

H.3.3 Altitude correction for standard equipment operating at altitudes up to 1 000 m

When equipment designed according to an existing IEC standard is used, the equipment should fulfill all requirements of the relevant standard concerning the environmental conditions. For the external insulation, it means that equipment shall be able to operate in the range of atmospheric conditions specified in the standards. Normal environmental conditions in IEC 60071-1 and in equipment standards (e.g. IEC 62271-1) specify an altitude of operation up to 1 000 m, among others.

It is evident that the insulation design shall take into account the variations of the atmospheric conditions within this specified range. Considering the compensating effect of humidity and temperature, the altitude up to 1 000 m can be covered by the pressure related altitude correction factor to meet the requirements of normal environmental conditions.

IEC 60071-1 has standardized a list of rated withstand voltages, which are based on the experience with equipment located in systems that are operated under normal environmental conditions. These conditions include altitudes up to 1 000 m and, consequently, the range of rated withstand voltages is assumed to cover the requirements for all external insulations to be located at altitudes up to 1 000 m.

As a conclusion, the following has to be stated.

- The rated withstand voltage values standardized in IEC 60071-1 are valid for the normal environmental conditions and are adjusted to the standard reference atmospheric conditions and only for these conditions.
- For each U_m value, the associated range of rated withstand voltages proposed in the present document cover the requirements for all equipment operating under normal environmental conditions including those to be installed at altitudes up to 1 000 m.

Following the general practice of insulation co-ordination procedure for standardized equipment an altitude correction factor according to Equation (H.11) has to be applied to cover the required installation altitude up to 1 000 m.

H.3.4 Altitude correction for standard equipment operating at altitudes above 1 000 m

Besides the normal environmental conditions, further requirements may arise from special environmental conditions, among which an altitude exceeding 1 000 m is of special interest for the external insulation.

For equipment which is standardized and has been designed for normal environmental conditions, i.e., designed and approved for altitudes up to 1 000 m and it is going to be installed at higher altitudes, i.e., above 1 000 m, the altitude correction should be done by using Equation (H.13). The standardized voltage levels will be increased by:

$$K_{a1\,000} = e^{m \times \frac{H - 1\,000}{8\,150}} \tag{H.13}$$

Therefore, an equipment already designed for certain U_{cw} and normal environmental conditions of maximum 1 000 m height, that it will be in service conditions at an altitude H higher than 1 000 m height will require a withstand voltage $U_{rw} = K_{a1\,000} \times U_{cw}$.

Equation (H.13) takes into account that rated withstand voltages of standardized equipment already covers the necessary correction up to altitudes of 1 000 m.

H.4 Selection of the exponent *m*

H.4.1 General

The exponent m in atmospheric and altitude correction takes into account the discharge behavior of the considered air gap.

For the following voltage and overvoltage classes, the exponent m may be applied.

1) Co-ordination long-duration power-frequency withstand voltages

   As long as specific values of exponent m to determine the pollution withstand voltage are not specified by IEC TC 36, the following value may be applied:

   m = 0,5 for overhead line insulators;

   m = 0,8 for station insulators, bushings and housings.

2) Co-ordination short-duration power-frequency withstand voltages

   A conservative estimate may be used:

   m = 1.

3) Co-ordination lightning impulse withstand voltages

   For lightning impulses, the exponent m is equal to 1, which has to be expected for a streamer discharge where the flashover voltage is linearly dependent on the gap clearance:

   m =1.

   This is valid also for the combined lightning impulse/power-frequency voltage of longitudinal insulations. Reason is that lightning impulses are so short in time duration that the flashover will be a streamer discharge. The flashover voltage, therefore, increases linearly with distance.

4) Co-ordination switching impulse withstand voltages

   For switching impulses, the exponent m is obtained for each co-ordination withstand voltage U_{cw}. An according dependency is given in Figure 10.

   The derivation of exponent m for standard switching impulse voltage shapes is shown in H.4.2. It shows in detail that the exponent m is, beside U_{cw}, depending on altitude H and gap factor K. Figure H.6 or Figure H.7 should be used for selection of exponent m to determine the altitude correction factor K_a when dealing with standard impulse shapes.

   The derivation of exponent m for critical switching impulse voltage shapes is shown in H.4.3 in the same way with the results in Figure H.8 and Figure H.9.

H.4.2 Derivation of exponent m for switching impulse voltage

The exponent m can be derived from a set of well-known and approved relations:

1) flashover characteristic based on rod-plane gaps (Equation (F.4)) for standard switching impulse voltage;
2) parameter g providing the exponent m (IEC 60060-1);
3) atmospheric correction;
4) normalized conventional standard deviation z = 0,06 for switching impulse;
5) pressure related exponential function of altitude correction.

With this set of relations a dependency of exponent m on the co-ordination withstand voltage U_{cw} with the parameters K and H can be derived as described in the following.

Basically, exponent m is derived from the equation of parameter g and the equation of the flashover characteristic of phase-to-earth configuration. In both equations, the air gap clearance L is used and will be set equal.

For both equations, the 50 % flashover voltages are needed. Taking Equation (7) and considering that

U_{cw} is the 10% flashover voltage U_{10}, and

U_{c50} is the 50% flashover voltage U_{50},

U_{c50} can be calculated as follows:

$$U_{c50} = \frac{U_{cw}}{1 - 1{,}3 \times z} \tag{H.14}$$

The normalized value of conventional standard deviation is 6 % for switching impulse voltage referred to U_{50}.

Air gap clearance d from parameter g

The minimum air clearance d of equipment is not known and has to be determined.

Based on the equation for the parameter g of IEC 60060-1 the applicable minimum clearance d at the location of installation is given by

$$d = \frac{U_{c50}}{500 \times g \times \delta \times k_h} \tag{H.15}$$

Air gap clearance d from flashover characteristic based on rod-plane gaps

To determine the air clearances necessary for a required 50 % flashover voltage, a voltage based on the characteristic of a rod-plane configuration has been used (Equation (F.4)).

$$U_{r50} = K \times 500 \times d^{0,6} \tag{H.16}$$

The required 50 % flashover voltage U_{r50} valid for reference conditions can be converted to the co-ordination flashover voltage U_{c50} by atmospheric correction (disregarding the safety factor K_s in this respect):

$$U_{r50} = \frac{U_{c50}}{K_t} = \frac{U_{c50}}{\left(\delta \times k_h\right)^m} \tag{H.17}$$

The air gap clearance is given now by:

$$d = \left[\frac{U_{c50}}{500 \times K \times \left(\delta \times k_h\right)^m}\right]^{1/0,6} \tag{H.18}$$

Setting equal Equations (H.15) and (H.18) leads to:

$$\frac{U_{c50}}{500 \times g \times \delta \times k_h} = \left[\frac{U_{c50}}{500 \times K \times \left(\delta \times k_h\right)^m}\right]^{1/0,6} \tag{H.19}$$

Replace g by (from IEC 60060-1):

$$g = 0,1 + \sqrt{0,8 \times m + 0,01} \tag{H.20}$$

The term of the atmospheric correction $\delta \times k_h$ is known from the designated installation and can be replaced by

$$\delta \times k_h = e^{\frac{-H}{8\,150}} \tag{H.21}$$

Including Equations (H.14), (H.20) and (H.21) into (H.19) leads to the dependency of exponent m on U_{cw} with the parameters H and K. Equation (H.19) can only be solved iteratively.

The dependency of exponent m on the co-ordination withstand voltage U_{cw} is plotted in Figure H.6 for selected gap factors K and selected altitudes H up to 4 000 m. Typical values of the gap factor K are indicated in Table G.1 and Table G.2.

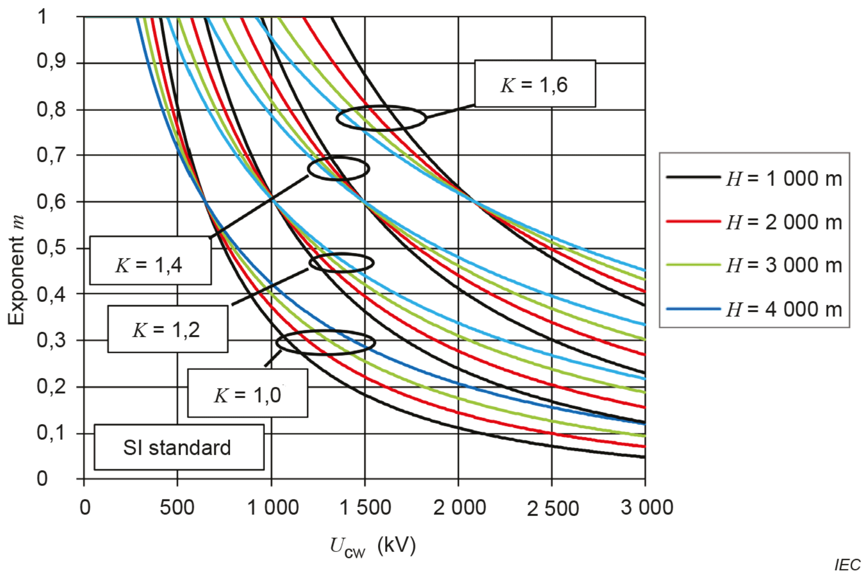


Figure H.6 – Sets of *m*-curves for standard switching impulse voltage including the variations in altitude for each gap factor

The exponent m varies in a wide range considering the two parameters altitude and gap factor. By examining the effect of exponent m on altitude correction factor K_a it can be stated that the sensitivity of K_a on variations in m is low. Due to the fact that the sensitivity is decreasing with altitude the m curves for the highest altitude can be used in a first approach for the lower altitudes by accepting a maximum failure within engineering tolerance of ±3 % (Figure H.7).

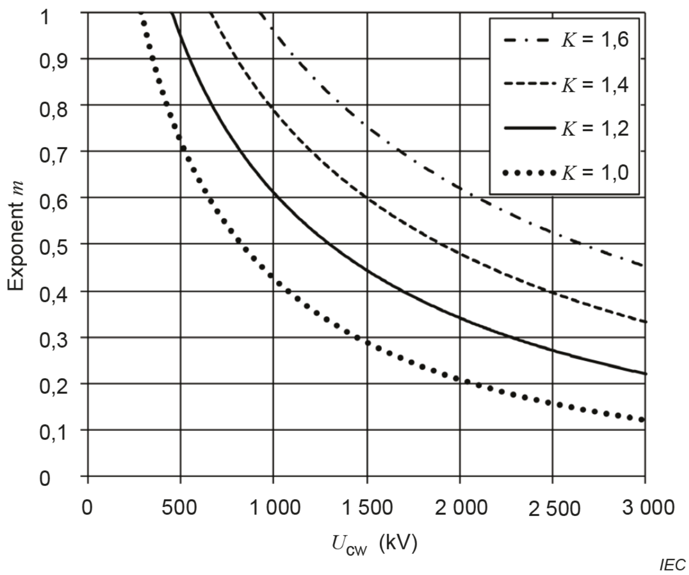


Figure H.7 – Exponent *m* for standard switching impulse voltage for selected gap factors covering altitudes up to 4 000 m

H.4.3 Derivation of exponent *m* for critical switching impulse voltage

If the critical switching impulse voltage is used for determination of exponent m the derivation can be done in the same way as for standard switching impulse (described in H.4.2) by just replacing the equation for the flashover characteristics. The characteristic based on rod-plane gaps (based on Equation (F.3)) for switching impulse voltage with critical front time strength has to be used.

$$U_{r50} = K \times 1\,080 \times \ln(0{,}46 \times d + 1) \tag{H.22}$$

All other relations remain unchanged.

The outcome is also a set of curves for each gap factor covering the selected altitudes 1 000 m up to 4 000 m (Figure H.8) and the reduced diagram for all altitudes up to 4 000 m (Figure H.9).

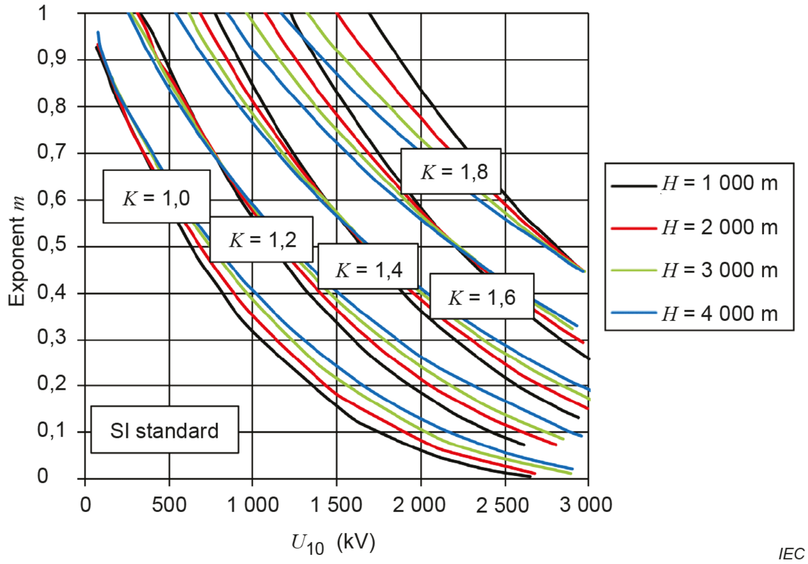


Figure H.8 – Sets of *m*-curves for critical switching impulse voltage including the variations in altitude for each gap factor

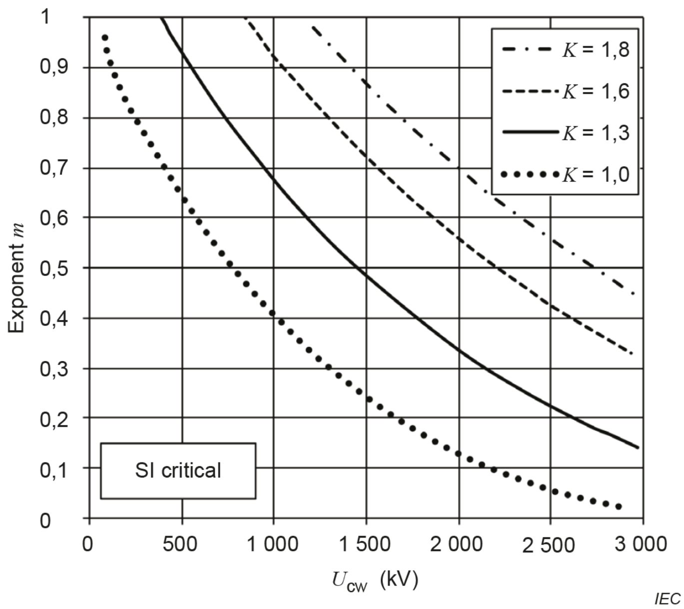


Figure H.9 – Exponent *m* for critical switching impulse voltage for selected gap factors covering altitudes up to 4 000 m

The curves are more flat than the curves determined by the equation for the standard switching impulse. They have a similar gradient in comparison with the m-curves of Figure 10.

After selection of appropriate parameters for gap factor K and altitude H, it can be shown that some curves are in good accordance with the curves of Figure 10. The conformity is visualized in Figure H.10, and a comparison of the functional expressions of Figure 10 to the selected parameters is listed in Table H.1.

Table H.1 – Comparison of functional expressions of Figure 10 with the selected parameters from the derivation of m-curves with critical switching impulse

Insulation according Figure 10		Determination by critical SI Equation (F.3) Parameter: gap factor/altitude
Phase-to-earth	curve a*	1,3/4 000
Longitudinal	curve b*	1,6/4 000
Phase-to-phase	curve c*	1,8/4 000
Rod-plane gap	curve d*	1,0/4 000
NOTE The asterisks defining the curves refer to Figure H.10.		

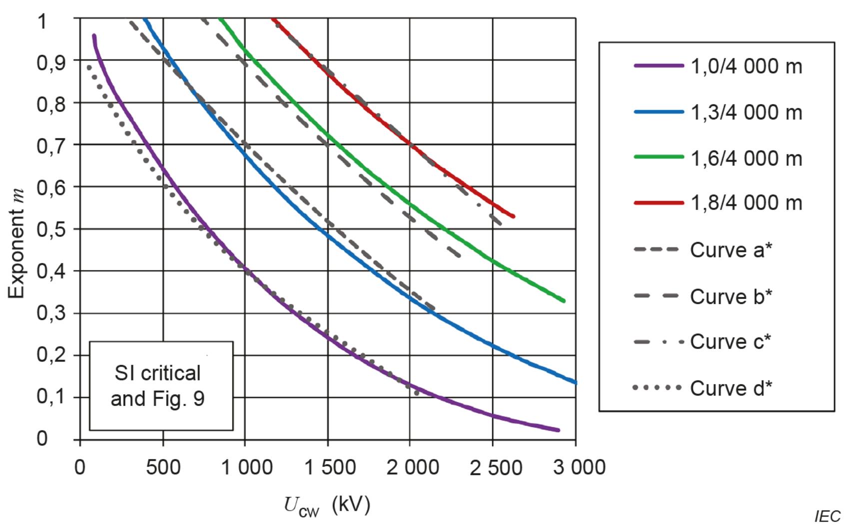


Figure H.10 – Accordance of m-curves from Figure 10 with determination of exponent m by means of critical switching impulse voltage for selected gap factors and altitudes

Figure 10 has been used for several years. To avoid changes in actual practical designs by replacing the curves of Figure 10 with the determined curves described above they can be used further on. It is recommended to investigate the validity of the new curves according Figure H.6 and Figure H.7 as well when dealing with standard impulse shapes only.

Annex I
(informative)

Evaluation method of non-standard lightning overvoltage shape for representative voltages and overvoltages

I.1 General remarks

In the insulation co-ordination stage of "representative overvoltage", overvoltage shapes are supposed to be the standard voltage shapes, which is especially significant for a lightning impulse. Recent researches have analysed field surges, clarified insulating characteristics for field real surges in comparison with those for the standard voltage shape in the lightning surge time region, and proposed the shape evaluation method for GIS (Gas insulated switchgear) [14] and transformer [15]. These techniques have been discussed in CIGRE working groups, and adopted in the technical brochures [11], [16], [17]. According to the aforementioned documents, the decay of the field overvoltage is generally large, making the insulation requirements not as severe as those of the standard overvoltage shape. Consequently, it could be possible in some cases to use lower withstand voltages.

I.2 Lightning overvoltage shape

From the results of the analyses of lightning overvoltage, disconnector switching overvoltage, and measurements at UHV and 550 kV substations, representative overvoltage shapes were extracted as the following five types, "Shape A" to "Shape E". The rise time of the shape crest varies, as a whole, in the range of 0,1 µs to 1,0 µs for GIS and 0,5 µs to 1,5 µs for transformer.

- Shape A: pulse-shape.
- Shape B: the shape front has a steep pulse-shaped part, and the shape tail is flat (ratio between peak and flat part: 0,7/0,9 both for GIS and transformer).
- Shape C: a damped oscillatory shape whose first peak is maximum (frequency: 0,5 MHz to 5,0 MHz for GIS, 0,4 MHz to 1,0 MHz for transformer).
- Shape D: a damped oscillatory shape whose second peak has the crest value (frequency: 0,5 MHz to 5,0 MHz for GIS,0,4 MHz to 1,0 MHz for transformer).
- Shape E: double-frequency oscillatory shape (lower frequency: approx. 1,0 MHz, upper frequency: approx. 5,0 MHz for GIS).

Shape B appears depending upon the positional relationships with protected points when the lightning arrester operates. Shapes C and D occur as a result of a negative and/or positive reflection inside and/or outside the substation. Shape A corresponds to the one when the decay of the DC component and/or oscillatory components of shapes B, C and D are large. Also, shape E occurs during a re-striking inside a substation as a disconnector surge, when there exist two oscillation routes within a substation. Thus, in general, it can be said that these shapes are representative shapes in view of the mechanism under which they occur. Figure I.1 a) to e) show examples of shapes A, B, C, D, and E.

I.3 Evaluation method for GIS

I.3.1 Experiments

The SF_6 gas gap and partly the insulating spacer surface were used as the insulating elements of GIS. The electrodes used in the tests generated quasi-equal electric fields whose utilization factors (η) were 0,60 and 0,45. The gas pressure was basically an absolute pressure of 0,50 MPa. With changing shape parameters, such as the frequency and the decay time, more than 200 cases were examined. Moreover, effects of other factors were investigated, like the scale, the gas pressure, the voltage polarity, superposition with DC, electrode material, and roughness.

As an example of the results, Figure I.2 shows the characteristics with respect to the shape E. The minimum value of the insulation breakdown V-t characteristics is 259 kV, which is 1,19 times that of the case of a standard lightning impulse. In other words, this means that it is possible to evaluate the overvoltage into the standard voltage with dividing the crest value by 1,19. This interpretation applies to the other experimental results as well.

The insulation characteristics are arranged according to the duration time of the 80 % level of the peak value. Figure I.3 presents how to calculate the duration time t_d: the sum of t_{d1}+t_{d2}. All of the characteristics for shape A, the pulse parts of shape B, and shapes C and D, and the double-frequency oscillatory shape E, lie roughly along one characteristic line. This characteristic corresponds to equations in the "Calculation of evaluation factor K_{ev}" box in Figure I.4 later discussed.

I.3.2 Evaluation of overvoltage shape

The overvoltage shape is resolved into elements including each oscillatory shape, the flat part, and so on. It is then evaluated based on the characteristics as described above, and finally the crest value that is evaluated into an equivalent standard voltage shape. Figure I.4 exhibits the whole evaluation flow for GIS together with for transformer referred to in I.4.2.

Figure I.5 shows an example of the lightning overvoltage applied to GIS in a UHV substation. This overvoltage is classified to the shape B whose tail level is approximately 60 % of the peak, after the steep oscillatory surge has decayed. Table I.1 shows the results of analyzing and evaluating this overvoltage shape using the flow of Figure I.4. In this case, the shape crest is severer than the shape tail, and the representative overvoltage is equivalent to a 2 094 kV (25 % lower).

I.4 Evaluation method for transformer

I.4.1 Experiments

The oil gap, section-to-section insulation and turn-to-turn insulation were used as the insulating elements of a transformer. About 100 cases were examined with changing shape parameters, such as the frequency and the decay time.

As an example of the results, Figure I.6 exhibits the characteristics with respect to shape C of the turn-to-turn insulation. The average value of the insulation breakdown V-t characteristics is 185 kV, which is 1,26 times that of the case of a standard lightning impulse. In a similar manner to GIS, this means that it is possible to evaluate the overvoltage into the standard voltage with dividing the crest value by 1,26. This interpretation applies to the other experimental results as well.

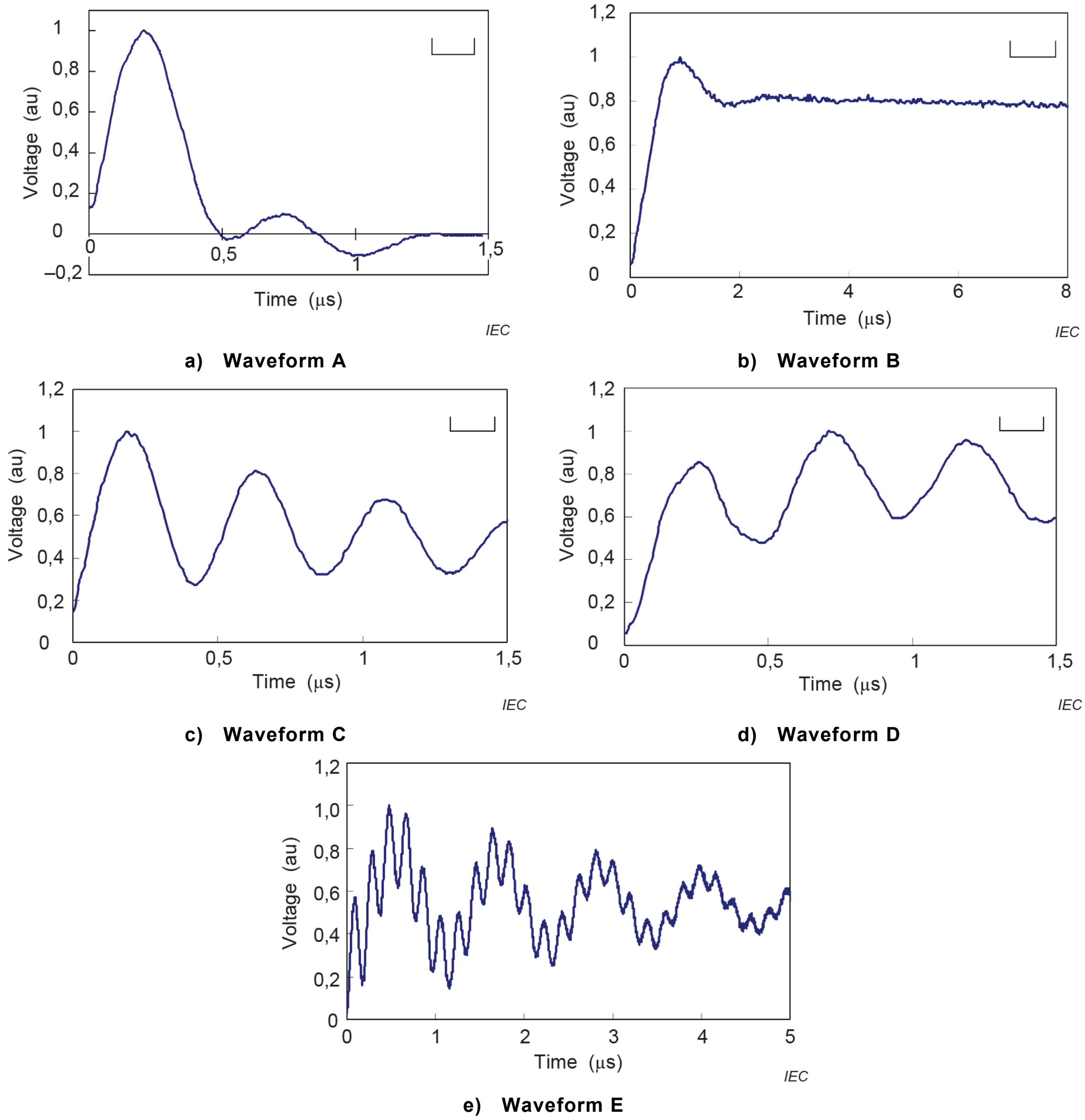
Concerning the oil gap and section-to-section insulation, when the insulation characteristics are arranged according to the duration time of the 80 % level of the peak value, all of the characteristics for shape A, the pulse parts of shape B, and shapes C and D, lie roughly along one characteristic line. Meanwhile, regarding the turn-to-turn insulation, when the insulation characteristics are arranged according to the duration time of the 90 % level of the peak value, all of the characteristics for shape A, the pulse parts of shape B, and shapes C and D, lie roughly along one characteristic line. However, in contrast to the other models, the duration time for 90 % and higher in the case of an oscillatory shape is not a total value, but is calculated separately for each shape as shape A.

I.4.2 Evaluation of overvoltage shape

The shape is resolved into elements V_{pij} including each oscillatory shape, the flat part, and so on. It is then evaluated based on the characteristics as described above, and finally the crest value is evaluated as the equivalent standard voltage V_{sij}. The whole overvoltage shape evaluation flow for an oil-filled transformer is presented in Figure I.4 together with for GIS.

Figure I.7 is an example of a lightning overvoltage applied to a transformer in a 550 kV substation. In this case, the shape tail maintains a level of about 70 % with respect to the peak after the steep oscillatory surge has decayed. Table I.2 summarizes the results of analyzing and evaluating this shape using the flow of Figure I.4. The severest part of the overvoltage is the pulse-shaped one "No. 2" with respect to the turn-to-turn insulation. The crest value of equivalent standard voltage is 934 kV (24 % lower).

To think of the principle of construction, these methods both for GIS and transformer can be generally applicable to lower voltage systems as well as 550 kV and above.



a) **Waveform A**

b) **Waveform B**

c) **Waveform C**

d) **Waveform D**

e) **Waveform E**

Figure I.1 – Examples of lightning overvoltage shapes

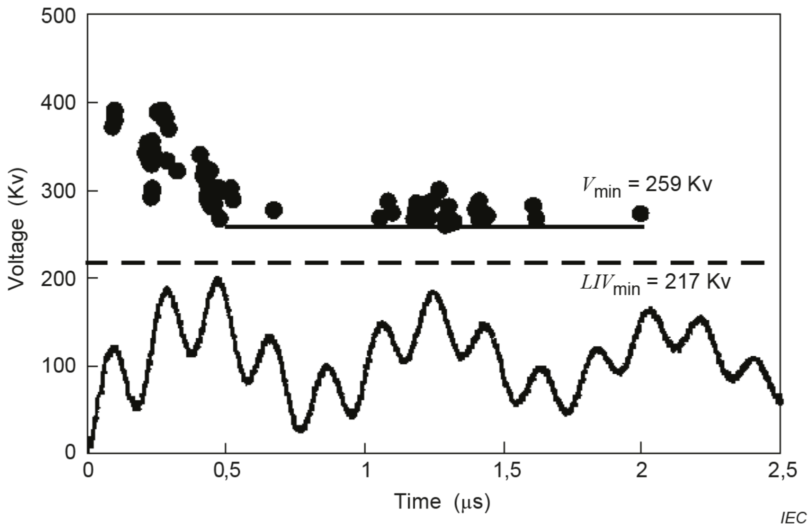


Figure I.2 – Example of insulation characteristics with respect to lightning overvoltages of the SF_6 gas gap (Shape E)

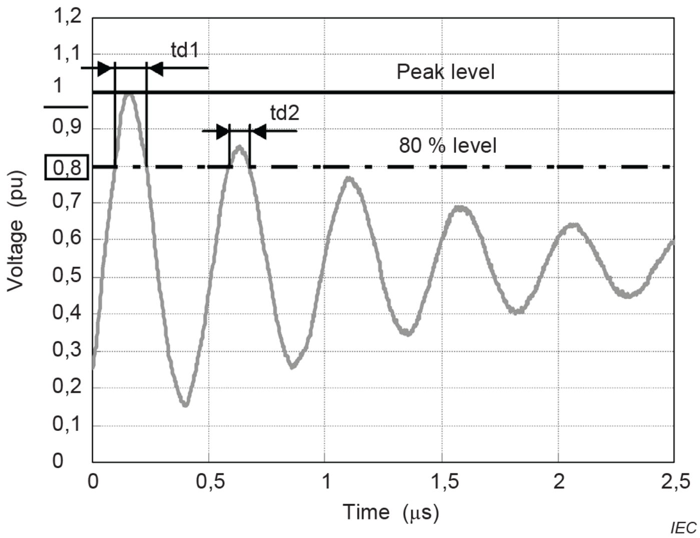


Figure I.3 – Calculation of duration time T_d

Table I.1 – Evaluation of the lightning overvoltage in the GIS of UHV system

Shape element	80 % duration time	Peak voltage	Evaluation ratio	Equivalent standard LI Vol.
B (shape crest)	0,16 µs	2 617 kV	1,25 (1,30)	**2 094 kV [η = 0,60]** **(2 016 kV [η = 0,45])**
B (shape tail)	-	1 517 kV	0,90	1 686 kV

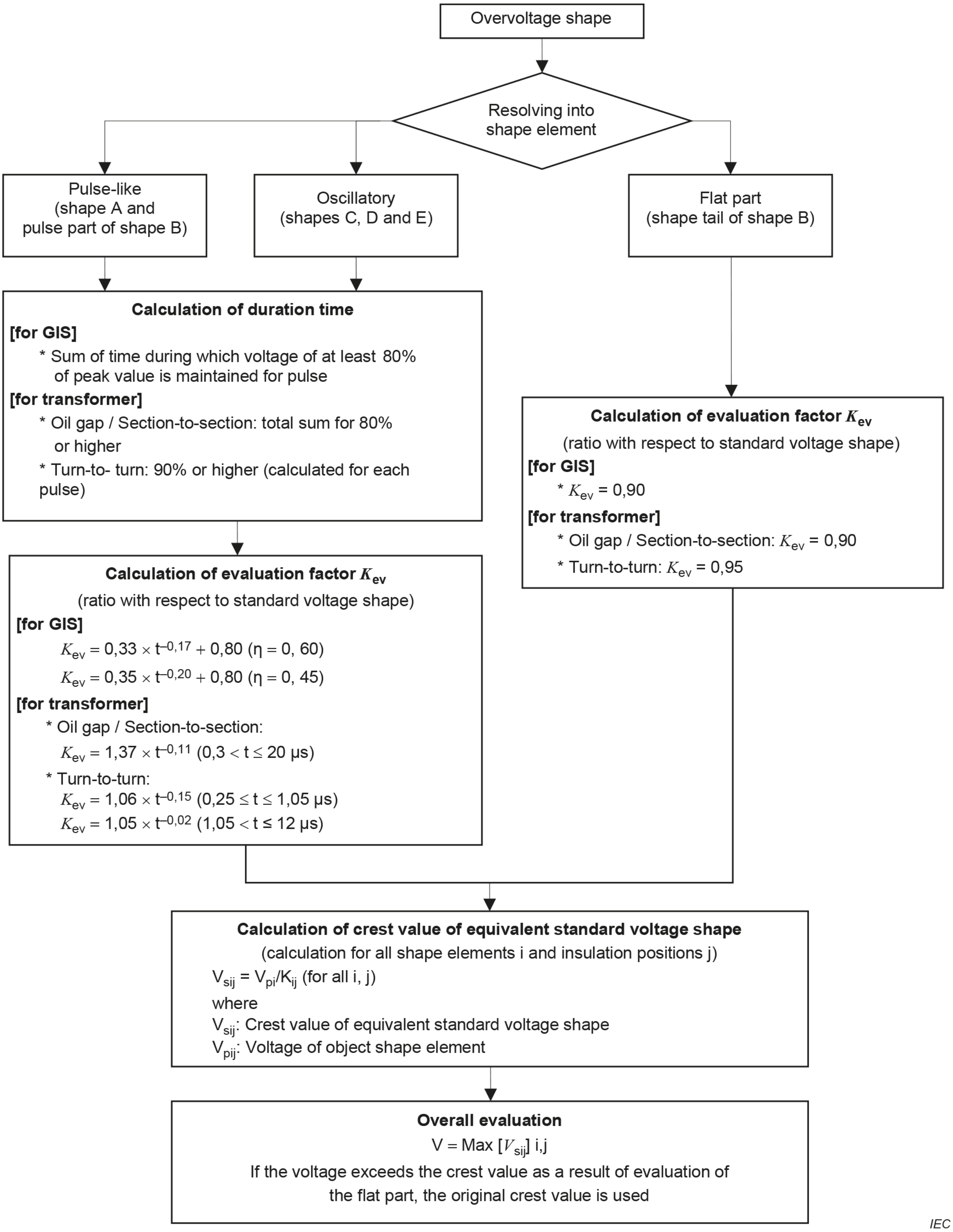


Figure I.4 – Shape evaluation flow for GIS and transformer

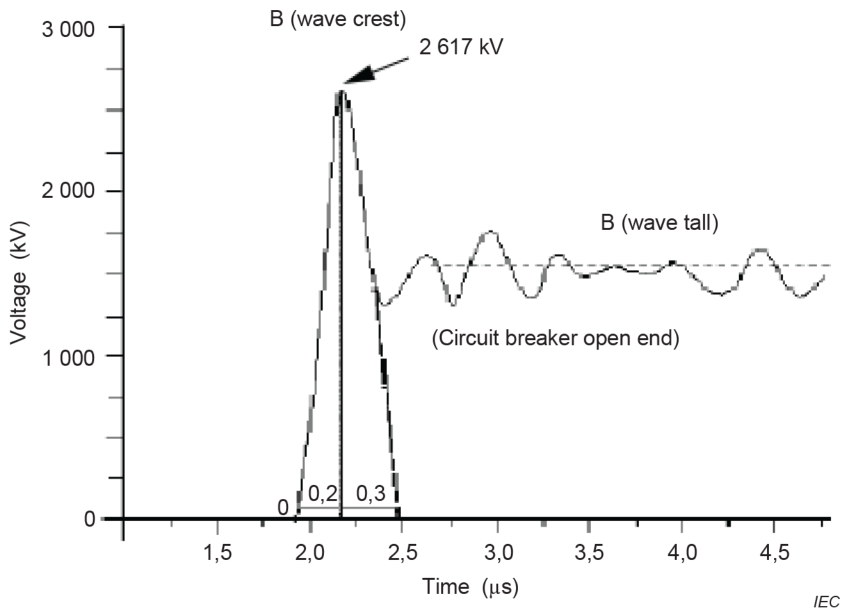


Figure I.5 – Application to GIS lightning overvoltage

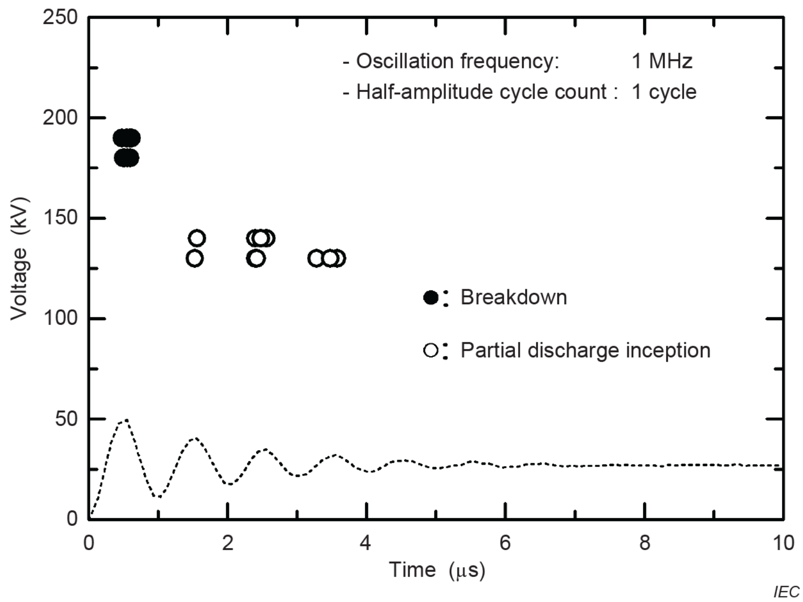


Figure I.6 – Example of insulation characteristics with respect to lightning overvoltage of the turn-to-turn insulation (Shape C)

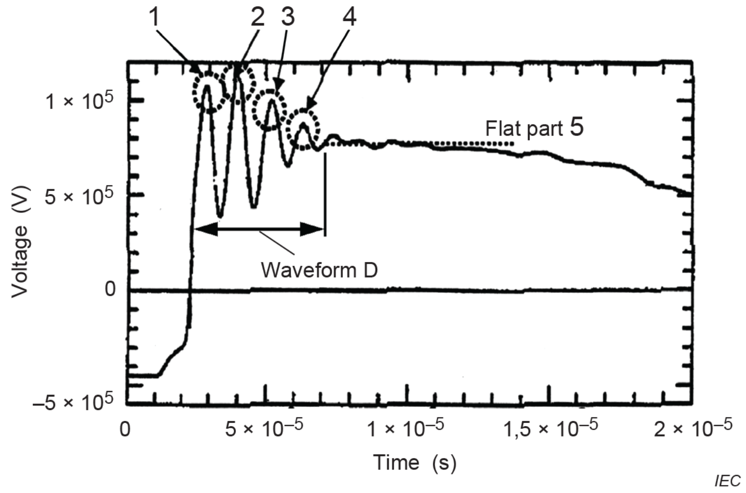


Figure I.7 – Application to transformer lightning overvoltage

Table I.2 – Evaluation of lightning overvoltage in the transformer of 500 kV system

Insulation element	**Shape element**	**Duration time**	**Peak voltage**	**Evaluation ratio**	**Equivalent standard LI Vol.**
Oil gap / Section-to-section	Oscillatory parts (1~4): C or D	0,84 µs	1 158 kV	1,40	827kV
	Flat part (5)	-	784 kV	0,90	871kV
Turn-to-turn	Max pulse (2)	0,35 µs	1 158 kV	1,24	**934kV**
	Other pulses (1)	0,35 µs	1 084 kV	1,24	874kV
	Flat part (5)	-	784 kV	0,95	825kV

Annex J
(informative)

Insulation co-ordination for very-fast-front overvoltages in UHV substations

J.1 General

VFFO in GIS have been studied by various CIGRÉ working groups and a common CIGRÉ technical brochure TB 519 [13] was published.

VFFO were considered to be more important for insulation co-ordination in UHV AC substations, than in HV substations. VFFO in GIS are of greater concern at UHV, because the ratio of the lightning impulse withstand voltage to the rated voltage is comparably low. VFFO can become the limiting dielectric stress.

Especially in the UHV range, the knowledge of the VFFO level is necessary as basis for the insulation co-ordination and the evaluation of potential risks and countermeasures. Because the VFFO are determined by superposition of traveling waves, they depend strongly on the specific configuration and it is not possible to give generally valid voltage values. It is necessary to perform a system analysis by accurate simulation for each substation to assess the VFFO.

As an indication, the required withstand voltage depends on the dielectric behavior of the equipment and the trapped charge behavior of the disconnector. As a result, the withstand voltages could vary for different equipment (transformer, SF_6 insulation, air insulation) and different disconnector design.

A three step procedure is recommended for VFFO insulation co-ordination. This procedure is outlined in Figure J.1, and its steps are described in Clause J.3.

A more detailed description of the procedure can be found in TB 519 [13]. The general approach is based on the insulation co-ordination procedure for the determination of rated or standard insulation level according to IEC 60071-1.

J.2 Influence of disconnector design

The value of the VFFO depends on the voltage drop at the disconnector just before striking. The voltage drop is dependent on the charge remaining on the load side of the disconnector from the preceding striking. The "trapped charge" is the charge remaining after the last striking of an opening operation, and the trapped charge voltage (TCV) is the voltage resulting from this charge.

This TCV is specific for each disconnector design and depends mainly on the contact speed and the field homogeneity of the contact system.

For slow acting disconnectors (contact speed < 1 m/s) the maximum trapped charge voltage lies well below 1 p.u. The resulting VFFO is in the range of 1,7 p.u. and reaches 2,0 p.u. for very specific cases.

Fast acting disconnectors (contact speed > 1 m/s) exhibit trapped charge levels up to 1 p.u. Consequently generally higher VFFO are produced compared to the slow acting disconnector. The integration of a damping resistor into the disconnector is a proven mitigation measure, VFFO amplitudes in the range around 1,3 p.u. can be reached.

J.3 Insulation co-ordination for VFFO

1) Step 1: Calculation of peak value and rise time of VFFO
   - System analysis (using a travelling wave computer simulation program).
   - Calculation of the maximum peak value $U_{max-VFFO}$ and rise time for the GIS and the connected equipment.
   - If known, the real trapped charge behavior of the disconnector should be used, i.e.
     - the 99 % probability value determined by simulation, or
     - maximum values measured during testing.
   - Otherwise, the worst case assumption of a trapped charge voltage of –1 p.u. should be used for the simulation.
   - The accuracy of the simulation model should be verified.

   In the context of insulation co-ordination process, travelling wave simulation is a well-established instrument. However, the accuracy of a VFFO simulation depends on the quality of the model of each individual GIS component. In order to achieve reasonable results, even for time periods of some micro-seconds or for very complex GIS structures, accurate models for all components, internal and external, connected to the GIS, are necessary. This allows for calculating VFFO which differ less than 5 % from measured voltage curves. The accuracy of a simulation is usually verified by VFFO measurement on a GIS test pole or the actual gas-insulated substation arrangement and the comparison of simulated and measured VFFO.

2) Step 2: Calculation of required VFFO withstand voltage ($U_{rw-VFFO}$) and comparison to LIWV

   The required VFFO withstand voltage $U_{rw-VFFO}$ should be calculated for the different equipment by multiplication of $U_{max-VFFO}$ with K-factors:
   - Co-ordination factor K_c: K_c covers the statistical distribution and frequency of occurrence of VFFO and the inaccuracy of simulation. In case of a proved simulation tool a co-ordination factor K_c of 1,05 is recommended. $U_{max-VFFO}$ multiplied with K_c gives the VFFO co-ordination voltage $U_{cw-VFFO}$.
   - Safety factor K_s and atmospheric correction factor K_t: K_s covers the aging behavior in service, quality of installation and other unknown influences. For external insulation a safety factor K_s of 1,05, for internal insulation (applicable for any equipment) a safety factor K_s of 1,15 is recommended. In case of external insulation the atmospheric correction factor K_t should be applied. $U_{cw-VFFO}$ multiplied with K_s and K_t gives the required VFFO withstand voltage $U_{rw-VFFO}$.

3) Step 3: Definition of measures according to the insulation co-ordination

   The required VFFO withstand voltage $U_{rw-VFFO}$ is compared to the LIWV in order to determine a risk of insulation failure. For this purpose, the required VFFO withstand voltage $U_{rw-VFFO}$ has to be multiplied with a test conversion factor K_{tc}:
   - K_{tc} describes the different withstand behavior under VFFO and standard LI voltage stress. For SF_6 insulated systems the recommended K_{tc} is 0,95. The recommended test conversion factor K_{tc} for oil or oil/solid insulated systems is 1,0.

   Based on the result of the comparison
   - if $K_{tc} \times U_{rw-VFFO} < \text{LIWV}$, no measures are required;
   - otherwise, measures to mitigate the risk of failure should be considered.

Mitigation may be achieved for instance by applying a disconnector with low(er) TCV or a disconnector with integrated damping resistor. Other measures may also be appropriate, for instance increasing of the LIWV.

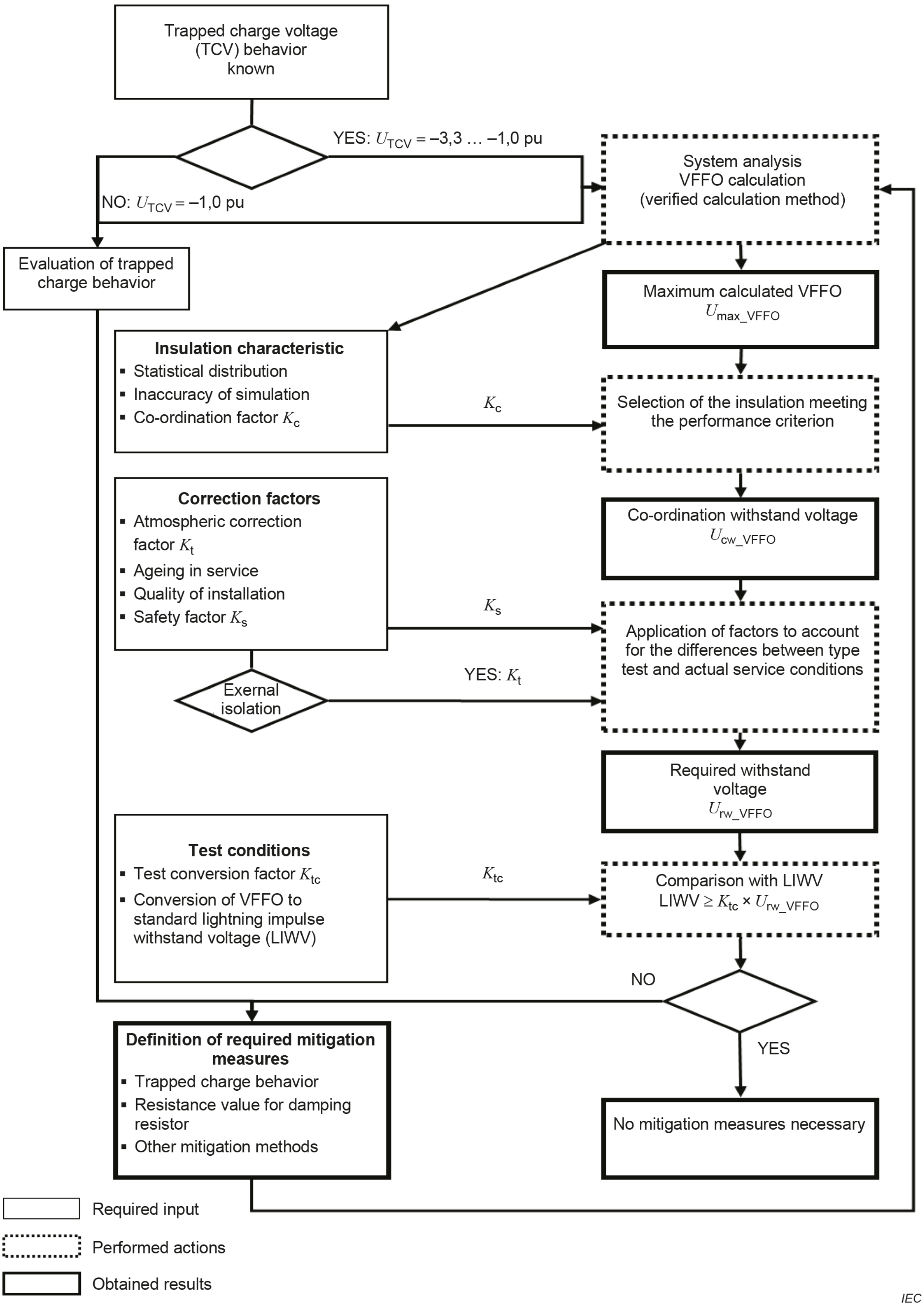


Figure J.1 – Insulation co-ordination for very-fast-front overvoltages

Annex K
(informative)

Application of shunt reactors to limit TOV and SFO of high voltage overhead transmission line

K.1 General remarks

A considerable number of overhead line or bus high-voltage shunt reactors (SR) are applied in the power grid of range II. The main purpose is to compensate the capacitive charging power of EHV and UHV overhead lines (hereinafter referred to as line) with a length of more than hundreds km and to balance the reactive power locally and stabilize the voltage during load variations of line. SR have the function of limiting TOV and SFO of the line, reducing the insulation level of line and substations and the self-excitation phenomenon can be eliminated caused by synchronous generator-transformer unit energizing unloaded long line. Combining with the neutral grounding reactor applied at the neutral point of SR, the secondary arc current can be restricted to be acceptable for adopting line fast single-phase reclosing.

K.2 Limitation of TOV and SFO

The effect of SR on limiting TOV of long line is related to the compensation factor K_{cmp}, which is defined as the ratio of reactive power of SR to reactive power of line positive sequence capacitance. K_{cmp} can be selected to reduce Ferranti effect and thus reduce TOV due to load rejection and earth fault with load rejection to meet the requirements both of predetermined TOV limitation and reactive power balance. The range of K_{cmp} is generally 70 %~90 %. The higher the K_{cmp} value is, the lower the TOV is. So the rated voltage of arresters can be reduced to obtain lower SIPL. Referring to IEC TR 60071-4 to establish TOV simulation model, the K_{cmp} value required to limit the rise of TOV along the line can be determined by digital program.

Since the SR reduces the TOV of the line, it reduces the forced component of the SFO caused by the unloaded line energization and single-phase reclosing. So SFO can be suppressed, natural frequency of unload line can be improved and the duration of SFO can be shortened. For the line breaker with pre-insert resistor, the compensation effect of SR reduces the current flowing through the pre-insert resistor, and SFO due to unloaded line energization is reduced. After the line de-energization, the residual charge on line is oscillatory released by the SR, which reduces the transient recovery voltage (TRV) between the contacts of the circuit breaker and prevents the re-ignition over-voltage produced by the re-ignition of the circuit breaker, and reduces the SFO caused by three-phase reclosing after line de-energization.

The installation location of the line SR should be determined according to whether the main function is TOV limitation of reactive power balance. Generally, for a line fed by single power plant, SR is installed at receive end of line to help synchronization operation of line circuit breakers with system. For a line fed by double power systems at both ends, SRs are installed at both ends of line or the end with larger system power capacity. However, SR is better to be de-energized if the power flow of line is heavy, to avoid increasing compensation capacity of capacitors banks installed at low-voltage side of the transformer.

K.3 Application of the neutral grounding reactor to limit resonance overvoltage and secondary arc current

During energization and de-energization of line with SR, if single-phase or two-phases of line breakers refuse to operate due to faults which is called Open Phase Operation state, the phase to earth inductance of SR in the open phase and the phase to phase capacitance between the live phase and the open phase will form a series resonant circuit, which may produce a linear resonant overvoltage or TOV on the open phase of the line. If the pure underground transmission line is composed of three single-phase GIL or high-voltage XLPE cable with grounding metal sheath outside the insulation of each phase conductor of cable, there is no phase to phase capacitance. So the Open Phase Operation of this underground transmission line will not produce linear resonance overvoltage on the open phases.

The TOV caused by linear resonance on the open phase can be limited by line arresters at the phase. The energy absorbed by the line arrester under the TOV depends on the fault clearing time after the Open Phase Protection of line breaker action. Whether the line arrester can withstand the TOV without damage or thermal instability can be checked according to its power-frequency voltage versus time characteristics. The measures to prevent linear resonance overvoltage due to Open Phase Operation of line are as follows:

– Choosing K_{cmp} value to avoid linear resonance overvoltage;
– Changing the neutral point of shunt reactor from direct grounding to grounding through a neutral grounding reactor.

For the lines with three-phase reclose operation, the Open Phase Operation belongs to the breaker failure operation, and the probability of occurrence is quite low. So neutral grounding reactor is not required. For the line with single-phase reclosing operation, after single-phase grounding fault, only fault phase breakers at both line ends open and the Open Phase Operation is the normal operation mode. Then, the non-fault two phases of line generate secondary arc current (SAC) on the grounding channel of the fault phase through the phase to phase capacitance and phase to phase mutual inductance between open phase and live two phase. When SAC extinguishes, TRV and even the linear resonance overvoltage appears on the open phase. If the TRV and SAC are too large, the arc current in grounding channel will re-ignites or delay extinguishes, resulting in the single-phase reclosing failure. The SAC and TRV can be limited by neutral grounding reactor. The principle of selecting the inductance value of neutral grounding reactor is to make the equivalent phase to phase reactance formed by it compensate the phase to phase capacitance of the line as much as possible. Then a parallel resonant circuit will be formed and the phase to phase impedance of the line tends to be infinite. In this way, the electrostatic induction of the open phase can be reduced, and there is only a small electromagnetic induction component in the SAC. Therefore, the amplitude and rising gradient of the TRV can be reduced, which accelerates the extinction of the SAC, and reduces the re-ignition probability, so as to adopt fast single-phase reclosing and improve the success rate of single-phase reclosing. The optimum value of neutral grounding reactor to limit SAC and TRV can be determined by digital program.

K.4 SFO and Beat frequency overvoltage limited by neutral arrester

The SFO and beat frequency overvoltage on the neutral grounding reactor will be caused by the non-synchronous operation of circuit breakers during the unloaded line energization/de-energization, the single-phase grounding fault or Open Phase Operation of the line, etc. and can be limited by the neutral arrester.

The rated voltage of neutral arrester can be selected without considering the continuous operation voltage. Instead, it is selected according to the TOV of the neutral grounding reactor caused by load rejection with asymmetrical earth fault. The duration of the TOV is generally no more than 0,5s. According to the ability to withstand the TOV for 0,5s, the rated voltage of the neutral arrester can be selected. Since the lightning overvoltage from the high voltage bushing of SR will be attenuated to the SFO when it is transferred to the neutral arrester, the nominal discharge current of neutral arrester cannot be selected according to the lightning discharge current. Instead, it is selected according to the energy absorption under SFO. Then the nominal discharge current is determined by corresponding thermal energy rating. The thermal energy rating is generally determined by beat frequency overvoltage caused by the Open Phase Operation of the line. The neutral arrester discharges continuously during 1-3 cycles of overvoltage at several ridge of beat frequency voltage until it decays. Beat frequency overvoltage can be classified as SFO. Due to the strongly non-linear V-I characteristics of the arrester, the influence of the front time of the neutral arrester discharge current impulse on the SIPL and insulation coordination of the SFO can be ignored. When the thermal energy rating of the neutral arrester is specified, repetitive discharge currents occurring during several cycles of the beat frequency overvoltage are considered as one single discharge, having an equivalent energy content and duration as the accumulated value of the actual energy impulses. Compared with the operation duty test verifying the arrester's ability of the thermal energy rating, the neutral arrester does not immediately withstand TOV equal to the rated voltage of the arrester and continuous operation voltage after absorbing rated thermal energy under the beat frequency voltage, so the specified thermal energy rating has sufficient safety margin.

K.5 SFO and FFO due to SR de-energization

Two kinds of overvoltage, chopping overvoltage and re-ignition overvoltage, which stress on the insulation of the SR are generated by SR de-energization. The former is similar to the SFO, and the latter is similar to the FFO. Arrester beside the SR, and the circuit breaker with the point on wave operation device can both effectively suppress the two kinds of overvoltages and see IEC 62271-100 for detailed information.

K.6 Limitation of TOV by Controllable SR

The application of controllable SR can automatically and smoothly adjust the reactive capacity with the change of transmission power, reduce the line loss and the capacity of the capacitor banks on the low voltage side of the transformers at the receive end. The controllable SR can be quickly adjusted to the rated capacity to limit the TOV during load rejection. In case of single-phase ground fault, the controllable SR can also be adjusted to the rated capacity quickly to coordinate with the neutral reactor and effectively restrain the SRC and TRV, thus improve the single-phase reclosing success rate. Controllable SR includes classified reactance regulation reactor, transformer low-voltage phase-controlled reactor and DC magnetizing reactor, etc.

K.7 Insulation coordination of the SR and neutral grounding reactor

The SR of the line or bus is to be protected directly by an arrester installed closely. Lightning overvoltage calculation is carried out to determine whether an arrester can be shared by the line SR and the line capacitance voltage transformer. Insulation level can be obtained by deterministic method according to impulse protect voltage of the arrester.

The insulation level of the neutral point of SR can be chosen as the same as that of neutral grounding reactor. Since the Insulation level of the neutral grounding reactor is within the range of range I apparatuses, the SIWV selected for the neutral grounding reactors should be converted into 1 minute power frequency withstand voltage and LIWV according to 8.2.1.

K.8 Self-excitation TOV of synchronous generator

The unloaded line energization of single synchronous generator- transformer unit may cause self- excitation TOV (parameter resonance over-voltage) of generator due to the periodic change of generator inductance parameter matching with the line capacitance. Line SR can be used to prevent self-excitation TOV.

Annex L
(informative)

Calculation of lightning stroke rate and lightning outage rate

L.1 General

It is important to evaluate the risk of lightning outages when designing especially large-sized transmission lines and substation facilities. In 1968, Armstrong and Whitehead proposed a relatively simple expression for the striking distance r (r = a × I b [m]; where I is the lightning current [kA], a = 6,72, b = 0,8) and then improved it by incorporating the electro-geometric model (EGM) to consider the stroke angle (A-W model). Later, other researchers proposed different values for the constants “a” and “b”. The lightning stroke rate to transmission lines is commonly predicted based on the A-W model, and the flashover rate (lightning outage rate) of the air gap insulation of transmission lines has been calculated based on distributed constant circuit theory to evaluate the overall risk.

CIGRE and IEEE have established the systematized and computer-programmed evaluation methods and are now widely used on a global basis. Further, other organizations have also independently developed evaluation methods. While these methods, namely the CIGRE method, IEEE’s FLASH, and others differ in detail, they have common basic principles. Recently, the new method has been developed utilizing the results of detailed field observations and large-scale experiments focusing on direct lightning strokes as well, and has been put into actual practice. In this Annex, the CIGRE and IEEE methods are reviewed, and further the new method is described as one example for a lightning outage evaluation method.

L.2 Description in CIGRE [37]

Figure L.1 outlines a general methodology for calculating the lightning outage rate of a transmission line in the CIGRE method. In the process, shielding failures and back-flashovers are calculated individually, and the sum of the two outage rates leads to the total lightning outage rate of the line. [47], [48]:

In the upper flow, the “Number of flashes to the line” (Box: B) is obtained from the “Lightning ground flash density” (Box: C) with Lightning Location Systems, Historical data, and the “Stroke attraction models (EGM or Leader Progression Model)” (Box: D). Meanwhile, in the lower flow, the “Probability of exceeding the critical current” (Box: E) is acquired based on the “Lightning current statistics (Observation results or Lightning location systems)” (Box: F), and the “Critical current” (Box: G). Finally, the “Lightning outage performance” (Box: A) is given by the product of the two quantities. More detailed description of the input data and subprocesses is in the reference [37].

Here, attention is to be paid to that the first return stroke currents of negative cloud-to-ground flashes are mainly supposed for estimates of the lightning performance of high-voltage transmission lines.

Furthermore, it is a customary practice to estimate the long-term average outage rate of the line, because the target phenomena are transient in nature. Also, it should be noticed that estimating the lightning performance of transmission lines described above is a complicated and uncertain task based on many assumptions and simplifications, which may lead to relatively limited accuracy and availability.

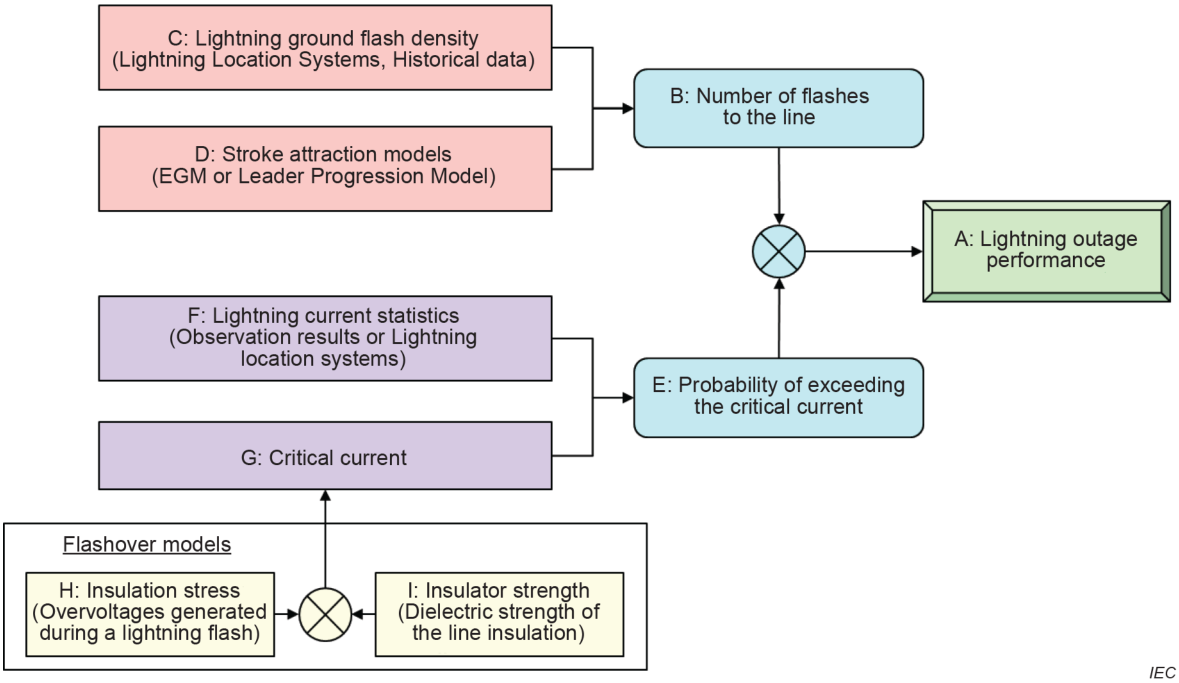


Figure L.1 – Outline of the CIGRE method for lightning performance of an overhead line

L.3 Flash program in IEEE [49]

The FLASH program was historically formed as an instrumentation of the IEEE methods [50], [51] for estimating lightning outage performance of overhead lines. Members of the IEEE PES Lightning Performance of Overhead Lines Working Group: 15.09.08, and its predecessor organizations, have developed this program (IEEE Flash is open-source software, available from www.sourceforge.net/projects/ieeeflash).

From technical viewpoint, the IEEE methods have come from the approach of J. G. Anderson [52], where a shielding-failure rate is obtained through 27 simple steps, and the back-flashover rate is calculated through 39 additional tasks. The FLASH program with increasing versions has been improved through frequent comparisons with observations, with coming into the present latest “FLASH 2.05”.

More detailed and concrete information for execution of the FLASH is available at https://sourceforge.net/projects/ieeeflash/.

L.4 [Case Study] Calculation of Lightning Stroke Rate and Lightning Outage Rate (Appendix D in CIGRE TB 839 [37])

L.4.1 Basic flow of calculation method

The basic flowchart is presented in Figure L.2 [53] for the calculation of the lightning outage rate of transmission lines, as well as the lightning stroke rate and other variables whose values are required as part of the calculation.

First, the lightning stroke rate to transmission lines is calculated based on an electro-geometric model (EGM). The new features include considering the lightning stroke current waveform distribution and revising the lightning stroke distance in consideration of the return stroke velocity distribution.

Next, for the lightning stroke probability to each conductor, the probability of a flashover across the air gap insulation of the transmission lines (mainly between arcing horns) is calculated. Here, the chance of a flashover occurring is judged and determined based on a comparison of the increased potential caused by a lightning stroke, also taking account of the AC phase of phase conductors, with the air gap withstand voltage between arcing horns. Subsequently, after a single line-to-ground (1LG) event, whether flashover will occur on other phases is judged in consideration of the potential decrease rate after the ground fault and thus calculation is continued and repeated for 2LG or a ground fault on additional phases.

The chance of a flashover occurring between conductors (e.g. ground wire – upper phase conductor) is also judged for lightning strokes to ground wires in mid-span. Whether a flashover caused by a lightning stroke will occur between arcing horns or between the ground wire and the upper phase conductor is predicted by calculation of the overvoltage across each insulation gap, based on distributed constant circuit theory. Simultaneous flashover is now also taken into consideration. The correction factors for estimating the flashover rate to the ground wire and to the ground have also been revised.

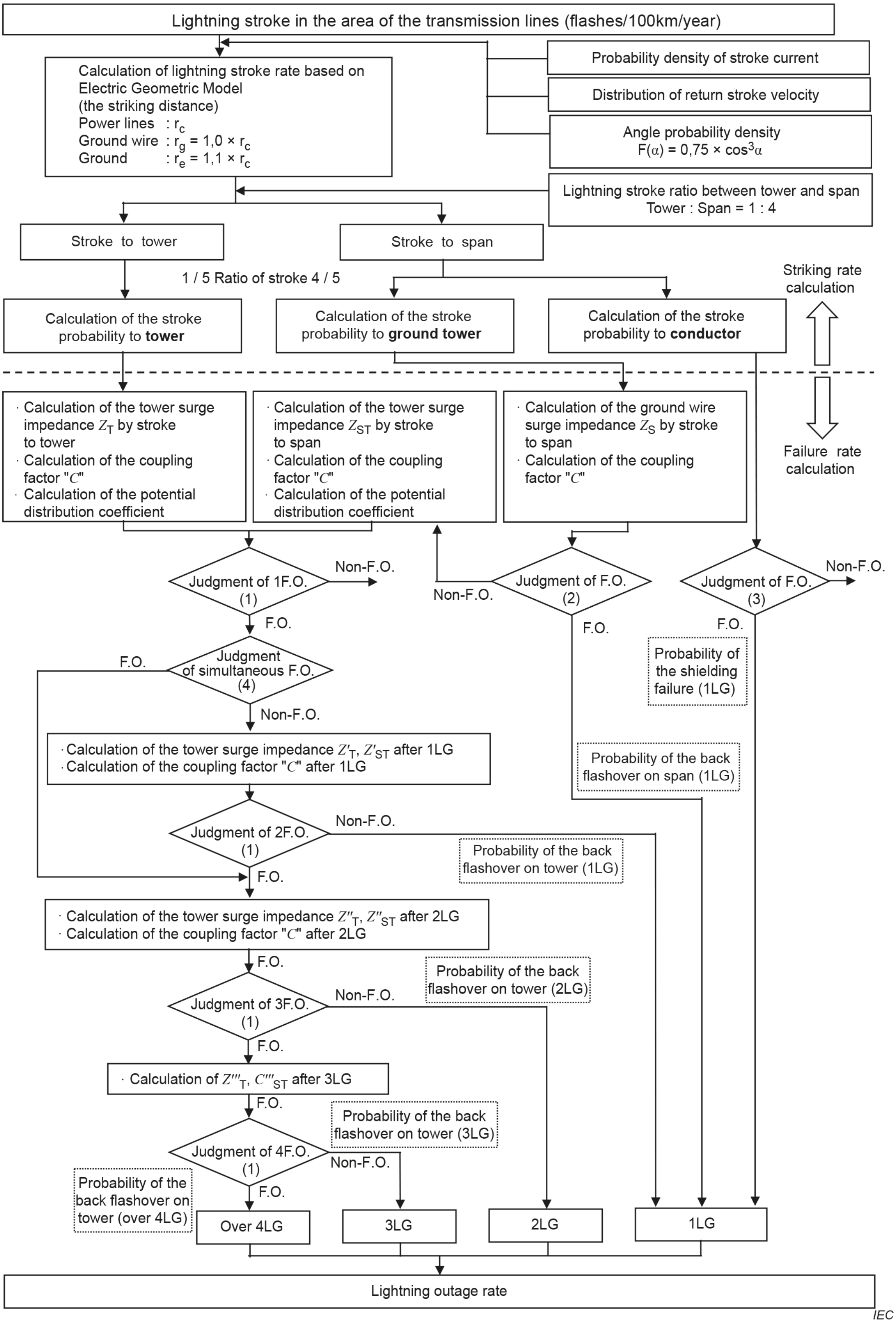


Figure L.2 – Flowchart to calculate lightning outage rate of transmission lines

L.4.2 Comparison of Calculation Results with Observations

L.4.2.1 Calculations on Lightning Strokes to Phase Conductor

Figure L.3 illustrates the representative conductor arrangements of UHV designed and 500 kV transmission lines used for the calculation. The calculated predictions of the present method developed are compared with actual observations regarding the “Lightning Strokes to Power Lines” in Figure L.4 [54]. The present method produces predictions closer to the actual observations, e.g. showing an increase in the lightning stroke rate to the upper phase power lines, while the conventional method did not match the observations, particularly in the distribution of strokes by phase.

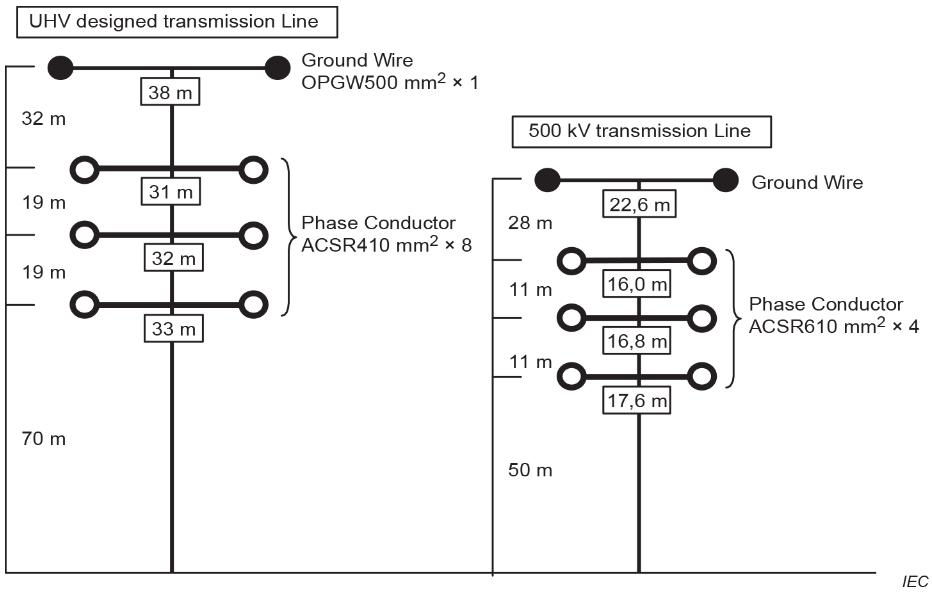
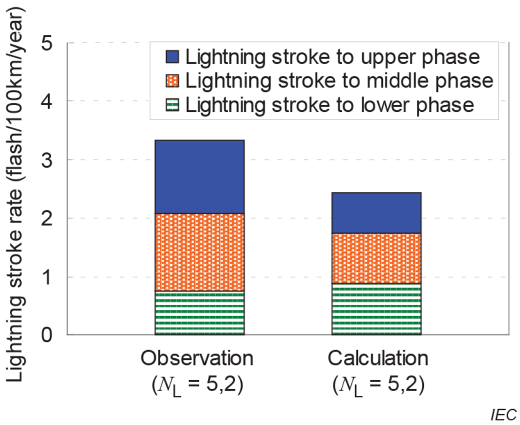
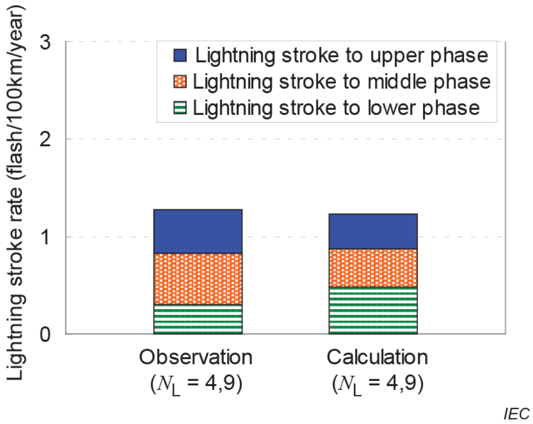


Figure L.3 – Typical conductor arrangements of large-scale transmission lines



(a) UHV designed transmission lines



(b) 500-kV transmission lines

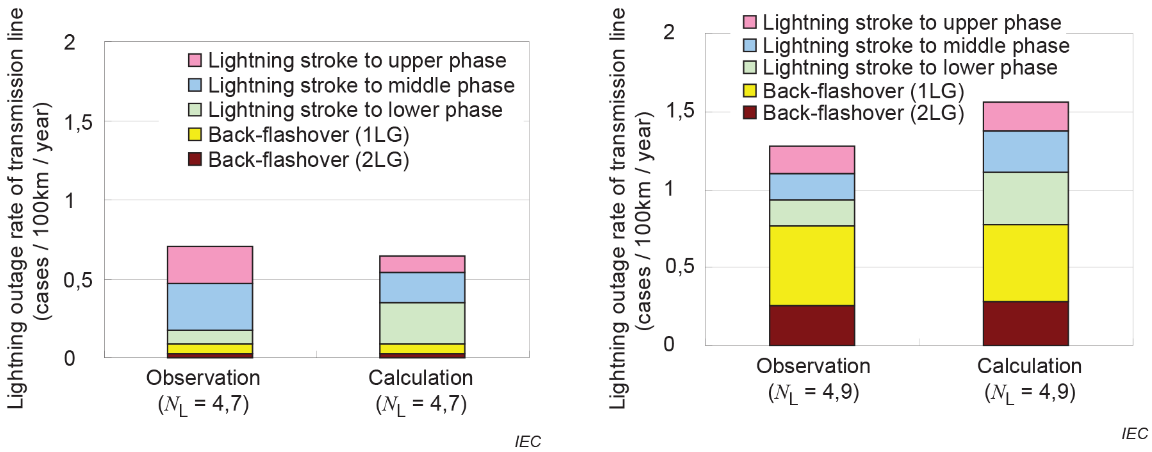
Figure L.4 – Lightning stroke rate to power lines -calculations and observations-

L.4.2.2 Calculations on lightning outage rate

For the lightning outage rate, the predictions of the present technique developed are compared with actual observations in Figure L.5 [55]. The representative conductor arrangements used for the calculation are shown in Figure L.3 above.

Conventional calculations tended to underestimate the actual outage rate in both UHV designed and 500 kV transmission lines. The difference in UHV designed transmission lines is caused by lightning strokes to the phase conductor, where the prediction was lower than the actuality, as well as the differing aspect of lightning outages, e.g. fewer predicted outages at upper phase conductors.

In contrast, the present technique presents predictions closer to the observed facts of lightning stroke rates to transmission lines. Furthermore, the lightning outage rate, which is calculated based on the lightning stroke rate, is also closer to the reality in terms of both the total number of outages and the occurrence of outages on different phases.



(a) UHV designed transmission lines **(b) 500-kV transmission lines**

Figure L.5 – Lightning outage rate -calculations and observations-

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(*Continued from second cover*)

The Committee has reviewed the provisions of the following international standards referred in this adopted standard and decided that they are acceptable for use in conjunction with this standard.

International Standard	*Title*
IEC 60060-1 : 2010	High-voltage test techniques — Part 1: General definitions and test requirements
IEC 60505 : 2011	Evaluation and qualification of electrical insulation systems

Only the English language text has been retained while adopting it in this Indian Standard, and as such, the page number given here are not the same as in the IEC publication.

For the purpose of deciding whether a particular requirement of this standard is complied with, the final value, observed or calculated expressing the result of a test, shall be rounded off in accordance with IS 2 : 2022 'Rules for rounding off numerical values (*second revision*)'. The number of significant places retained in the rounded off value should be the same as that of the specified value in this standard.

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Amendments Issued Since Publication

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