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Insulation co-ordination –

Part 2: Application guide

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FOREWORD

1) The IEC (International Electrotechnical Commission) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object to the IEC is to promote international cooperation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, the IEC publishes International Standards. Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. The IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.
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International Standard IEC 71-2, has been prepared by IEC technical committee 28: Insulation co-ordination.

This third edition cancels and replaces the second edition published in 1976 and constitutes a technical revision.

The text of this standard is based on the following documents:

FDIS	Report on voting
28/115/FDIS	28/117/RVD

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

Annex A forms an integral part of this standard.

Annexes B to J are for information only.

INSULATION CO-ORDINATION –

Part 2: Application guide

1 General

1.1 *Scope*

This part of IEC 71 constitutes an application guide and deals with the selection of insulation levels of equipment or installations for three-phase electrical systems. Its aim is to give guidance for the determination of the rated withstand voltages for ranges I and II of IEC 71-1 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 application guide.

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

It covers phase-to-earth, phase-to-phase and longitudinal insulation.

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

The content of this guide strictly follows the flow chart of the insulation co-ordination process presented in figure 1 of IEC 71-1. Clauses 2 to 5 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.

The guide emphasizes the necessity of considering, at the very beginning, all origins, all classes and all types of voltage stresses in service irrespective of the range of highest voltage for equipment. Only at the end of the process, when the selection of the standard withstand voltages takes place, does the principle of covering a particular service voltage stress by a standard withstand voltage apply. Also, at this final step, the guide refers to the correlation made in IEC 71-1 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.

1.2 *Normative references*

The following normative documents contain provisions which, through reference in this text, constitute provisions of this part of IEC 71. At the time of publication, the editions indicated were valid. All normative documents are subject to revision, and parties to agreements based on this part of IEC 71 are encouraged to investigate the possibility of applying the most recent editions of the normative documents indicated below. Members of IEC and ISO maintain registers of currently valid International Standards.

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

IEC 60-1: 1989, *High-voltage test techniques – Part 1: General definitions and test requirements*

IEC 71-1: 1993, *Insulation co-ordination – Part 1: Definitions, principles and rules*

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

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

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

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

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

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

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

1.3 *List of symbols and definitions*

For the purpose of this part of IEC 71, the following symbols and definitions apply. The symbol is followed by the unit to be normally considered, dimensionless quantities being indicated by (-).

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

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

c_f (p.u.) coupling factor of voltages between earth wire and phase conductor of overhead lines.

E_0 (kV/m) soil ionization gradient.

F function describing the cumulative distribution of overvoltage amplitudes, where $F(U) = 1 - P(U)$. See annex C.3.

f function describing the probability density of overvoltage amplitudes.

g (-) ratio of capacitively transferred surges.

H (m) altitude above sea-level.

h (-) power-frequency voltage factor for transferred surges in transformers.

Ht (m) height above ground.

I (kA) lightning current amplitude.

I_g (kA) limit lightning current in tower footing resistance calculation.

J (-) winding factor for inductively transferred surges in transformers.

K (-) gap factor taking into account the influence of the gap configuration on the strength.

K_a (-) atmospheric correction factor. [3.28 of IEC 71-1]

K_c (-) co-ordination factor. [3.25 of IEC 71-1]

K_s (-) safety factor. [3.29 of IEC 71-1]

K_{cd} (-) deterministic co-ordination factor.

K_{co} (µs/(kVm)) corona damping constant.

K_{cs} (-) statistical co-ordination factor.

K_{ff}^{+} (-) gap factor for fast-front impulses of positive polarity.

K_{ff}^{-} (-) gap factor for fast-front impulses of negative polarity.

k (-) earth-fault factor. [3.15 of IEC 71-1]

L (m) separation distance between surge arrester and protected equipment.

L_a (m) overhead line length yielding to an outage rate equal to the acceptable one (related to R_a).

L_t (m) overhead line length for which the lightning outage rate is equal to the adopted return rate (related to R_t).

L_{sp} (m) span length.

M (-) number of insulations in parallel considered to be simultaneously stressed by an overvoltage.

m (-) exponent in the atmospheric correction factor formula for external insulation withstand.

N (-) number of conventional deviations between U_{50} and U_0 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.

R (-) risk of failure (failures per event).

R_a (1/a) acceptable failure rate for apparatus. For transmission lines, this parameter is normally expressed in terms of (1/a)/100 km.

R_{hc} (Ω) high current value of the tower footing resistance.

R_{km} (1/(m.a)) overhead line outage rate per year for a design corresponding to the first kilometre in front of the station.

R_{lc} (Ω) low current value of the tower footing resistance.

R_p (1/a) shielding penetration rate of overhead lines.

R_{sf} (1/a) shielding failure flashover rate of overhead lines.

R_t (1/a) adopted overvoltage return rate (reference value).

R_u (kV) radius of a circle in the U^+/U^- plane describing the phase-phase-earth slow-front overvoltages.

R_0 (Ω) zero sequence resistance.

R_1 (Ω) positive sequence resistance.

R_2 (Ω) negative sequence resistance.

S (kV/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 (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_0 (kV) truncation value of the discharge probability function $P(U)$ of a self-restoring insulation: $P(U \leq U_0) = 0$.

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 71-1.

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) positive component defining the centre of a circle which describes the phase-phase-earth slow-front overvoltages.

U_c^- (kV) negative component defining the centre of a circle which describes the phase-phase-earth slow-front overvoltages.

U_{cw}	(kV)	co-ordination withstand voltage of equipment. [3.24 of IEC 71-1]
U_e	(kV)	amplitude of a phase-to-earth overvoltage.
U_{et}	(kV)	truncation value of the cumulative distribution $F(U_e)$ of the phase-to-earth overvoltages: $F(U_e \geq U_{et}) = 0$; see annex C.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 annex C.3.
U_{e50}	(kV)	50 % value of the cumulative distribution $F(U_e)$ of the phase-to-earth overvoltages; see annex C.3.
U_l	(kV)	amplitude of the impinging lightning overvoltage surge.
U_m	(kV)	highest voltage for equipment. [3.10 of IEC 71-1]
U_p	(kV)	amplitude of a phase-to-phase overvoltage.
U_{p2}	(kV)	value of the phase-to-phase overvoltage having a 2 % probability of being exceeded: $F(U_p \geq U_{p2}) = 0{,}02$; see annex C.3.
U_{p50}	(kV)	50 % value of the cumulative distribution $F(U_p)$ of the phase-to-phase overvoltages; see annex C.3.
U_s	(kV)	highest voltage of a system. [3.9 of IEC 71-1]
U_w	(kV)	standard withstand voltage.
U_{pl}	(kV)	lightning impulse protective level of a surge arrester. [3.21 of IEC 71-1]
U_{ps}	(kV)	switching impulse protective level of a surge arrester. [3.21 of IEC 71-1]
U_{pt}	(kV)	truncation value of the cumulative distribution $F(U_p)$ of the phase-to-phase overvoltages: $F(U_p \geq U_{pt}) = 0$; see annex C.3.
U_{rp}	(kV)	amplitude of the representative overvoltage. [3.19 of IEC 71-1]
U_{rw}	(kV)	required withstand voltage. [3.27 of IEC 71-1]
U_{T1}	(kV)	overvoltage applied at the primary winding of a transformer which produces (by transference) an overvoltage on the secondary winding.
U_{T2}	(kV)	overvoltage at the secondary winding of a transformer produced (by transference) by an overvoltage applied on the primary winding.
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	(-)	ratio of transformer secondary to primary phase-to-phase voltage.
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.
δ	(kV)	truncation value of a Weibull cumulative function.
Φ		Gaussian integral function.
ϕ	(-)	inclination angle of a phase-to-phase insulation characteristic.
γ	(-)	shape parameter of a Weibull-3 cumulative function.
σ	(p.u.)	per unit value of the conventional deviation (S_e or S_p) of an overvoltage distribution.
ρ	(Ωm)	soil resistivity.
τ	(µs)	tail time constant of a lightning overvoltage due to back-flashovers on overhead lines.

2 Representative voltage stresses in service

2.1 *Origin and classification of voltage stresses*

In IEC 71-1 the voltage stresses are classified by suitable parameters such as the duration of the power-frequency voltage or the shape of an overvoltage according to their effect on the insulation or on the protective device. The voltage stresses within these classes have several origins:

- continuous (power-frequency) voltages: 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 2.3. 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 E).

In general, all classes of overvoltages may exist in both voltage ranges I and II. 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 guide. 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.

2.2 *Characteristics of overvoltage protective devices*

2.2.1 *General remarks*

Two types of standardized protective devices are considered:

– non-linear resistor-type surge arresters with series gaps;

– metal-oxide surge arresters without gaps.

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

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

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

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

2.2.2.1 *Protection characteristics related to fast-front overvoltages*

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

– the sparkover voltage for a standard full lightning impulse;

– the residual voltage at the selected nominal discharge current;

– the front-of-wave sparkover voltage.

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

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

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

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

2.2.2.2 *Protection characteristics related to slow-front overvoltages*

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

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

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

2.2.3 *Metal oxide surge arresters without gaps*

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

2.2.3.1 *Protection characteristics related to fast-front overvoltages*

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

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

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

2.2.3.2 *Protection characteristics related to slow-front overvoltages*

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

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

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

2.2.4 *Spark gaps*

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

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

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

2.3 *Representative voltages and overvoltages*

2.3.1 *Continuous (power-frequency) voltages*

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.

2.3.2 *Temporary overvoltages*

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;

– the amplitude/duration power frequency withstand characteristic of the insulation considered.

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

In particular cases, a statistical co-ordination procedure may be adopted describing the representative overvoltage by an amplitude/duration distribution frequency of the temporary overvoltages expected in service (see 3.3.1).

2.3.2.1 *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 B. In normal system configurations, the representative overvoltage amplitude should be assumed equal to its maximum value. Abnormal system configurations, e.g. system parts with unearthed neutrals in a normally earthed neutral system, should be dealt with separately, taking into account their probability of occurrence simultaneously with earth faults.

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

NOTE – Attention is drawn to the fact that the highest voltage at power-frequency which may 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.

2.3.2.2 *Load rejection*

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

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

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

NOTE – From the point of view of overvoltages, a distinction should be made between various types of system layouts. As examples, the following extreme cases may 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 usual in the extra-high voltage range at their initial stage, and on which very high overvoltages may 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: $\sqrt{2}\,U_s/\sqrt{3}$):

– 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).

2.3.2.3 *Resonance and ferroresonance*

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

Temporary overvoltages due to resonance phenomena can reach extremely high values. They shall be prevented or limited by measures recommended in 2.3.2.6. 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 2.3.2.7).

2.3.2.4 *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.

2.3.2.5 *Combinations of temporary overvoltage origins*

Temporary overvoltages of different origin 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.

2.3.2.5.1 *Earth fault with load rejection*

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

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

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.

2.3.2.5.2 *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.

2.3.2.6 *Limitation of temporary overvoltages*

2.3.2.6.1 *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.

2.3.2.6.2 *Sudden changes of load*

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

2.3.2.6.3 *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.

2.3.2.7 *Surge arrester protection against temporary overvoltages*

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

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

2.3.3 *Slow-front overvoltages*

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;
- 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 2500 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 C).

The assumed maximum value of the representative overvoltage is equal to the truncation value of the overvoltages (see 2.3.3.1 to 2.3.3.6) or equal to the switching impulse protective level of the surge arrester (see 2.3.3.7), whichever is the lower value.

2.3.3.1 *Overvoltages due to line energization and re-energization*

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

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

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* Figures in square brackets refer to the bibliography given in annex J.

– **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, on insulator surface conductivity, or on conductor corona conditions, and on the 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 D, figure 1 may be used for both the phase-peak and case-peak methods.

2.3.3.1.1 *Phase-to-earth overvoltages*

A procedure for the estimation of the probability distribution of the representative overvoltages is given in annex D.

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

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

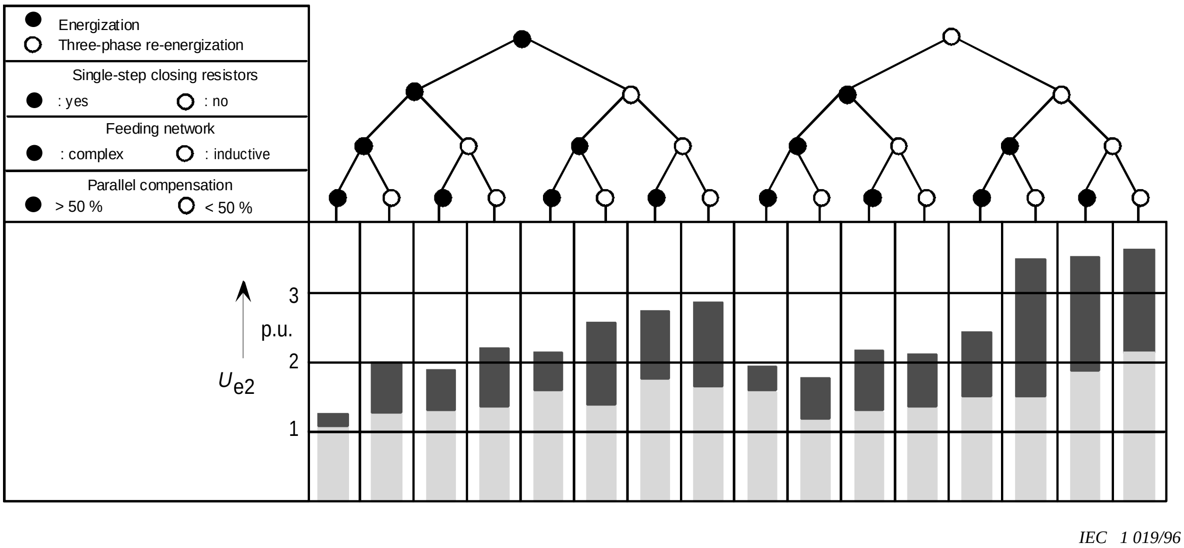


Figure 1 – Range of 2 % slow-front overvoltages at the receiving end due to line energization and re-energization

2.3.3.1.2 *Phase-to-phase overvoltages*

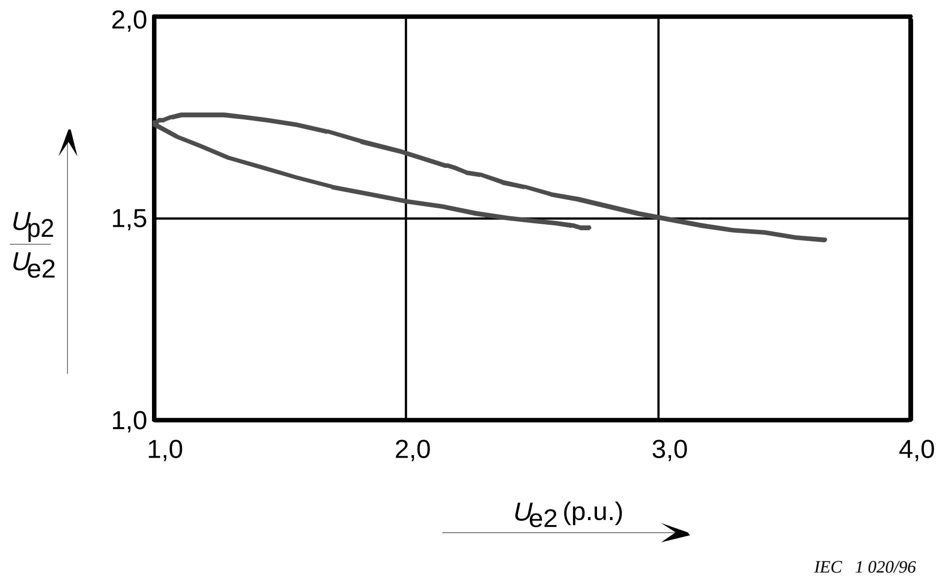
In the evaluation of the phase-to-phase overvoltages, an additional parameter needs to be added. As the insulation is sensitive to the subdivision of a given phase-to-phase overvoltage value into two phase-to-earth components, the selection of a specific instant shall take into account the insulation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

a) **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;

b) **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 D. 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 D.

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



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

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

2.3.3.1.3 *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.

2.3.3.1.4 *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 D, 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).

2.3.3.2 *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)

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

where k is the earth-fault factor.

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.

2.3.3.3 *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.

2.3.3.4 *Overvoltages due to switching of inductive and capacitive currents*

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

– interruption of the starting currents of motors;

– interruption of inductive currents, e.g. when interrupting the magnetizing current of a transformer or when switching off a shunt reactor [6];

– switching and operation of arc furnaces and their transformers, which may lead to current chopping;

– switching of unloaded cables and of capacitor banks;

– interruption of currents by high-voltage fuses.

Restrikes of circuit-breakers occurring while interrupting capacitive currents (switching off unloaded lines, cables or capacitor banks) may generate particularly dangerous overvoltages and the use of restrike-free breakers is necessary. Furthermore, when energizing capacitor banks, in particular ungrounded banks, care should be taken to assess the phase-to-phase overvoltages (see also 2.3.4.3).

2.3.3.5 *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.

2.3.3.6 *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.

2.3.3.7 *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. It should be noted that when the arresters are installed at the ends of long transmission lines for the purpose of limiting slow-front overvoltages, the overvoltages in the middle of the line may 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 r.m.s). 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 less than about 0,5 – 2 kA through the arresters. In this current range the knowledge of the exact current amplitude is not so important owing to the extreme non-linearity of the metal-oxide material. The slight dependence on current front times which the metal-oxide surge arresters exhibit is also negligible for slow-front overvoltages and can be neglected. Furthermore, it is not necessary to take separation effects into account within substations. Distant overhead line insulation, however, may be stressed by overvoltages substantially higher than the protective level.

Surge arresters are usually installed phase-to-earth and it should be observed that, if metal-oxide arresters are used to limit slow-front overvoltages to a level lower than 70 % of the 2 % value of the uncontrolled overvoltage phase-to-earth, the phase-to-phase overvoltages may reach about twice the phase-to-earth protective 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 3.3.3.1.

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

For the phase-to-phase overvoltages it is twice the protective level or the truncation value of the phase-to-phase overvoltages determined in annex D, 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 class.

2.3.4 *Fast-front overvoltages*

2.3.4.1 *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.

2.3.4.2 *Lightning overvoltages affecting substations*

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;

– 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 F).

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

2.3.4.2.1 *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 lighting 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;
- 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.

2.3.4.2.2 *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).

2.3.4.3 *Overvoltages due to switching operations and faults*

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

Although in general oscillatory, for insulation co-ordination purposes the representative overvoltage shape can be considered to correspond to the standard lightning impulse (1,2/50 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. As the overvoltage peak values are usually smaller than those caused by lightning, their importance is restricted to special cases. It is, therefore, technically justified to characterize the amplitude of the representative overvoltage by the maximum following values (in p.u. of $\sqrt{2}\,U_s/\sqrt{3}$):

- 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 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.

2.3.4.4 *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:

– 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.

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.

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.).

2.3.4.5 *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);

– the number and surge impedance of the connected lines.

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

– for systems with U_m in range I: 5 kA or 10 kA;

– for systems with U_m in range II: 10 kA or 20 kA.

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

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

The protective characteristics of a surge arrester are only valid at its location. The corresponding overvoltage limitation at the equipment location, therefore, should account for the separation between the two locations. The greater the separation distance of the surge arrester from the protected equipment, the less is its protection efficient for this equipment, and, in fact, the overvoltage applied to the equipment increases above the protective level of the arrester with increasing separation distance. Furthermore, if the effect due to the length of the arrester is neglected in the determination of its protection characteristics, this length must 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, formula (1) can be used. However, for transformer protection, formula (1) should be used with caution since a capacitance of more than a few hundred picofarads may result in higher overvoltages.

$$U_{rp} = U_{pl} + 2\,ST \qquad \text{for } U_{pl} \geq 2ST \qquad (1)$$

$$U_{rp} = 2\,U_{pl} \qquad \text{for } U_{pl} < 2ST \qquad (2)$$

where

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

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

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

$$T = L\,/\,c \qquad (3)$$

where

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

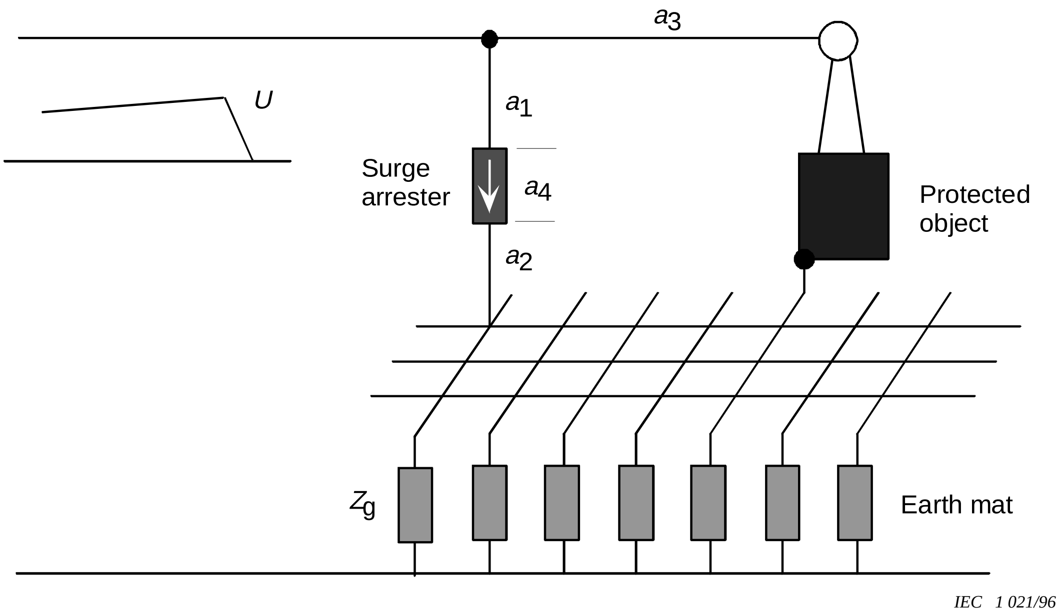
$L = a_1 + a_2 + a_3 + a_4$: distances from figure 3 (m).

The values of the steepness must 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 F.

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 F.

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 F. 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 F.



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

a_2 : length of the lead connecting the surge arrester to earth

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

a_4 : length of the active part of the surge arrester

Z_g : earthing impedance

U : impinging overvoltage surge.

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

2.3.5 *Very-fast-front overvoltages*

Very-fast-front overvoltages 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, e.g. at a bushing, and their front times are usually increased into the range of those of fast-front overvoltages. Very-fast-front overvoltages may also occur at medium voltage dry-type transformers with short connections to the switchgear.

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

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

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

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

3 Co-ordination withstand voltage

3.1 *Insulation strength characteristics*

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

Breakdown takes place in three main stages:

– the initial ionization at a point or points;

– the growth of an ionized channel across the gap;

– the bridging of the gap and the transition to a self-sustaining discharge.

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

– the magnitude, shape, duration and polarity of the applied voltage;

– the electric field distribution in the insulation: homogeneous or non-homogeneous electric field, electrodes adjacent to the considered gap and their potential;

– the type of insulation: gaseous, liquid, solid or a combination of these. The impurity content and the presence of local inhomogeneities;

– the physical state of the insulation: temperature, pressure and other ambient conditions, mechanical stress, etc. The history of the insulation may also have an importance;

– the deformation of the insulation under stress, chemical effects, conductor surface effects, etc.

Breakdown in air is strongly dependent on the gap configuration and on the polarity and wave shape of the applied voltage stress. In addition, relative atmospheric conditions affect the breakdown strength regardless of shape and polarity of applied stress. Relationships for the breakdown strength of air derived from laboratory measurements are referred to standard atmospheric conditions as defined by IEC 60-1, i.e.:

– temperature : 20 °C;

– pressure : 101,3 kPa (1013 mbar);

– absolute humidity : 11 g/m^3.

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

For outdoor insulation, the effects of humidity, rain, and surface contamination become particularly important. IEC 60-1 also defines test procedures for external insulation in dry and wet conditions. For metal-enclosed gas-insulated switchgear, the effect of the internal pressure and temperature as well as local inhomogeneities and impurities play a significant role.

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

The breakdown process is also statistical in nature and this should be taken into account. Due to the restoring feature of self-restoring insulation, its statistical response to stresses can be obtained by suitable tests. Therefore, self-restoring insulation is typically described by the statistical withstand voltage corresponding to a withstand probability of 90 %. For non-self-restoring insulation, the statistical nature of the strength cannot usually be found by testing and the assumed withstand voltage deemed to correspond to a withstand probability of 100 % is applied (see definition 3.23 of IEC 71-1).

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 3.1.1 to 3.1.4 give information on the different factors influencing the insulation response. For more detailed information, reference can be made to the CIGRE technical brochure [7].

3.1.1 *Influence of polarity and overvoltage shapes*

3.1.1.1 *Influence of overvoltage polarity*

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

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

3.1.1.2 *Influence of overvoltage shape*

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

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

For external insulation, it is typical that for each gap length there is an impulse time-to-peak for which the breakdown voltage is a minimum (the critical time to peak). Usually the minimum is in the range of times-to-peak for slow-front overvoltages. The larger the gap length, the more pronounced is the minimum. For air gaps in range I the effect is negligible and can be ignored. For air clearances to be used in range II, this minimum breakdown voltage is, to all intents and purposes, equal to the breakdown voltage at the standard 250 µs time-to-peak. This means that the use of the withstand voltage of the insulation at the standard voltage shape 250/2500 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.

3.1.2 *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 D); tests to verify the required withstand voltage shall therefore be so designed as to reflect this phenomenon. The representative overvoltage shape standardized in IEC 71-1 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 2.3.3.1 and annex D where a particular example is given).

For longitudinal insulation structures, the voltage components are specified by the representative overvoltages (see clause 2).

The values for the conventional deviation for the phase-to-earth insulation strength given in 3.1.4 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.

3.1.3 *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 60-1 for different types of voltage stresses.

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

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

3.1.4 *Probability of disruptive discharge of insulation*

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

For self-restoring insulation, the ability to withstand dielectric stresses caused by the application of an impulse of given shape can be described in statistical terms. The methods to be followed in the determination of the withstand probability curve are given in IEC 60-1. For a given insulation, and for impulses of given shape and different peak values U, a discharge probability P can be associated with every possible value U, thus establishing a relationship $P = P(U)$. Usually the function P is monotonically increasing with values of U. The resulting curve can be defined by three parameters:

a) U_{50}: corresponding to the voltage under which the insulation has a 50 % probability to flashover or to withstand;

b) Z: the conventional deviation which represents the scatter of flashover voltages. It is defined as the difference between the voltages corresponding to flashover probabilities 50 % and 16 % as shown in equation (4):

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

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

Usually the function P is given by a mathematical function (cumulative probability distribution) which is fully described by parameters U_{50}, Z and U_0. 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 coordination 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 C). Equation (5) represents a Weibull cumulative function with parameters chosen to match a Gaussian cumulative probability function at the 50 % and 16 % probability of flashover and to truncate the distribution at $U_{50} - NZ$ (see annex C).

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

where

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

x being the number of conventional deviations corresponding to U, and

N being the number of conventional deviations corresponding to the truncation voltage U_0 for which $P(U_0) = 0$.

At one conventional deviation of the Gaussian probability distribution (at $x = -1$) $P(U) = 0,16$ in equation (5). If $N = 4$ is chosen, then the exact value of γ must 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 guide is described in equation (6).

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

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

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

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

The influence of weather conditions (refer to 3.1.3) is included in the values of derived deviations given above.

In IEC 71-1 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 C contains detailed information and statistical formulae to be applied in the context of many identical insulations in parallel being simultaneously stressed.

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

3.2 *Performance criterion*

According to definition 3.22 of IEC 71-1, the performance criterion to be required from the insulation in service is the acceptable failure rate (R_a).

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

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

3.3 *Insulation co-ordination procedures*

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.

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);

– 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.

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, e.g. using Monte Carlo methods.

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

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

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

The co-ordination withstand voltage for the continuous (power-frequency) voltage is equal to the highest system voltage for phase-to-phase and 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 2.3.1) with a duration equal to the service life.

With the deterministic method, the co-ordination short-duration withstand voltage is equal to the representative temporary overvoltage. When a statistical procedure is adopted and the representative temporary overvoltage is given by an amplitude/duration distribution frequency characteristic (see 2.3.2), the insulation that meets the performance criterion shall be determined, and the amplitude of the co-ordination withstand voltage shall be equal to that corresponding to the duration of 1 min on the amplitude/duration withstand characteristic of the insulation.

3.3.1.1 *Pollution*

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

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

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

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

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

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

Table 1 – Recommended creepage distances

Pollution level	Examples of typical environments	Minimum nominal specific creepage distance mm/kV [1)]
I Light	– Areas without industries and with low density of houses equipped with heating plants – Areas with low density of industries or houses but subjected to frequent winds and/or rainfall – Agriculture areas[2)] – Mountainous areas – All these areas shall be situated at least 10 km to 20 km from the sea and shall not be exposed to winds directly from the sea[3)]	16,0
II Medium	– Areas with industries not producing particularly polluting smoke and/or with average density of houses equipped with heating plants – Areas with high density of houses and/or industries but subjected to frequent winds and/or rainfall – Areas exposed to wind from the sea but not too close to coasts (at least several kilometres distant)[3)]	20,0
III Heavy	– Areas with high density of industries and suburbs of large cities with high density of heating plants producing pollution – Areas close to the sea or in any case exposed to relatively strong winds from the sea[3)]	25,0
IV Very heavy	– Areas generally of moderate extent, subjected to conductive dusts and to industrial smoke producing particularly thick conductive deposits – Areas generally of moderate extent, very close to the coast and exposed to sea-spray or to very strong and polluting winds from the sea – Desert areas, characterized by no rain for long periods, exposed to strong winds carrying sand and salt, and subjected to regular condensation	31,0

NOTE – This table should be applied only to glass or porcelain insulation and does not cover some environmental situations such as snow and ice in heavy pollution, heavy rain, arid areas, etc.

1) According to IEC 815, minimum creepage distance of insulators between phase and earth related to the highest system voltage (phase-to-phase).

2) Use of fertilizers by spraying, or the burning of crop residues can lead to a higher pollution level due to dispersal by wind.

3) Distances from sea coast depend on the topography of the coastal area and on the extreme wind conditions.

3.3.2 *Insulation co-ordination procedures for slow-front overvoltages*

3.3.2.1 *Deterministic method*

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

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

For equipment not protected by surge arresters, the assumed maximum overvoltage is equal to the truncation value (U_{et} or U_{pt}) according to 2.3.3.1 and the deterministic co-ordination factor is K_{cd} = 1.

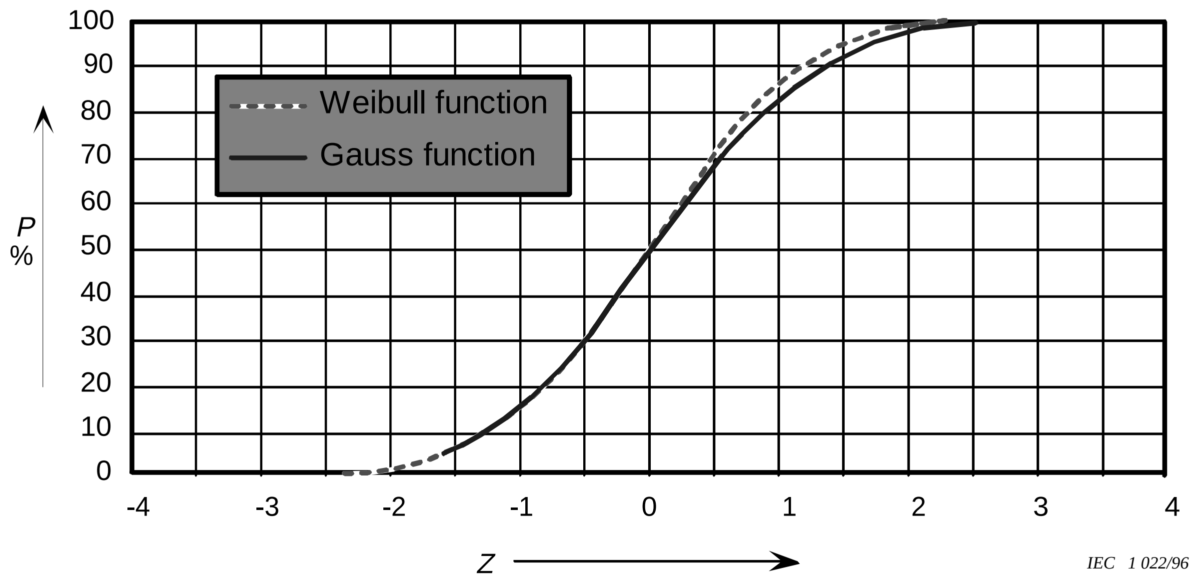


Figure 4 – Distributive discharge probability of self-restoring insulation described on a linear scale

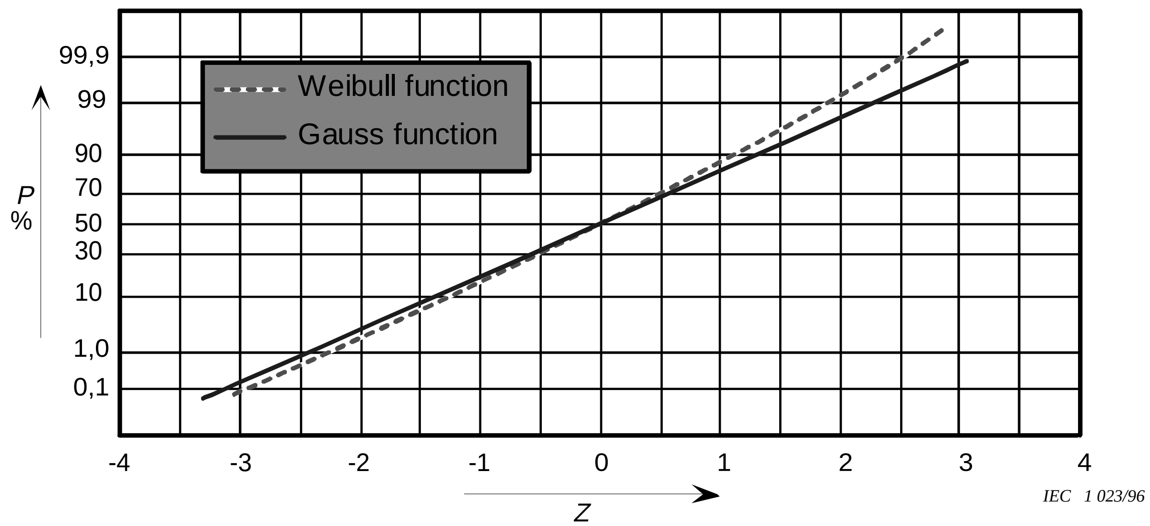
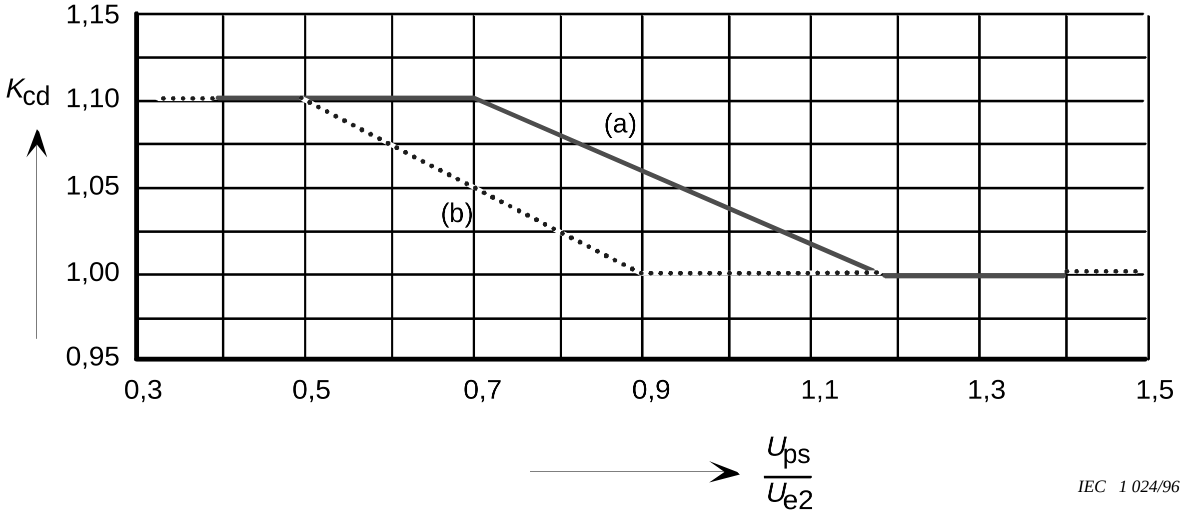


Figure 5 – Disruptive discharge probability of self-restoring insulation described on a Gaussian scale



a): coordination factor applied to the surge arrester protective 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 protective level to obtain the co-ordination withstand voltage phase-to-phase.

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

3.3.2.2 *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 3.2, 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 guide 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.

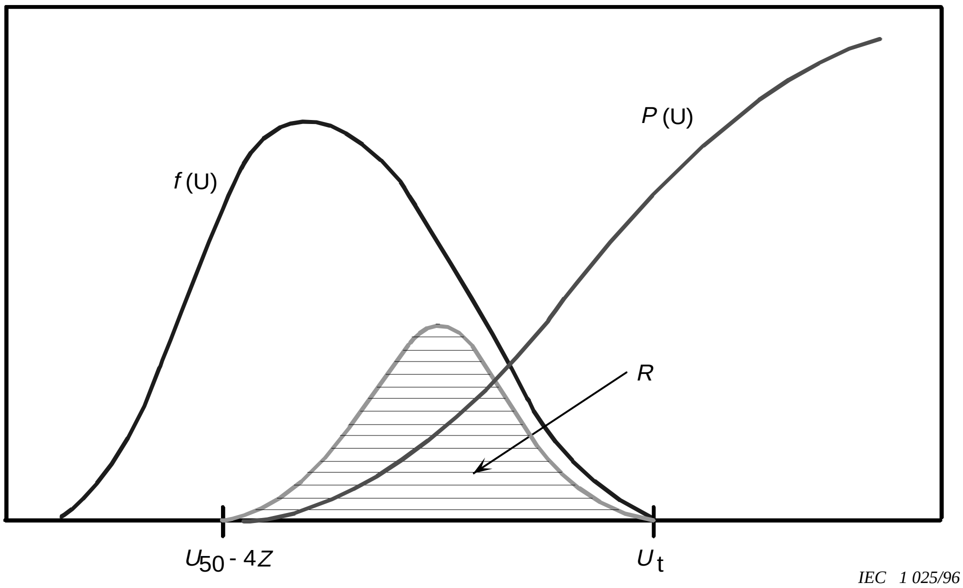
Once the frequency distribution of the overvoltages and the corresponding breakdown probability distribution of the insulation are given, the risk of failure of the insulation between phase and earth can be calculated as follows:

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

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 7).



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

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

$P(U)$ = discharge probability of insulation described by a modified Weibull function

U_t = truncation value of the overvoltage probability distribution

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

Figure 7 – Evaluation of the risk of failure

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

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

If the overvoltage distribution is based on the phase-peak method (see 2.3.3.1), and the insulations in the three phases are the same, the total risk of failure is:

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

If the case-peak method (see 2.3.3.1) is used, the total risk is: $R_{total} = R$

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

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

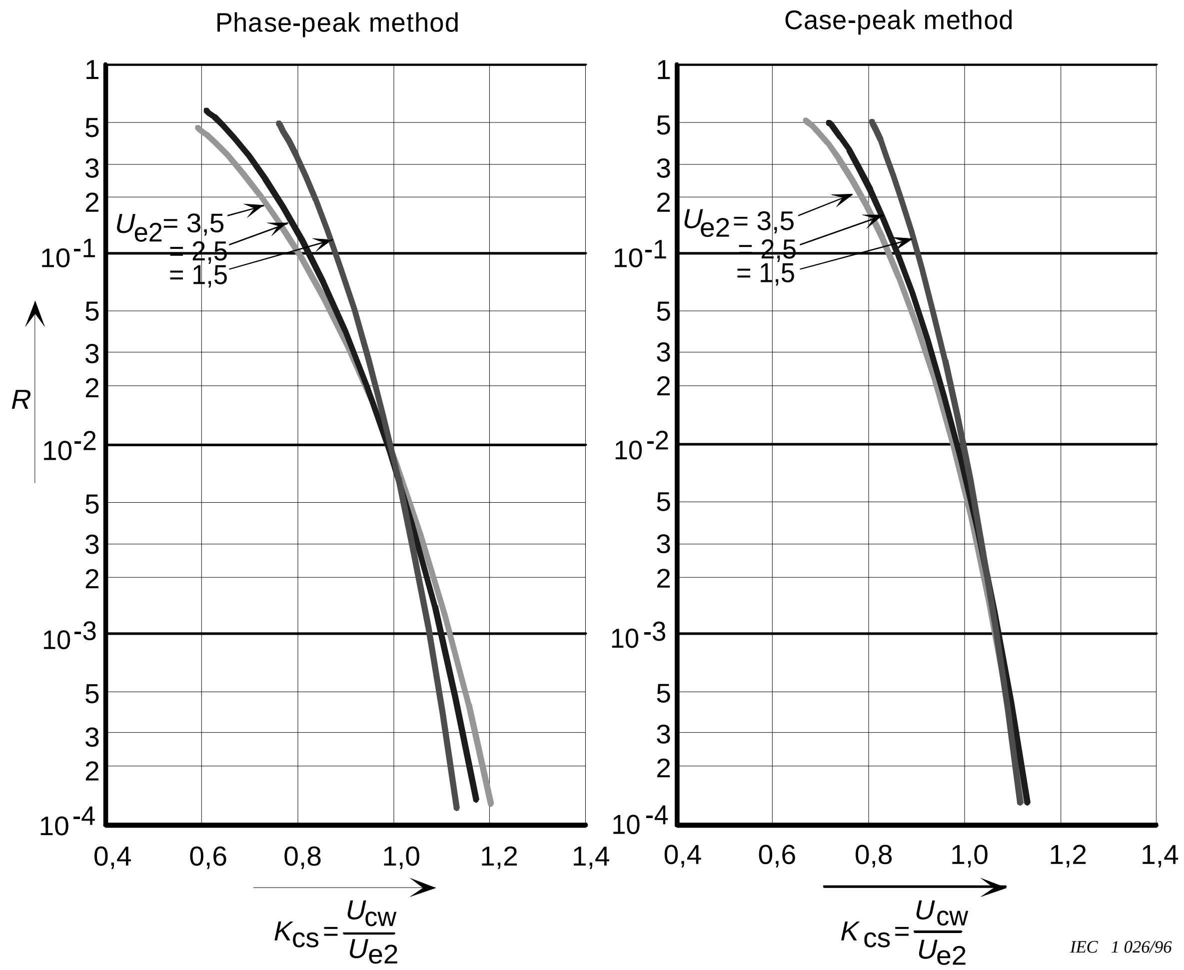
For the important case of the application of the statistical method to many identical parallel insulations, see detailed discussion in annex C.

Simplified statistical method for slow-front overvoltages

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

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

Figure 8 shows an example of the relationship between the risk of failure and the statistical co-ordination factor for both the phase-peak and the case-peak methods outlined in annex D, 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 D. Extreme variations in the deviation of the insulation strength, markedly non-Gaussian distribution of overvoltage and, most of all, the shape of the overvoltage may cause the curve to be in error by as much as one order of magnitude. On the other hand, the curves show that a variation of one order of magnitude in the risk corresponds to only a 5 % variation in the electric strength.



Overvoltage parameters: see 2.3.3.1 and annex D

Strength parameters: see 3.1.4.

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

3.3.3 *Insulation co-ordination procedures for fast-front overvoltages*

3.3.3.1 *Deterministic method*

For fast-front lightning overvoltages, a deterministic co-ordination factor of K_{cd} = 1 is applied to the assumed maximum value of the overvoltages. This is because for lightning, the representative overvoltage includes probability effects. For fast-front switching overvoltages, the same relations apply as for slow-front overvoltages (see 3.3.2.1).

3.3.3.2 *Statistical method*

The statistical method recommended in this guide is based on the probability distribution of the representative lightning overvoltages (see annex F). 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 3.3.2.2. The insulation failure rate is equal to the risk of failure multiplied by the total number of lightning overvoltages.

For internal insulation the assumed withstand voltage has a withstand probability of 100 % (see definition 3.23 of IEC 71-1). The withstand probability at higher voltages is assumed to be 0 %. This means that the co-ordination withstand voltage is equal to the representative lightning overvoltage amplitude at a return rate equal to the adopted acceptable failure rate.

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

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 formula as for the internal insulation applies.

4 Required withstand voltage

4.1 *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.

4.2 *Atmospheric correction*

4.2.1 *General remarks*

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

The rules for the atmospheric correction of withstand voltages of the external insulation are specified in IEC 60-1. These rules are based on measurements in altitudes up to 2000 m and their application to higher altitudes should be made with care. For insulation co-ordination purposes, the following additional recommendations apply:

a) for air clearances and clean insulators, the correction shall be carried out for the co-ordination switching and lightning impulse withstand voltages. For insulators requiring a pollution test, a correction of the long duration power-frequency withstand voltage is also necessary;

b) for the determination of the applicable atmospheric correction factor, it may be assumed that the effects of ambient temperature and humidity tend to cancel each other. Therefore, for insulation co-ordination purposes, only the air pressure corresponding to the altitude of the location need 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.

4.2.2 *Altitude correction*

The correction factor K_a is based on the dependence of the atmospheric pressure on the altitude as given in IEC 721-2-3. The correction factor can be calculated from:

$$K_a = e^{m\left(\frac{H}{8150}\right)} \tag{11}$$

where

H is the altitude above sea level (in metres) and the value of m is as follows:

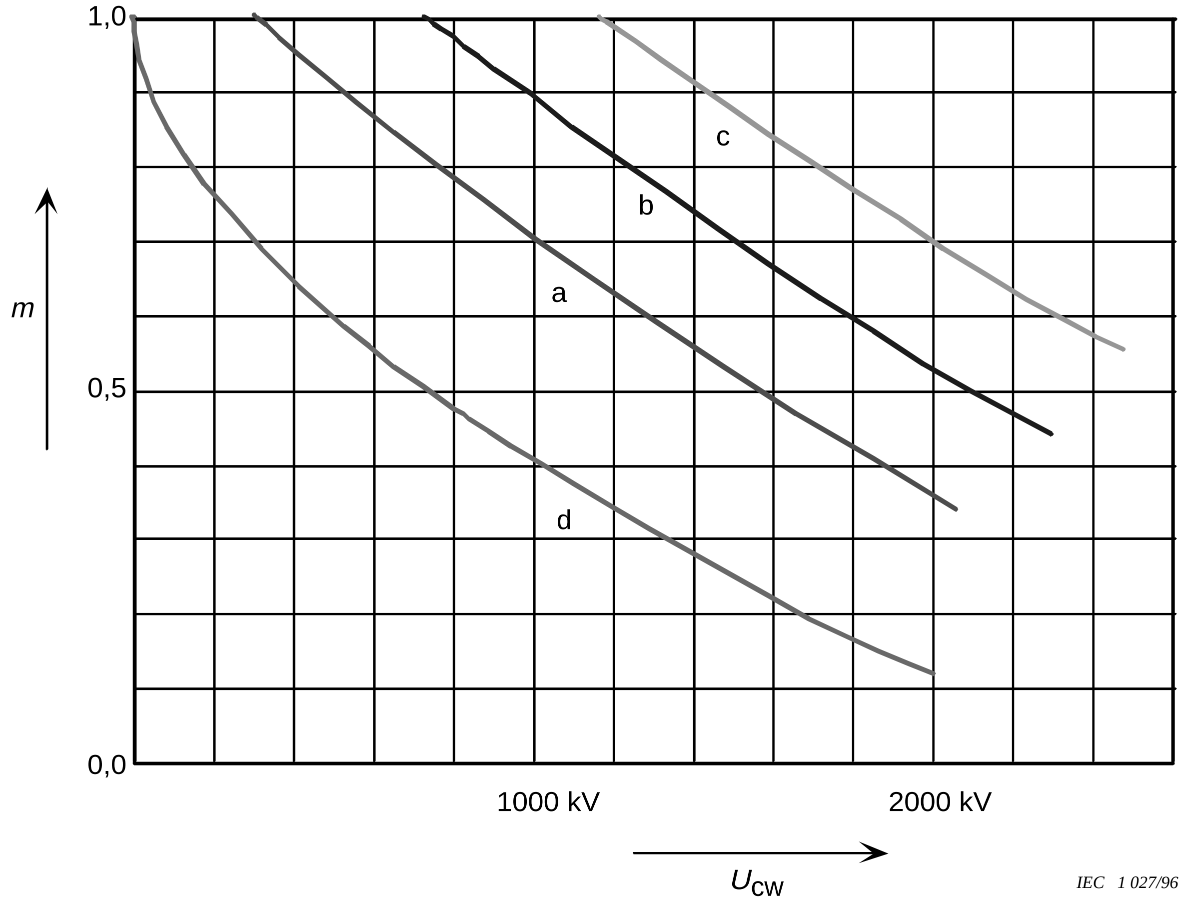
m = 1,0 for co-ordination lightning impulse withstand voltages;

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

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

NOTE – The exponent m depends on various parameters including minimum discharge path which is generally unknown at the specification stage. However, for insulation co-ordination purposes, the conservative estimates of m shown in figure 9 may be used for the correction of co-ordination switching impulse withstand voltages. The determination of the exponent m is based on IEC 60-1 in which the given relations are obtained from measurements at altitudes up to 2000 m. In addition, for all types of insulation response, conservative gap factor values have been used (refer to annex G).

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



a) phase-to-earth insulation

b) longitudinal insulation

c) phase-to-phase insulation

d) rod-plane gap (reference gap)

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

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

4.3 *Safety factors*

The main factors of influence and related operating modes for electrical insulations are indicated in annex B of IEC 505. 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;
– other unknown influences.

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

4.3.1 *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 4.3.4.

4.3.2 *Production and assembly dispersion*

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

For equipment fully assembled in the factory, this dispersion, for insulation co-ordination purposes, is negligibly small. For equipment assembled on site, the actual withstand voltage may be lower than the required withstand voltage, which shall be taken into account in the safety factors given in 4.3.4.

4.3.3 *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 4.3.4.

For internal insulation for which a withstand probability of 100 % is assumed in 3.23 of IEC 71-1, 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 4.3.4 (see also 5.3.2).

4.3.4 *Recommended safety factors (K_s)*

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

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

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

5 Standard withstand voltage and testing procedures

5.1 *General remarks*

IEC 71-1, tables 2 and 3, 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 71-1 reflect the experience of the world, taking into account modern protective 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 guide and should take into account the insulation characteristics of the particular equipment being considered.

5.1.1 *Standard switching impulse withstand voltage*

In IEC 71-1, table 3, standard switching impulse withstand voltages associated with a particular highest voltage for equipment have been chosen in consideration of the following:

a) for equipment protected against switching overvoltages by surge arresters:

- the expected values of temporary overvoltages;
- the characteristics of presently available surge arresters;
- the co-ordination and safety factors between the protective level of the surge arrester and the switching impulse withstand voltage of the equipment;

b) for equipment not protected against switching overvoltages by surge arresters:

- the acceptable risk of disruptive discharge considering the probable range of overvoltages occurring at the equipment location;
- the degree of overvoltage control generally deemed economical, and obtainable by careful selection of the switching devices and in the system design.

5.1.2 *Standard lightning impulse withstand voltage*

In IEC 71-1, table 3, standard lightning impulse withstand voltages associated with a particular standard switching impulse withstand voltage have been chosen in consideration of the following:

a) for equipment protected by close surge arresters, the low values of lighting impulse withstand level are applicable. They are chosen by taking into account the ratio of lightning impulse protective level to switching impulse protective level likely to be achieved with surge arresters, and by adding appropriate margins;

b) for equipment not protected by surge arresters (or not effectively protected), only the higher values of lightning impulse withstand voltages shall be used. These higher values are based on the typical ratio of the lightning and switching impulse withstand voltages of the external insulation of apparatus (e.g. circuit-breakers, disconnectors, instrument transformers, etc.). They are chosen in such a way that the insulation design will be determined mainly by the ability of the external insulation to withstand the switching impulse test voltages;

c) in a few extreme cases, provision should be made for a higher value of lightning impulse withstand voltage. This higher value should be chosen from the series of standard values given in 4.6 and 4.7 of IEC 71-1.

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 continuous power-frequency voltage if no value is specified by the relevant apparatus committee, and the required short-duration power-frequency withstand voltage.

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 5.2. 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 71-1 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 507).

5.2 *Test conversion factors*

5.2.1 *Range I*

If adequate factors are not available (or specified by the relevant apparatus committee), suitable test conversion factors to be applied to the required switching impulse withstand voltages are given in table 2. 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 2 – Test conversion factors for range I, to convert required switching impulses withstand voltages to short-duration power-frequency and lightning impulse withstand voltages

Insulation	Short-duration power-frequency withstand voltage [1)]	Lightning impulse withstand voltage
External insulation		
– air clearances and clean insulators, dry:		
– phase-to-earth	$0,6 + U_{rw} / 8500$	$1,05 + U_{rw} / 6000$
– phase-to-phase	$0,6 + U_{rw} / 12700$	$1,05 + U_{rw} / 9000$
– clean insulators, wet	0,6	1,3
Internal insulation		
– GIS	0,7	1,25
– liquid-immersed insulation	0,5	1,10
– solid insulation	0,5	1,00

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

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

5.2.2 *Range II*

If adequate factors are not available (or specified by the relevant apparatus committee), suitable test conversion factors for the conversion of the required short-duration power-frequency withstand voltage to switching impulses are given in table 3. They also apply to the longitudinal insulation.

Table 3 – Test conversion factors for range II to convert required short-duration power-frequency withstand voltages to switching impulse withstand voltages

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 r.m.s to peak value.	

5.3 *Determination of insulation withstand by type tests*

5.3.1 *Test procedure dependency upon insulation type*

The verification of the electric strength of insulation is achieved through tests. The type of test to be selected for a given equipment shall consider the nature of its insulation(s). Subclauses 3.4 and 3.5 of IEC 71-1, define the sub-division of insulation into self-restoring and non-self-restoring insulation. This constrains the selection of the test procedure to be adopted for a particular equipment from the list provided in 5.3 of IEC 71-1, and more fully described in IEC 60-1.

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

5.3.2 *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, 20.1.1 of IEC 60-1, 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).

5.3.3 *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 60-1 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 3.1.4) or the latter may be determined by a multiple level test. For an evaluation of the statistical significance of the test method, reference may be made to appendix A of IEC 60-1.

5.3.4 *Mixed insulation*

For equipment which has self-restoring insulation that cannot be tested separately from its non-self-restoring insulation (e.g. bushings and instrument transformers), a compromise in test method must 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 selectivity purpose). Experience shows that withstand test procedure B, 20.1.2 of IEC 60-1 (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 4.

Table 4 – Selectivity of test procedures B and C of IEC 60-1

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

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

An alternative to the above test procedure is withstand test procedure C, 20.1.3 of IEC 60-1, 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 4 and also in figure 10.

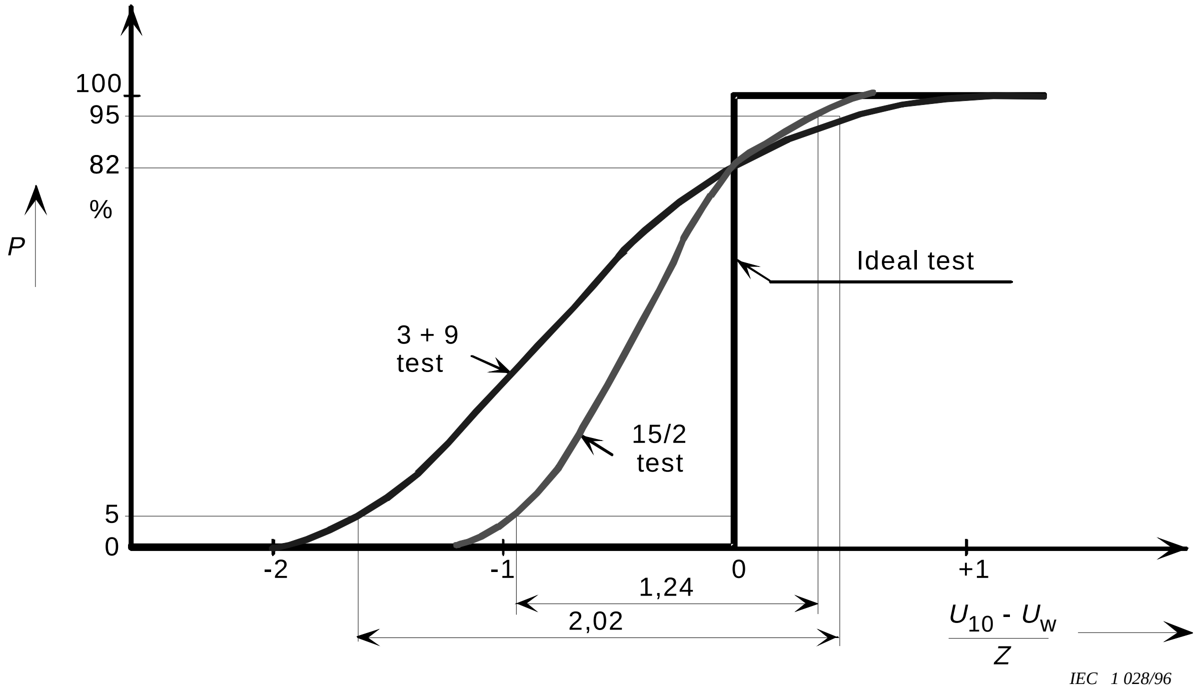


Figure 10 – Probability *P* of an equipment to pass the test dependent on the difference *K* between the actual and the rated impulse withstand voltage

5.3.5 *Limitations of the test procedures*

Since the recovery of insulation from a disruptive discharge is a time-dependent process, an adequate time interval between test voltage applications must 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.

5.3.6 *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, 20.1.4 of IEC 60-1);

– non-self-restoring insulation should be tested with the three impulse withstand test (withstand test procedure A, 20.1.1 of IEC 60-1);

– 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, 20.1.2 of IEC 60-1). 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, 20.1.3 of IEC 60-1) is an acceptable alternative;

– also, where power-frequency tests are required for insulation co-ordination purposes, the short-duration power-frequency withstand tests (IEC 71-1) should be applied to the insulation, whether self-restoring, non-self-restoring, or mixed.

5.3.7 *Selection of the type test voltages*

For equipment containing only external air insulation, the test is performed with the standard withstand voltage applying the atmospheric correction factors specified in IEC 60-1.

For equipment containing only internal insulation, the test is performed with the uncorrected standard withstand voltage.

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.

5.3.7.1 *Test voltage of the external insulation higher than that of the internal (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:

– test of the external insulation only on dummies;

– interpolation between existing results;

– estimation of the withstand voltages from the dimensions.

In general, a test of the external insulation is not necessary if the air clearances are equal to or larger than those given in tables A.1, A.2 and A.3 of annex A.

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 815.

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 815.

5.3.7.2 *Test voltage of the external insulation lower than that of the internal (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, e.g. by corona control electrodes of different gap. The strengthening measure should not affect the behaviour of the internal insulation.

6 Special considerations for overhead lines

6.1 *General remarks*

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

– where the design employs free-swinging insulators, the dielectric strength of air clearances should take into account conductor movement;

– insulator standards specify the dimensions of insulator units without making reference to a highest voltage for equipment or a highest system voltage. Consequently the insulation co-ordination procedure terminates with the determination of the required withstand voltage U_{rw}. The selection of a rated voltage from the series in IEC 71-1 is not necessary and tables 2 and 3 of IEC 71-1 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.

6.2 *Insulation co-ordination for operating voltages and temporary overvoltages*

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

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

6.3 *Insulation co-ordination for slow-front overvoltages*

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;

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

6.3.1 *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.

6.3.2 *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 – 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 – 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 6.2) and slow-front overvoltages need not be considered.

6.4 *Insulation co-ordination for lightning overvoltages*

The lightning performance for 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.

6.4.1 *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.

6.4.2 *Transmission lines*

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

7 Special considerations for substations

7.1 *General remarks*

The voltage stresses which can arise in a substation as shown in figure 11 are described in the following subclauses 7.1.1 to 7.1.4.

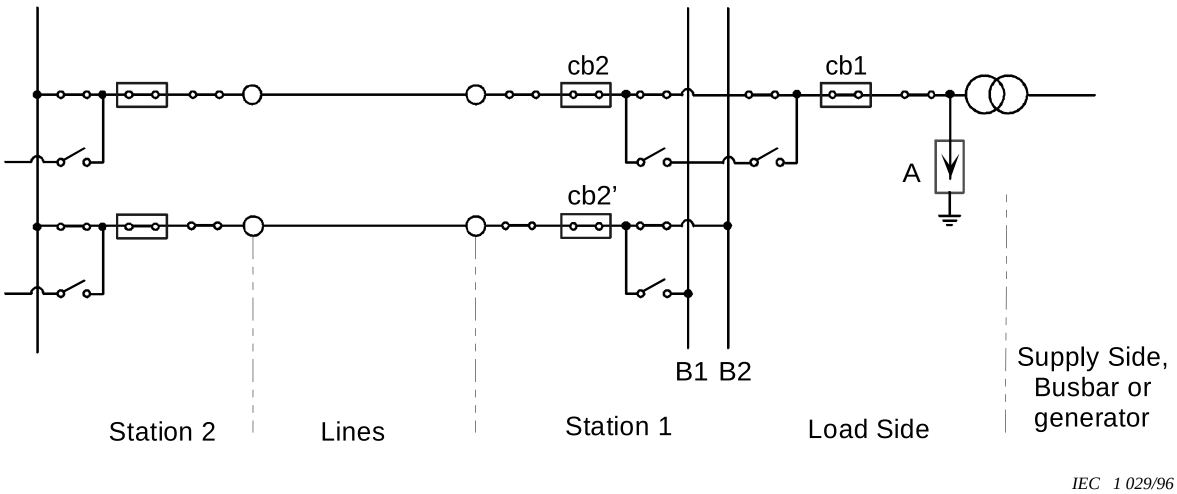


Figure 11 – Example of a schematic substation layout used for the overvoltage stress location (see 7.1)

7.1.1 *Operating voltage*

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

7.1.2 *Temporary overvoltage*

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

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

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

7.1.3 *Slow-front overvoltages*

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

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

7.1.4 *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 H.

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

NOTES

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

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

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

7.2 *Insulation co-ordination for overvoltages*

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

For equipment in this voltage range, IEC 71-1 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 71-1, table 2, may be suitable for installations such as the following:

a) systems and industrial installations not connected to overhead lines;

b) systems and industrial installations connected to overhead lines only through transformers where the capacitance to earth of cables connected to the transformer low-voltage terminals is at least 0,05 μF per phase. When the cable capacitance to earth is insufficient, additional capacitors should be added on the transformer side of the switchgear, as close as possible to the transformer terminals, so that the combined capacitance to earth of the cables plus the additional capacitors is at least 0,05 μF per phase;

c) systems and industrial installations connected directly to overhead lines, when adequate overvoltage protection by surge arresters is provided.

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

7.2.1.1 *Equipment connected to an overhead line through a transformer*

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

Analytical expressions for the electrostatic and electromagnetic terms of the transferred voltage are given in annex E.

7.2.1.2 *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 71-1, table 2, should be selected and surge arresters installed at the line-cable junction. When wood poles are used in the overhead line and when only one line may be connected to the substation, additional arresters may be required at the cable entrance of the substation.

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

For equipment in this voltage range, IEC 71-1 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 F.

7.2.3 *Substations in transmission systems in range II*

For equipment in this voltage range, IEC 71-1 specifies standard rated switching and lightning impulse withstand voltages.

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

Annex A
(normative)

Clearances in air to assure a specified impulse withstand voltage installation

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

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

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

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

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

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

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

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

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

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

A.1 Range I

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

A.2 Range II

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

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

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

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

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

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

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

NOTE – The standard lightning impulse is applicable phase-to-phase and phase-to-earth.

For phase-to-earth, the minimum clearance for conductor-structure and rod-structure is applicable.

For phase-to-phase, the minimum clearance for rod-structure is applicable

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

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

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

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

Annex B
(informative)

Determination of temporary overvoltages due to earth faults

The earth-fault factor is at a given location of a three-phase system, and for a given system configuration, the ratio of the highest r.m.s. 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 r.m.s. phase-to-earth power frequency voltage which would be obtained at the given location in the absence of any such fault (see definition 3.15 of IEC 71-1).

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

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

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

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

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

Figure B.1 shows the overall situation for $R_1 << X_1$ and $R = 0$

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

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

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

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

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

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

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

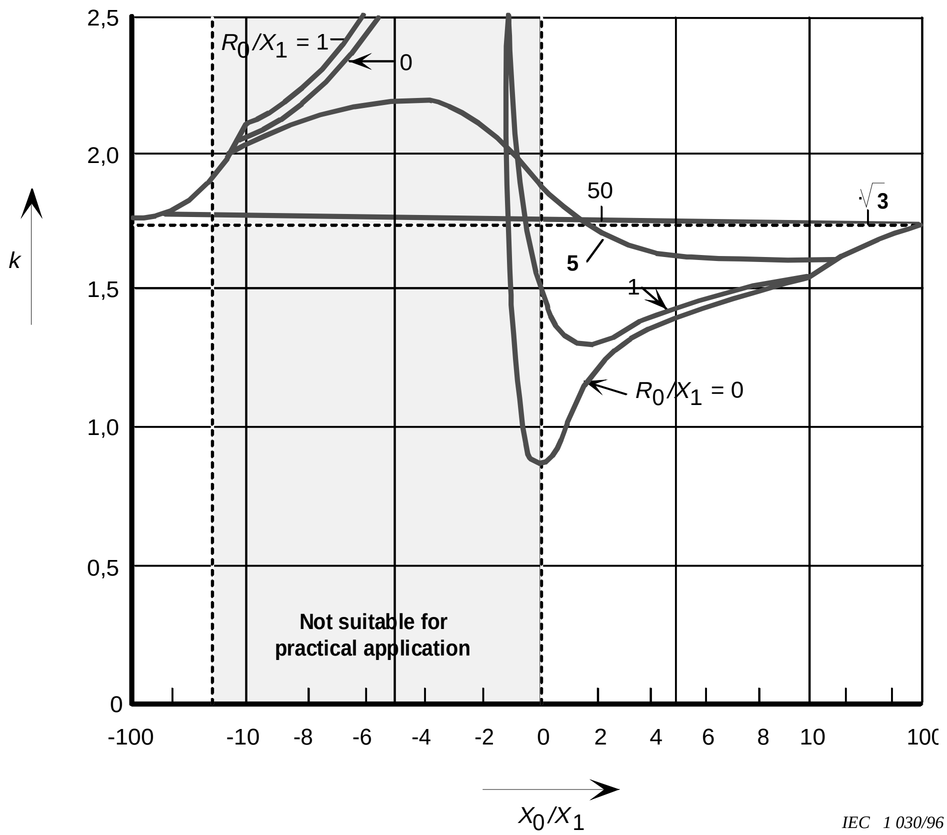


Figure B.1 – Earth-fault factor *k* on a base of X_0/X_1 for $R_1/X_1 = R = 0$

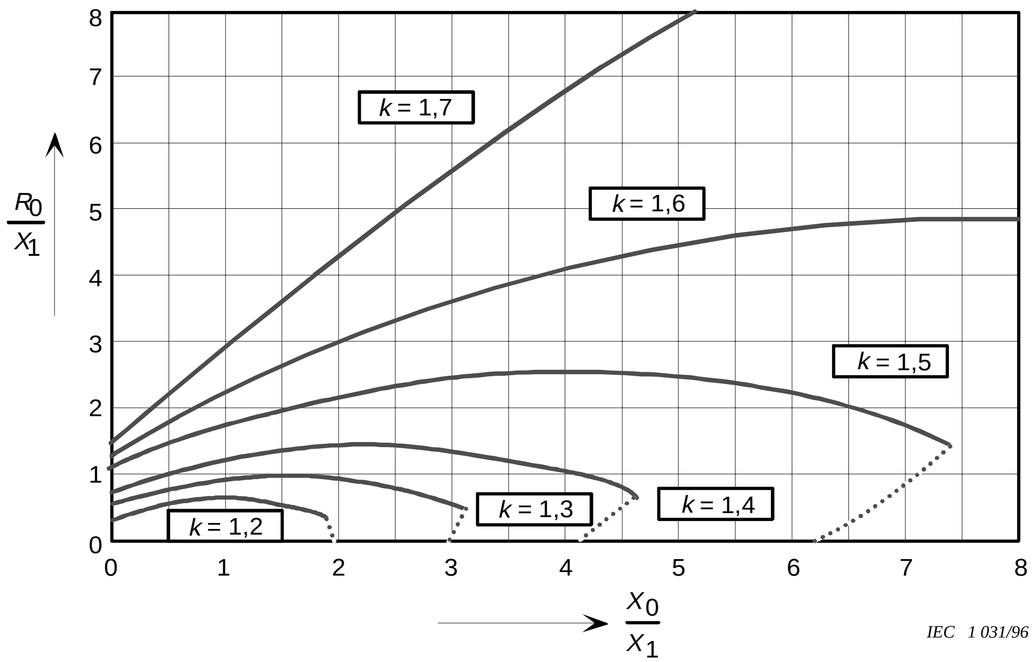


Figure B.2 – Relationship between R_0/X_1 and X_0/X_1 for constant values of earth-fault factor *k* where $R_1 = 0$

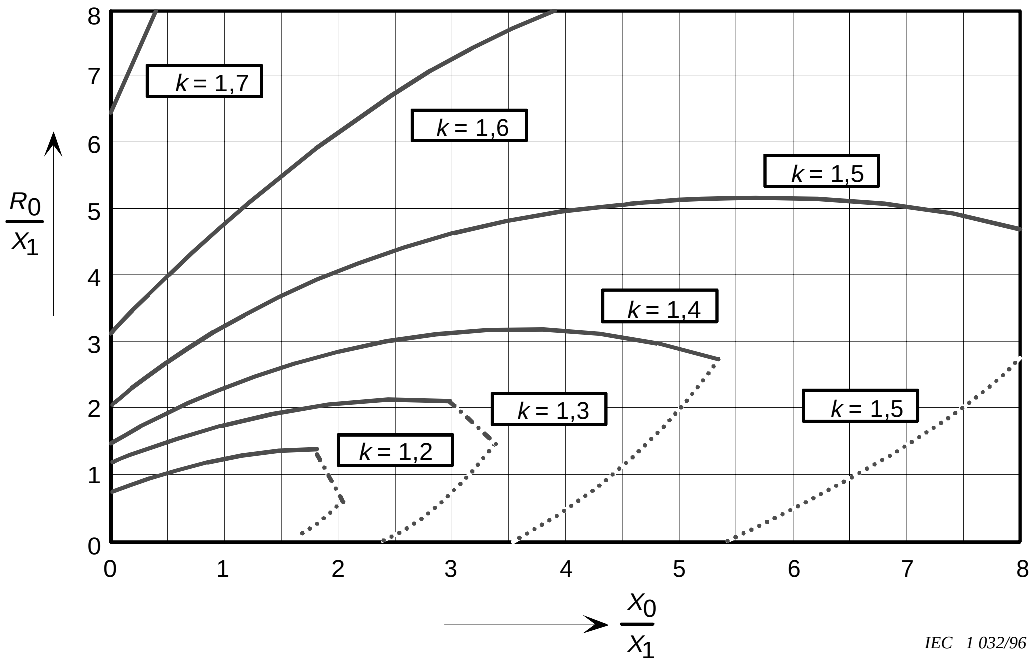


Figure B.3 – Relationship between R_0/X_1 and X_0/X_1 for constant values of earth-fault factor *k* where R_1 = 0,5 X_1

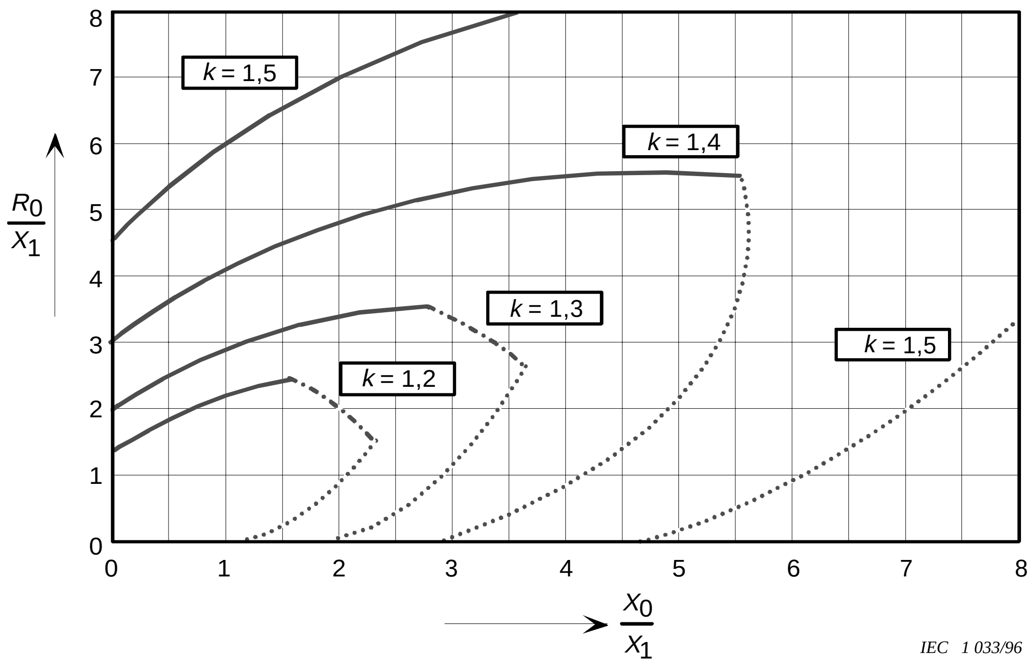


Figure B.4 – Relationship between R_0/X_1 and X_0/X_1 for constant values of earth-fault factor *k* where R_1 = X_1

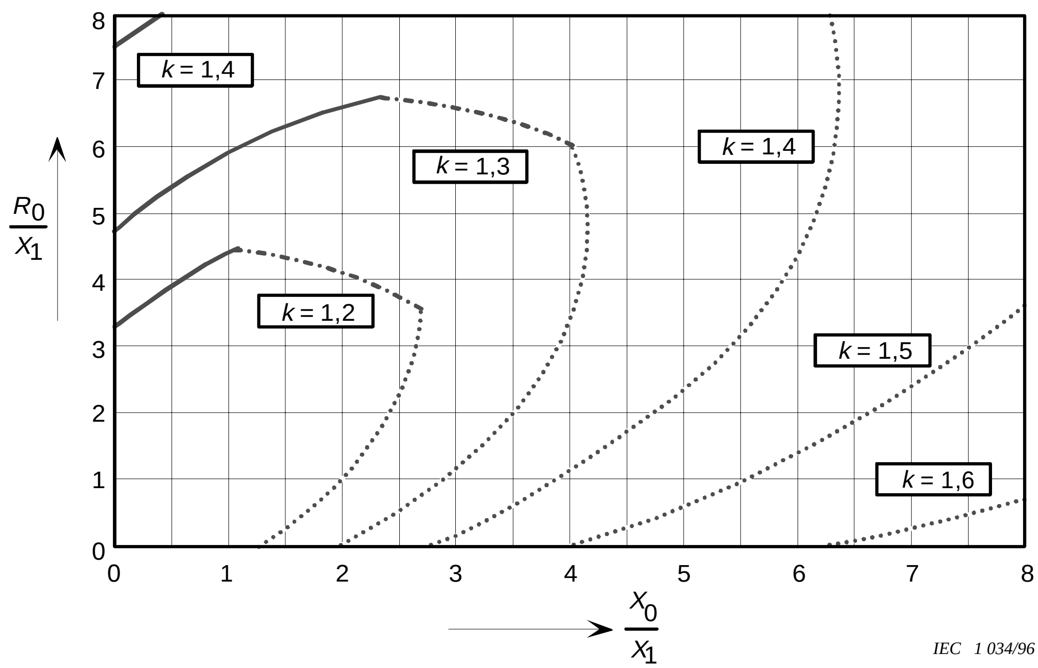


Figure B.5 – Relationship between R_0/X_1 and X_0/X_1 for constant values of earth-fault factor k where $R_1 = 2X_1$

Annex C
(informative)

Weibull probability distributions

C.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:

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

where

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

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

Z being the conventional deviation according to IEC 60-1.

A fundamental observation, however, is that there is no physical support to the adoption of this function for $P(U)$. An evidence of this lack of support is that physically no discharge can occur below a minimum value of U. The function is therefore truncated at ($U_0 = U_{50} - 3\,Z$) or at ($U_0 = U_{50} - 4\,Z$), so that $P(U) = 0$ for $U \leq U_0$. The main reason why the expression (C.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 guide recommends the use of Weibull probability functions both for the overvoltages and for the disruptive discharge of self-restoring insulation, because it offers the following advantages:

– the truncation values U_0 and U_{et} are mathematically included in the Weibull expression;

– the functions are easily evaluated by pocket calculators;

– the inverse functions $U = U(P)$ and $U_e = U_e(F)$ can be expressed mathematically and are easily evaluated by pocket calculators;

– the modified Weibull expressions are defined by the same parameters characterizing the two truncated Gaussian expressions: (U_{50}, Z and U_0) 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.

This annex 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.

C.2 Disruptive discharge probability of external insulation

The general expression for the Weibull distribution is:

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

where δ is the truncation value, β is the scale parameter and 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 δ and the scale factor β:

$$\delta = U_{50} - N\,Z \qquad \text{(C.3)}$$

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

which leads to the modified Weibull function:

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

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:

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

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

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

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

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

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

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

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

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

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

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

From equations (C.9) and (C.10) is obtained:

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

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 (C.11) *x* and x_M by their respective extended definition, and because at the truncation point ($U_{50} - 4Z = U_{50M} - 4Z_M = U_0$), the following relationships are obtained:

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

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

For example applying preceding formulas for *M* = 200:

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

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

As another example, for 100 parallel insulations, each one with U_{50} = 1600 kV and *Z* = 100 kV, then $Z_M = 100 / (100)^{1/5}$ = 39,8 kV and U_{50M} = 1359,2 kV. Table C.1 completes this example giving the values of *U* and U_M for various flashover probabilities *P*(*U*).

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

P(*U*)(%)	50	16	10	2	1,	0,1	0 1)
U (kV)	1600	1500	1475	1400	1370	1310	1200
U_M (kV)	1359	1319	1308	1280	1268	1244	1200

1) The truncation value remains constant.

Calculation of the risk of failure

To calculate the risk of failure for the preceding example, assume U_{e2} = 1200 kV and S_e = 100 kV. Then, for one insulator:

$K_{cs} = U_{10} / U_{e2}$ = 1475 / 1200 = 1,23

and $R = 10^{-5}$

For 100 identical parallel insulations:

K_{cs} = 1308 /1200 = 1,09

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

As an approximation, one could calculate the risk of failure of M parallel insulations using the following equation:

$$R = M\Phi\left[\frac{U_{e50} - U_{50}}{\sqrt{S_e^2 + Z^2}}\right] \qquad \text{(valid for } R<0{,}1\text{)} \qquad \text{(C.13)}$$

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 D (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 Φ ((1000 – 1600) / 140) = 100 Φ (-4,3) = 100 (10^{-5}) = 10^{-3}, which is the same result as above. For low risk values, the use of this formula may be too conservative.

C.3 Cumulative frequency distribution of overvoltages

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

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

With the assumptions made in annex D 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 (C.6) becomes γ = 3,07, which can be approximated to γ = 3. The scale parameter with these assumptions becomes $\beta = 3{,}5\ S_e$ to be used in equation (C.14).

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

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

With these factors, both equations (C.14) and (C.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 2.3.3.1) are compared, and the overvoltages at the three phases are statistically independent, then the probability distribution is:

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

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

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

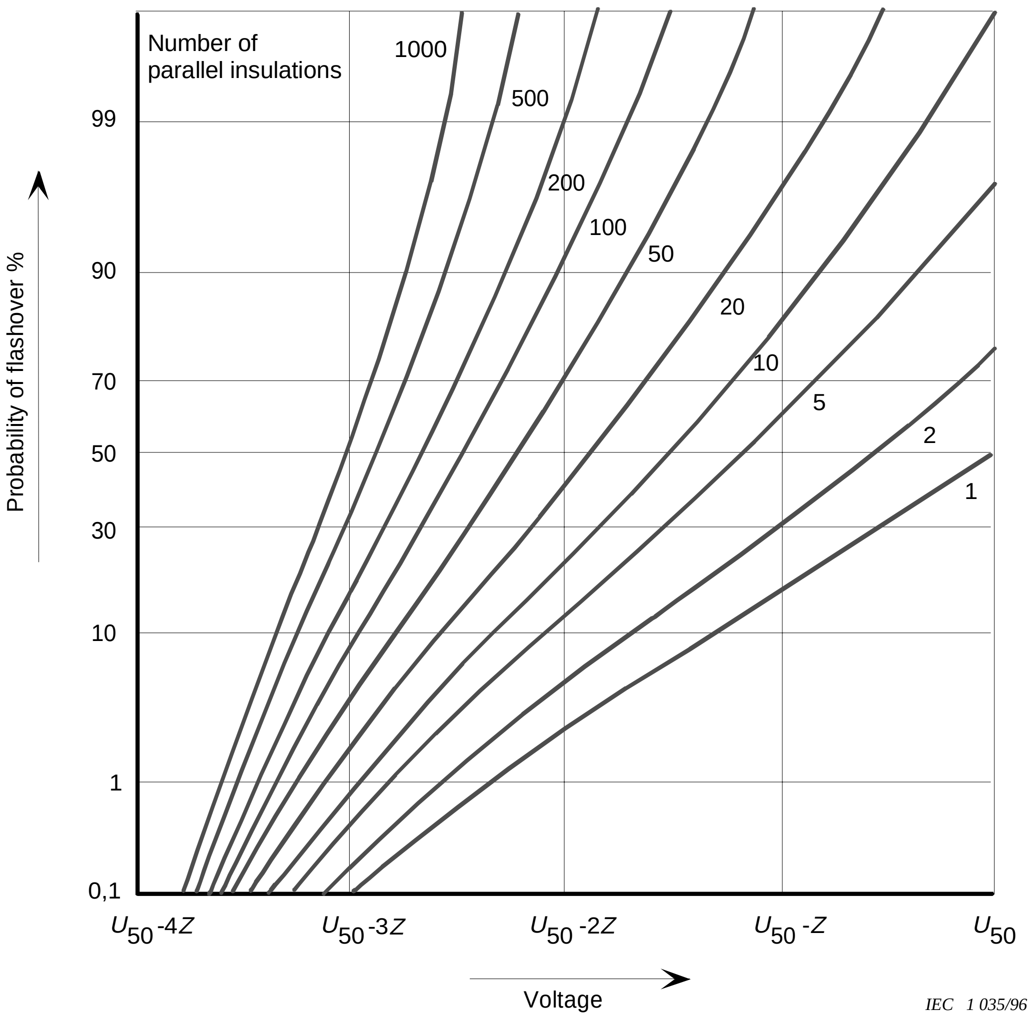
$$\beta_{c\text{-}p} = 3^{-1/3}\,\beta_{p\text{-}p} = 0{,}69\,\beta_{p\text{-}p} \qquad \text{(C.17)}$$

and consequently, the relation between the deviations is:

$$S_{c\text{-}p} = 0{,}69\,S_{p\text{-}p} \qquad \text{(C.18)}$$

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

$$u_{e2c\text{-}p} = 1{,}08\,u_{e2p\text{-}p} - 0{,}08 \qquad \text{(C.19)}$$



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

Z: conventional deviation of a single gap

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

Annex D
(informative)

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

D.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. This annex, therefore, summarizes the results and introduces the simplifications which are considered necessary for the use of this guide. For an explanation of the results, reference is made to the relevant ELECTRA publication.

The principles are derived for the phase-peak method (defined in 2.3.3.1) 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.

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

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

Phase-peak method:

- 2 % value: u_{e2} ;
- deviation: $\sigma_e = 0,25\ (u_{e2} - 1)$; (D.1)
- truncation value: $u_{et} = 1,25\ u_{e2} - 0,25$. (D.2)
- It can be noted that if ($u_{e2} = u_{e50} + 2\sigma_e$) then ($u_{et} = u_{e50} + 3\sigma_e$)

Case-peak method:

- 2 % value: u_{e2} ;
- deviation: $\sigma_e = 0,17\ (u_{e2} - 1)$; (D.3)
- truncation value: $u_{et} = 1,13\ u_{e2} - 0,13$. (D.4)

As shown in annex C, for the same switching operation, the truncation values obtained for the two methods are the same. Consequently, the 2 % values and the deviations must 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.

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

In general, the insulation characteristic must 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 D.4). This most critical instant is sufficiently defined by one of the three following instants:

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;

– the lowest negative component from the two neighbouring terminals.

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.

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;

– 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 D.1 shows an example from [7] corresponding to a tangent probability of 2 % for the three instants mentioned above. According to the evaluation of overvoltages only one of the three curves corresponds to the most critical instant for the insulation and only this curve is representative for the overvoltages.

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

$$U_c^+ = U_c^- = \frac{U_p - \sqrt{2}U_e}{2 - \sqrt{2}} \qquad \text{(D.5)}$$

and a radius:

$$R_u = \frac{2U_e - U_p}{2 - \sqrt{2}} \qquad \text{(D.6)}$$

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

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

Phase-peak method:

– 2 % value: u_{p2} ;

– deviation: $\sigma_p = 0{,}25\ (u_{p2} - 1{,}73)$; (D.7)

– truncation value: $u_{pt} = 1{,}25\ u_{p2} - 0{,}43$. (D.8)

Case-peak method:

– 2 % value: u_{p2} ;

– deviation: $\sigma_p = 0{,}17\ (u_{p2} - 1{,}73)$; (D.9)

– truncation value: $u_{pt} = 1{,}14\ u_{p2} - 0{,}24$. (D.10)

D.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 3.1.1). Figure D.3 shows two-phase terminals and the earth terminal of a complete insulation configuration in which the third phase is disregarded for simplification reasons. For the description of the dielectric strength of such a configuration two methods have been used.

– The positive component belonging to a given discharge probability is reported dependent on the negative component. With this description an insulation characteristic is obtained as shown in figure D.4 a) for the 50 % discharge probability.

– The total discharge voltage equal to the sum of the two components corresponding to a given discharge probability is reported dependent on a ratio α:

$$\alpha = U^- / (U^+ + U^-) = 1 / [1 + (U^+/U^-)] \qquad \text{(D.11)}$$

where

U^+ is the positive component;

U^- is the negative component

The example of figure D.4 a) then results in the dependency shown in figure D.4 b).

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

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

– electrode configurations in which the discharges phase-to-earth and the discharges phase-to-phase occur at different parts of the configuration, e.g. 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 D.4 a) or is constant in figure D.4 b). Such configurations exist in three-phase power transformers or in GIS;

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

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

a) configurations with homogeneous or quasi-homogeneous electric field

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

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

b) short air clearances with inhomogeneous electric field

The discharge voltage is substantially higher than the corona inception voltage. This discharge process corresponds to a streamer discharge, as a leader does not develop owing to the short air clearance. The discharge probability is determined by the sum of the two components, which means that the insulation characteristic in range b decreases with 45° in figure D.4 a) or is constant in figure D.4 b). The air clearances in range I of IEC 71-1 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 71-1 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 D.4);

– the negative switching impulse withstand voltage phase-to-earth (range c in figure D.4);

– the insulation characteristic between phases (range b in figure D.4) where it can be described, for the representation of figure D.4 a) by:

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

or, for the representation in figure D.4 b), by:

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

The value of the constant *B* is:

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

In range II:

– internal insulation: *B* = 1;

– external insulation: *B* < 1.

Figure D.5 gives the angle ϕ ($B = \text{tg}\,\phi$) dependent on the ratio of *D*/*Ht*.

IEC 71-1 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 α = 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 (D.12). The most critical stress is given by the voltage component at which the characteristic is tangent to the circle proposed as a simplification to describe the overvoltages. Figure D.2 shows that the most critical stress does not correspond with the representative overvoltage, if the inclination B is smaller than 1. In this case, the representative overvoltage must be increased in order to test at α = 0,5. This results in a new value for the phase-to-phase representative overvoltage U_{p2re} given by:

$$U_{p2re} = 2\ (F_1\ U_{p2} + F_2\ U_{e2}) \qquad \text{(D.14)}$$

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

$$S_{pre} = 2\ (F_1\ S_p + F_2\ S_e) \qquad \text{(D.15)}$$

$$U_{ptre} = 2\ (F_1\ U_{pt} + F_2\ U_{et}) \qquad \text{(D.16)}$$

where:

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

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

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

D.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 phase-to-earth overvoltage parameters (phase-peak):

- U_{e2} = (1,98 p.u.) = 1238 kV;
- S_e = (0,25 p.u.) = 156 kV;
- U_{et} = (2,225 p.u.) = 1391 kV.

The phase-to-phase overvoltage parameters are derived:

- U_{p2} = (3,366 p.u.) = 2104 kV;
- S_p = (0,42 p.u.) = 263 kV;
- U_{pt} = (3,778 p.u.) = 2361 kV.

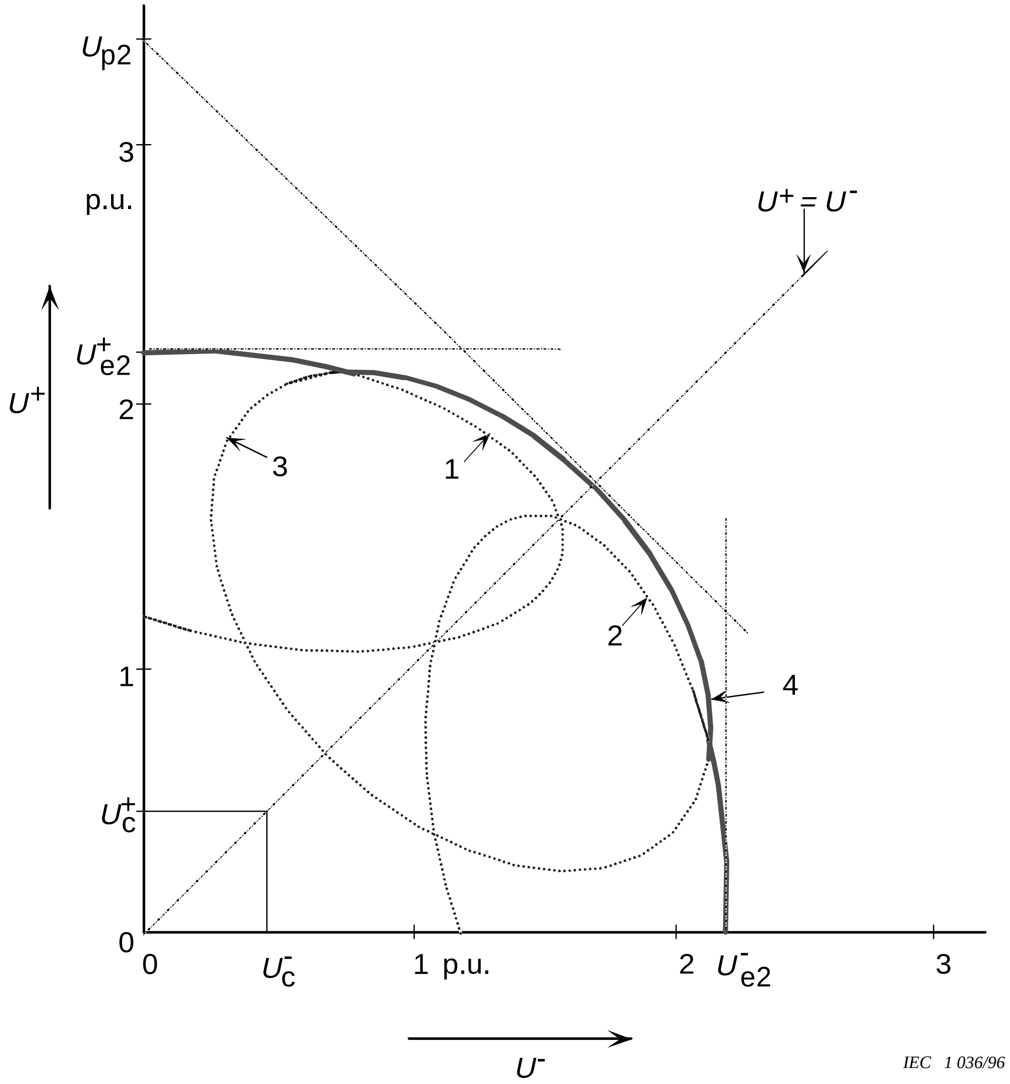
The representative overvoltage amplitude phase-to-earth is equal to the phase-to-earth overvoltage. The representative overvoltage amplitude phase-to-phase is derived from equations (D.14) to (D.16) with the above-given constants:

- U_{p2re} = (3,41 p.u.) = 2131 kV;
- S_{pre} = (0,44 p.u.) = 266 kV;
- U_{ptre} = (3,828 p.u.) = 2392 kV.

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

- phase-to-earth: $U_w = U_{e2} \times 1{,}15$ = 1424 kV;
- phase-to-phase (nominal): $U_w = U_{p2} \times 1{,}15$ = 2420 kV;
- phase-to-phase (derived): $U_w = U_{p2re} \times 1{,}15$ = 2451 kV.

In IEC 71-1, table 3 provides standard withstand voltages of 1425 kV phase-to-earth and 2422 (1425 × 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 2451 kV. Therefore the next highest standard withstand voltages of 1550 kV phase-to-earth and 2480 (1550 × 1,6) kV phase-to-phase must be selected and the insulation is to be tested with positive and negative switching impulses of equal magnitude.



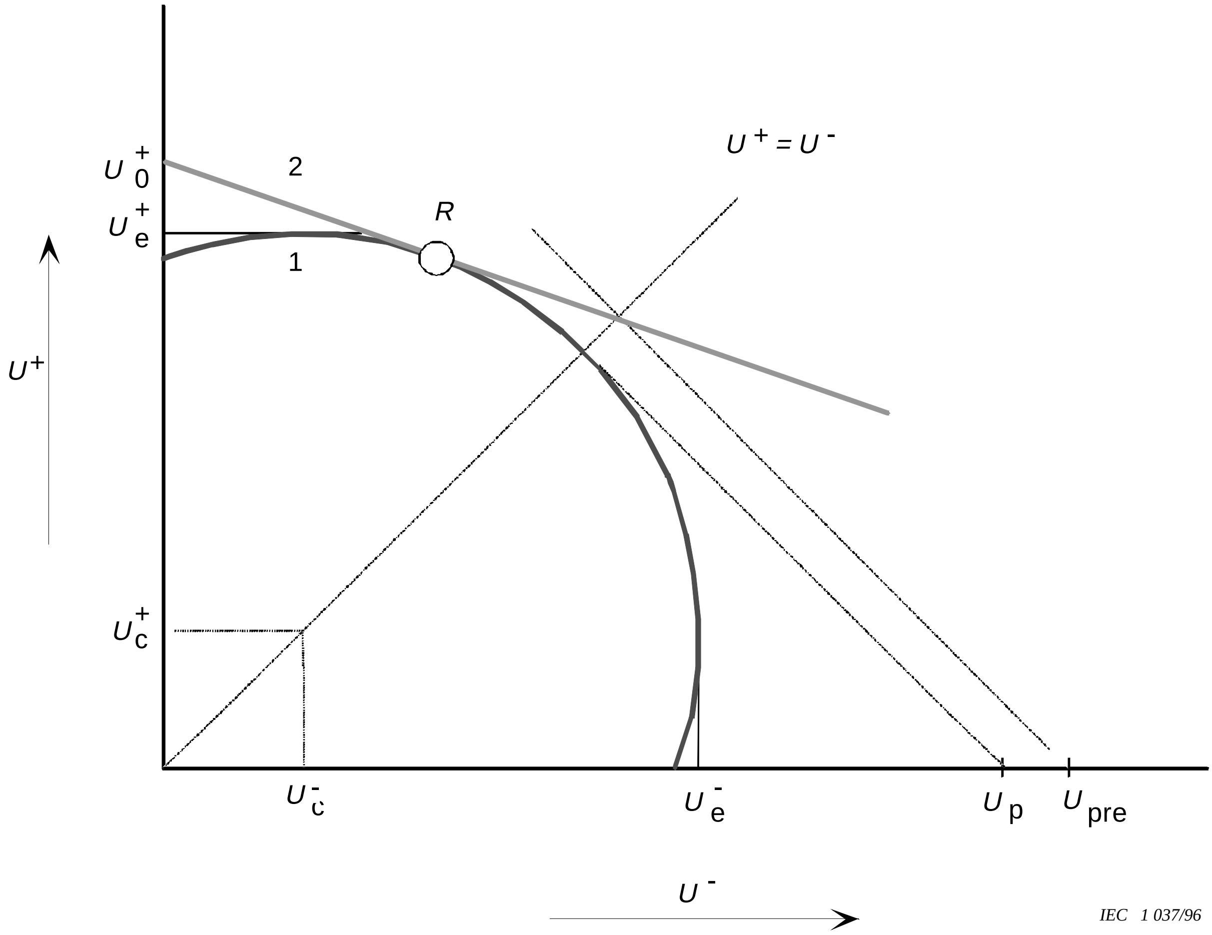
1: overvoltage at the instant of the positive phase-to-earth overvoltage peak

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

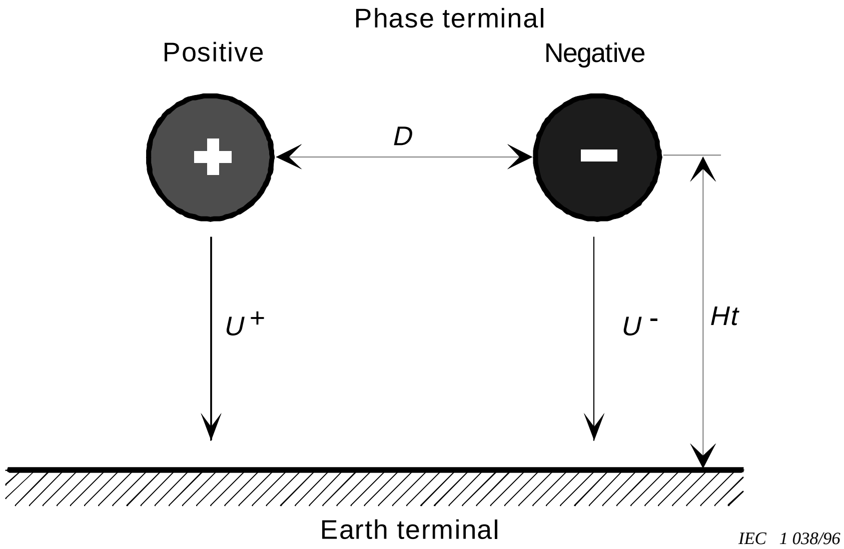
Figure D.1 – Example for bivariate phase-to-phase overvoltage curves with constant probability density and tangents giving the relevant 2 % values



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

R: most critical overvoltage stress

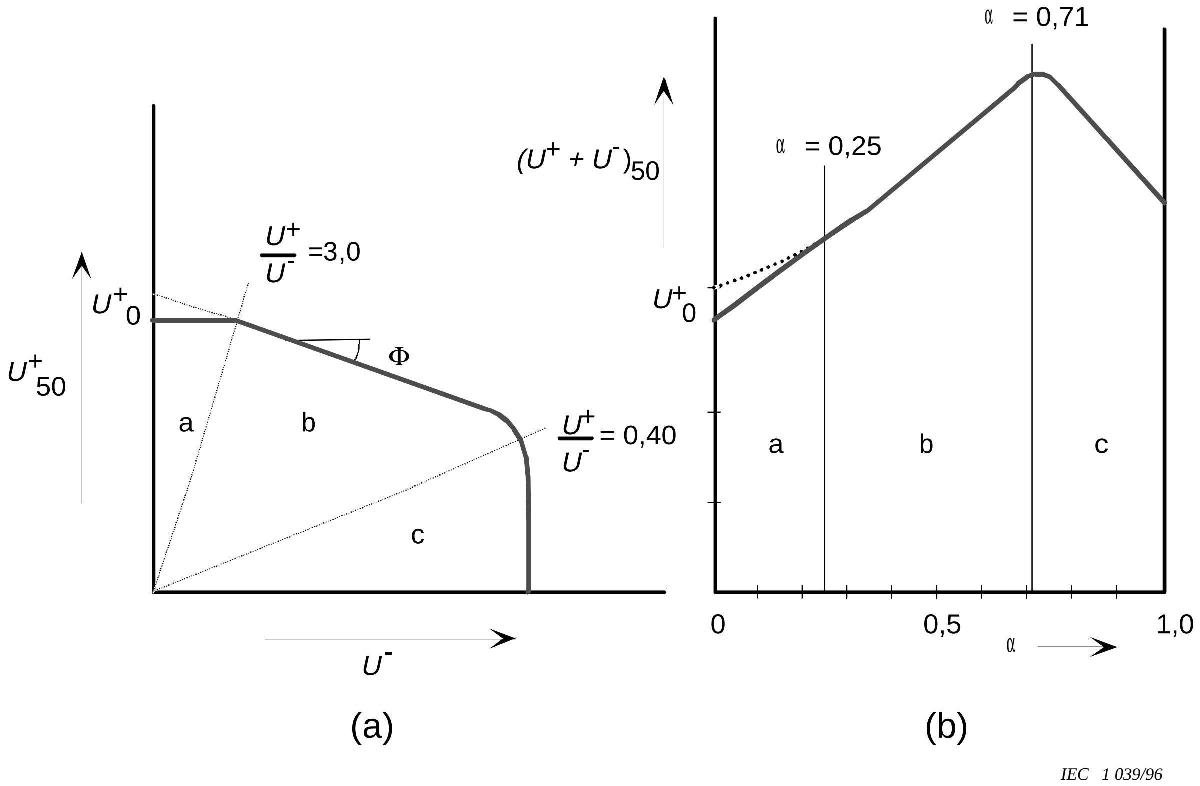
Figure D.2 : Principle of the determination of the representative phase-to-phase overvoltage U_{pre}



U^+ : positive voltage component

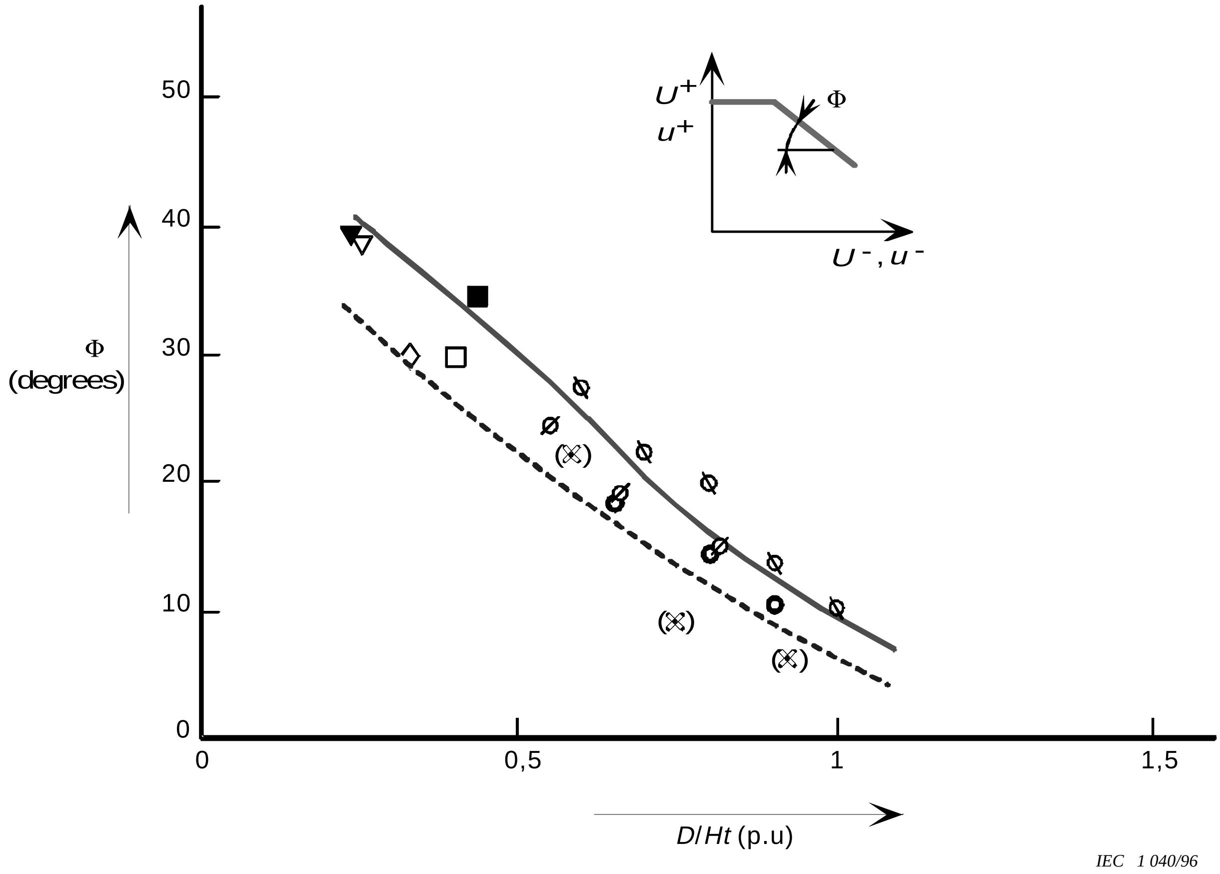
U^- : negative voltage component

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



a) 50 % positive component dependent on the negative component
b) 50 % total flashover dependent on α
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 D.4 – Description of the 50 % switching impulse flashover voltage of a phase-phase-earth insulation



Mean value

Minimum value

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

Annex E
(informative)

Transferred overvoltages in transformers

E.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, e.g. 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.

E.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:

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

where

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

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

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

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

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

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

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

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

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

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

E.3 Capacitively transferred surges

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

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

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

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 E.1) which can be used in the rough estimation of the magnitude of the capacitively transferred surges. When the effect of the power-frequency voltage is encountered, the resulting initial voltage spike on the open secondary side is given by:

$$U_{T2} = g\ h\ U_{T1} \quad \text{(E.3)}$$

where

$g = C_{1in} / (C_{1in} + C_{3in})$: dividing ratio of the divider

h is the power-frequency voltage factor.

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

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

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

In the case of fast-front overvoltages, the value of U_{T1} can be the protective 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 equipments 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.

E.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;

– the characteristics of the load.

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

$$U_{T2} = h\, q\, J\, w\, U_{T1} \tag{E.4}$$

where

h is the factor defined under equation (E.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 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 E.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);

– the winding is the tertiary of a three-winding transformer.

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

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

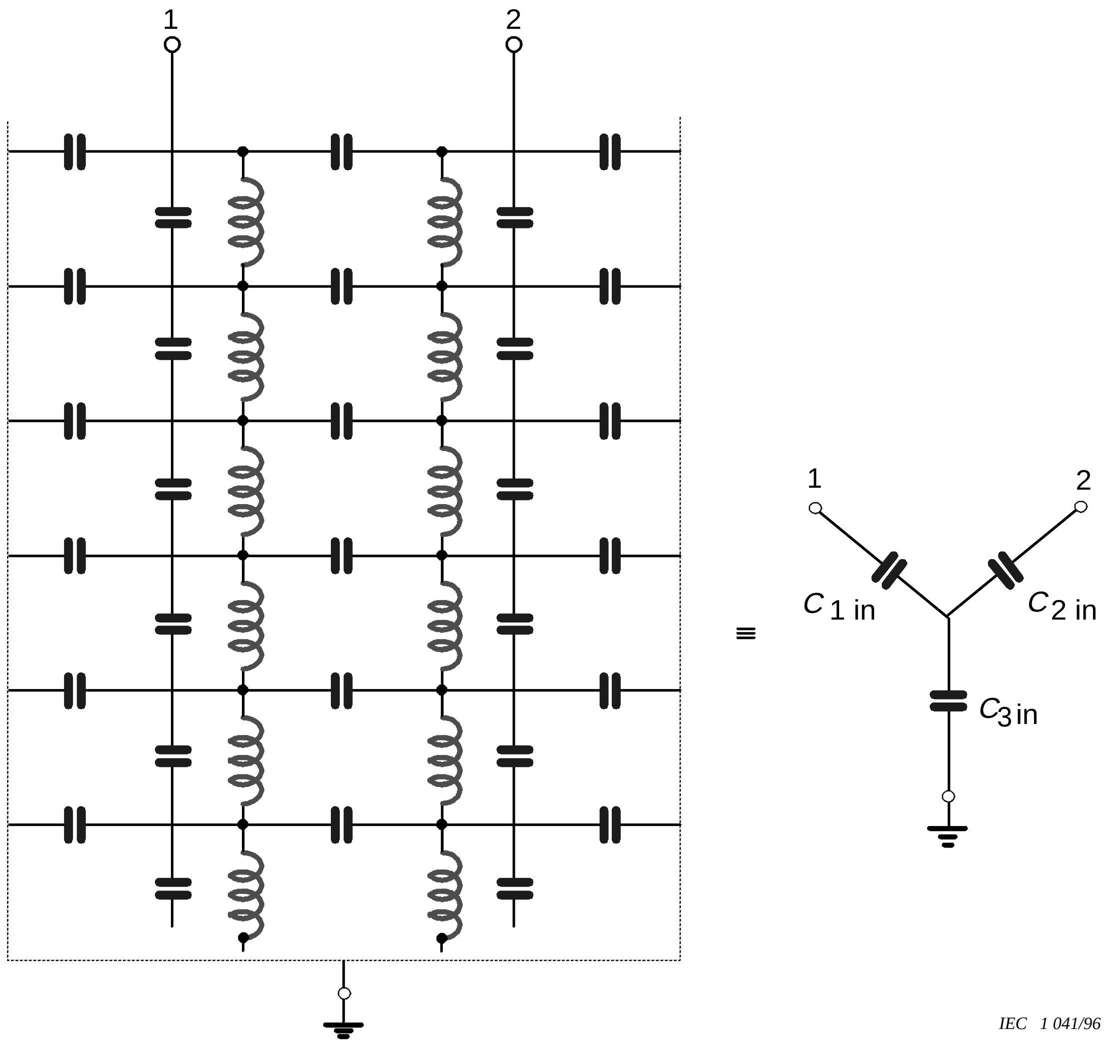
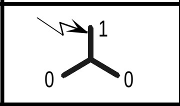
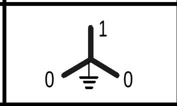
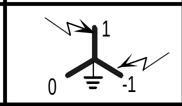
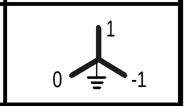
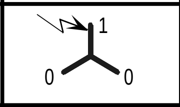
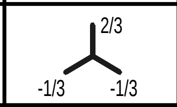
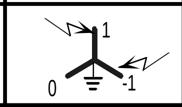
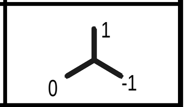
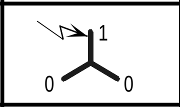
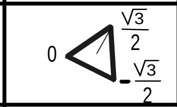
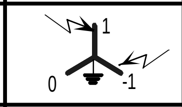
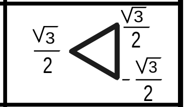
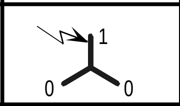
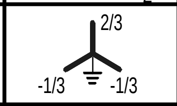
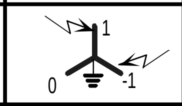
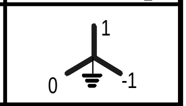
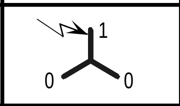
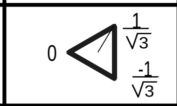
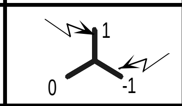
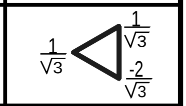
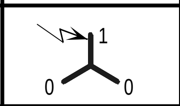
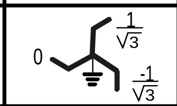
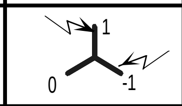
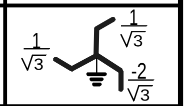
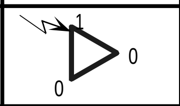
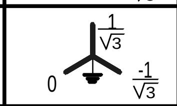
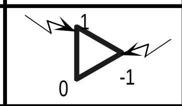
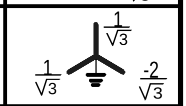
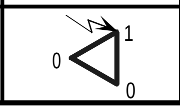
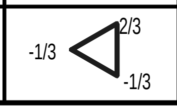
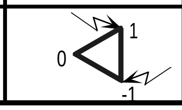
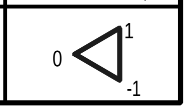


Figure E.1 – Distributed capacitances of the windings of a transformer and the equivalent circuit describing the windings

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)				

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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 E.2 – Values of factor *J* describing the effect of the winding connections on the inductive surge transference

Annex F
(informative)

Lightning overvoltages

F.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 F.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.

F.2 Determination of the limit distance (*Xp*)

F.2.1 *Protection with arresters in the substation*

This subclause contains more detailed information on surge arrester protection discussed in 2.3.4.5.

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:

$$S = 1 / (n\, K_{co}\, X) \qquad \text{(F.1)}$$

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 F.1 (µs/(kV.m));
- X is the distance between struck point of lightning and substation (m).

NOTE – The formula 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 formula (F.2) because here low steepnesses of the impinging surge are relevant. For the calculation of actual overvoltages resulting from an assumed impinging surge, this simplification may be not conservative.

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

$$X_p = 2T / [nK_{co} (U - U_{pl})] \tag{F.2}$$

where

U is the lowest considered overvoltage amplitude;

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

U_{pl} is the lightning impulse protective 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 F.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	$0{,}4 \times 10^{-6}$

F.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:

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

where

n is the number of overhead lines;

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

U is the overvoltage amplitude considered.

In addition the impinging surge must 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 lumped element. This can be considered as valid when the lightning struck-point is beyond the limit distance:

$$X_p \geq 4\ (T / K_{co} U) \tag{F.4}$$

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

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

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

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:

X_p = 1 span – for shielding failures;

X_p = 2 towers – for back flashovers.

F.3 Estimation of the representative lightning overvoltage amplitude

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.

F.3.1 *Shielding penetration*

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

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

where

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

R_t is the considered return rate;

R_p is the shielding penetration rate withing the limit distance.

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

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

where

R_{sf} is the shielding failure flashover rate;

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

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

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

$$U_I = Z_L I \ / \ 2 \quad \text{(F.8)}$$

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

where $X_T = X_P / 4$.

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

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

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

F.3.2 *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:

$$F(I) = R_t / R_f \tag{F.10}$$

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:

$$R_{hc} = \frac{R_{lc}}{\sqrt{1+\frac{I}{I_g}}} \tag{F.11}$$

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:

$$I_g = \frac{1}{2\pi}\frac{E_0 \rho}{R_{lc}^2} \tag{F.12}$$

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:

$$U_I = \frac{(1-c_f)R_{lc}I}{\sqrt{1+\frac{I}{I_g}}} \tag{F.13}$$

where c_f is the coupling factor between earth-wire and phase conductor. Typical values 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 (F.14) and a linear increasing front whose steepness S is given by equation (F.15):

$$\tau = \frac{Z_e}{R_{lc}} \frac{L_{sp}}{c} \qquad \text{(F.14)}$$

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).

$$S = 1 / (K_{co} X_T) \qquad \text{(F.15)}$$

where

K_{co} is given by equation (F.1);

X_T is given by equation (F.9).

For travelling wave calculations in the considered substation, a single conductor of the length X_T and surge impedance equal to that of the phase conductors is connected to the substation. A voltage source with the internal impedance of the low current footing resistance R_{lc} is placed at the end of the conductor. It produces a voltage with the shape parameters of the impinging surge.

If the impinging surge amplitude is higher than 1,6 times the positive 50 % lightning impulse flashover voltage, the simplifications are no longer applicable and more careful studies may be recommendable. The same applies for tower footing extensions larger than 30 m in radius.

Two dependencies of the representative overvoltage amplitude on the return rate are obtained, one for shielding failures and one for back flashovers. The overall dependency is obtained by adding the return rates for a constant amplitude.

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

F.4 Simplified method

A further simplification to the procedures described in F.2 and F.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 (F.1).

As mentioned already both assumptions are not strictly valid. Firstly, not all events within a certain distance are equally severe. They depend on the lightning current or on the amplitude of the impinging overvoltage surge. Secondly, the overvoltages may be higher than that calculated with equations (1) and (F.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 (F.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:

$$S_{rp} = 1 / [K_{co}(L_{sp} + L_t)] \qquad (F.16)$$

where $L_t = (R_t / R_{km})$ is the overhead line section in which the lightning flashover rate is equal to the desired return rate [8].

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 formula F.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:

$$U_{rp} = U_{pl} + \frac{A}{n}\frac{L}{L_{sp} + L_t} \qquad (F.17)$$

where

- U_{rp} is the representative lightning overvoltage amplitude (kV);
- A is a factor given in table F.2 describing the lighting 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);
- 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 (F.16)) [usual unit: 1/(100 km.year); recommended unit: 1/(m.year)].

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:

$$L_a = R_a / R_{km} \qquad (F.18)$$

and the co-ordination lightning impulse withstand voltage is equal to:

$$U_{cw} = U_{pl} + \frac{A}{n}\frac{L}{L_{sp} + L_a} \qquad (F.19)$$

where

- U_{cw} is the co-ordination lightning impulse withstand voltage;
- L_a is the overhead line section with outage rate equal to acceptable failure rate;
- R_a is the acceptable failure rate for equipment.

For transmission lines, the factors A are obtained from table F.2 and the corona damping constants K_{co} from table F.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 (F.19) for the open-air substation results in conservative estimates of the co-ordination lightning impulse withstand voltage or of the protective range and a reduction of the ratio *A*/*n* to half the value used for outdoor stations is still suitable.

Table F.2 – Factor *A* for various overhead lines
(applicable in equations (F.17) and (F.19))

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)	2700
Transmission lines (single-phase flashover to earth)	
– single conductor	4500
– double conductor bundle	7000
– four conductor bundle	11000
– six and eight conductor bundle	17000

F.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:

$$\frac{U_{rp2}}{U_{pl2}} = 1 + \left[\frac{n_1}{n_2}\frac{L_2}{L_1}\frac{U_{pl1}}{U_{pl2}}\left(\frac{U_{rp1}}{U_{pl1}} - 1\right)\right] \qquad (F.20)$$

where

U_{rp} is the assumed maximum representative overvoltage;

U_{pl} is the lightning impulse protective level of the surge arrester;

n is the minimum number of in-service overhead lines connected to the station;

$L = a_1 + a_2 + a_3 + a_4$ (see figure 3).

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 (F.16) equal to zero thus leading to $L_t = 0$, and:

$$U_{rp} = U_{pl} + \frac{A}{n}\frac{L}{L_{sp}} \qquad (F.21)$$

Annex G
(informative)

Calculation of air gap breakdown strength from experimental data

The intent of this annex is not to provide the apparatus committees with a method to calculate air clearances. The purpose is rather to provide help to the user to estimate the size of equipment and the dielectric strength of air gaps for the purpose of determining the atmospheric correction factor.

It must be noted that the formulae provided here are based on experimental data and for the purposes of insulation co-ordination. For distances greater than 1 m they can be assumed to give an approximate fit to these experimental results.

The user who is tempted to use these formulae to verify the minimum clearances given in annex A or to justify a deviation from those values given in annex A should do so with caution. The values given in annex A do not correspond to U_{50} but to withstand conditions and embody additional considerations including feasibility, economy, experience and environmental conditions (pollution, rain, insects, etc.).

Discrepancies may be particularly significant for distances less than 1 m where the accuracy of the given formulae is questionable.

G.1 Insulation response to power-frequency voltages

For air gap breakdown under power-frequency voltage, the lowest withstand voltage is obtained for the rod-plane gap configuration. The 50 % breakdown voltage for a rod-plane gap may be approximated by the following equation, for air gaps d up to 3 m:

$$U_{50RP} = 750\ \sqrt{2}\ \ln\,(1+0{,}55\ d^{1,2}) \qquad \text{(kV crest, m)} \qquad \text{(G.1)}$$

The peak value of U_{50RP} under power-frequency voltage is about 20–30 % higher than the corresponding value under positive switching impulse at critical front time. Withstand can be taken to be 90 % of U_{50}, based on an assumed conventional deviation of 3 % of U_{50}.

The influence of gap configuration on the strength is generally lower under power-frequency than under switching impulse:

– it is quite small for gaps up to about 1 m clearance;

– for gaps larger than 2 m, the strength can be evaluated according to the following equation (applicable to dry conditions):

$$U_{50} = U_{50RP}\ (1{,}35\ K - 0{,}35\ K^2) \qquad \text{(G.2)}$$

where K is the gap factor (determined from switching impulse tests) as shown in table G.1;

– for gaps between 1 m and 2 m, formula (G.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 3.3.1.1). These conditions may in fact dictate the external insulation design. Comparative insulation contamination levels can be simulated by the equivalent salt deposit density (ESDD) in grams per square metre of NaCl. ESDD relates the steady-state conductivity of dissolved contaminant to an equivalent amount of dissolved NaCl. The determination of the ESDD requires an analysis of either performance of existing insulation in the area or statistical data gathered from on-site investigations.

Analysis of existing performance may be the more desirable but may not provide sufficient information if existing insulation never suffers pollution flashovers.

Analysis of statistical data requires several years of on-site monitoring as data is gathered by direct measurement of ESDD from washdown of exposed insulators or by other methods, e.g. leakage current measurement, chemical analysis or conductivity measurements.

NOTE – The applicability of the concept of ESDD to non-ceramic insulators is not clear. The present research indicates that the phenomenon of surface hydrophobicity may be more important. The user is advised to use caution.

The statistical description of ambient conditions usually requires a greater amount of data. The statistical description of aging is even more difficult. Therefore, statistical procedures are not recommended in this guide for estimation of the insulation response at power-frequency voltages.

G.2 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 [11]:

$$U_{50RP} = 1080 \ln (0{,}46\, d + 1) \qquad \text{(kV crest, m)} \qquad \text{(G.3)}$$

For standard switching impulses, the following formula provides a better approximation [12]:

$$U_{50RP} = 500\, d^{\,0{,}6} \qquad \text{(kV crest, m)} \qquad \text{(G.4)}$$

Formulas (G.3) and (G.4) are applicable to sea-level (H = 0). Therefore, correction for altitude is required (according to 4.2.2) when applying the insulation co-ordination procedure.

Insulators in the air gap generally decrease the breakdown strength, for positive slow-front impulses. For dry cap and pin insulators, the influence is small but can be important for post insulators.

For other gap configurations, a gap factor as described in table G.1 is applied as follows:

$$U_{50} = K\, U_{50\mathrm{RP}} \qquad \text{(G.5)}$$

Note that for $K \geq 1{,}45$, the breakdown voltage under negative polarity may become lower than that for positive polarity.

For phase-to-phase configurations, a similar gap factor may be applied. In this case however, the gap factor is influenced not only by the gap configuration, but also by the ratio α defined as the peak negative component divided by the sum of the peak negative and positive components (see annex D).

Table G.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.

G.3 Insulation response to fast-front overvoltages

Under fast-front impulse stress, the negative polarity breakdown strength of a rod-plane gap configuration is much higher than that with positive polarity stress. Furthermore, the gap strength when plotted against the gap clearance is non-linear with negative polarity while it is linear with positive polarity. For standard lightning impulses applied to rod-plane gaps from 1 m up to 10 m, the experimental data for positive polarity strength may be approximated by:

$$U_{50\mathrm{RP}} = 530\, d \qquad \text{(kV crest, m)} \qquad \text{(G.6)}$$

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:

$$K_{\mathrm{ff}}^{+} = 0{,}74 + 0{,}26\ \mathrm{K} \qquad \text{(G.7)}$$

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 formula may be used:

$$U_{50} = 700\, d \qquad \text{(kV crest, m)} \qquad \text{(G.8)}$$

The formulas (G.6) and (G.8) are applicable to sea-level (H = 0). Therefore, correction for altitude is required (according to 4.2.2) when applying the insulation co-ordination procedure.

For configurations such as conductor-upper structure and conductor-crossarm, the influence of the insulators on the strength is negligible so that the strength of these configurations is close to that of air gaps.

For other unusual configurations and particularly when large clearances are involved (like in range II), specific testing is advised for accurate results. For these configurations, the presence of insulators between the electrodes can play an important role on the discharge process, thus also heavily affecting the value of U_{50}. The degree of influence depends on insulator type (capacitance between units, distance between metal parts along the insulator set). A lower influence is to be expected for insulators with few metal parts (e.g. post insulators, long rod, composite). The generalization of the results similar to that made for configurations without insulators is not easy when cap and pin insulators are included in the gap. It can be stated however that the influence of cap and pin insulators is reduced when the stress on the first insulator at both extremities of the string is reduced using shielding rings. It is also reduced for more practical configurations with insulators at both extremities less stressed than in the case of rod-plane gaps.

For air gaps, the conventional deviation is about 3 % of U_{50} under positive impulses and about 5 % of U_{50} under negative impulses. When insulators are present, the conventional deviation is increased reaching a maximum of 5 % to 9 % in connection with cases presenting the largest reduction of U_{50}. In other cases, a value close to that of air gaps is applicable.

The influence of rain on a flashover voltage is generally secondary, both in the case of air gaps and insulator strings.

For fast-front overvoltages, the time-to-breakdown is markedly influenced by the amplitude of the applied impulse relative to the breakdown voltage. For impulses close to the value of $U_{50,}$ flashover occurs on the tail of the standard impulse. As amplitude is increased, time to flashover decreases giving rise to the well-known volt-time curve.

Tableau G.1 – Typical gap factors *K* for switching impulse breakdown phase-to-earth (according to [1] and [4])

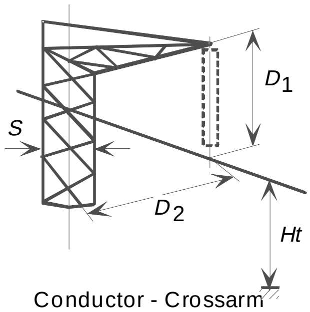
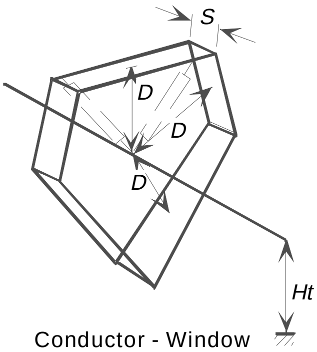
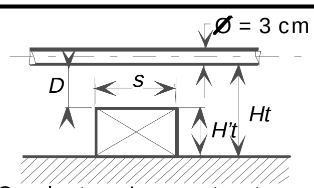
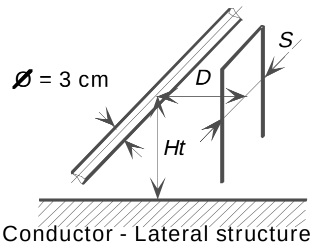
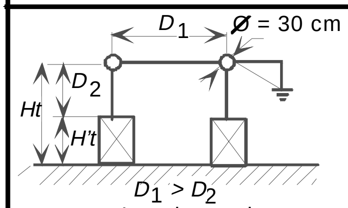
Gap type	Parameters	Typical range	Reference value	
	K	1,36 - 1,58	1,45	
	D_2 / D_1	1 - 2	1,5	
	Ht / D_1	3,34 - 10	6	
Conductor - Crossarm	S / D_1	0,167 - 0,2	0,2	
	*K*	1,22 - 1,32	1,25	
	Ht/D	8 - 6,7	6	
Conductor - Window	*S/D*	0,4 - 0,1	0,2	
	*K*	1,18 - 1,35	1,15 Conductor-Plane	1,47 Conductor-Rod
	H't/Ht	0,75 - 0,75	0	0,909
	H't/D	3 - 3	0	10
Conductor - Lower structure	*S/D*	1,4 - 0,05	-	0
	*K*	1,28 - 1,63	1,45	
	Ht/D	2 - 10	6	
Conductor - Lateral structure	*S/D*	1 - 0,1	0,2	
	*K*	1,03 - 1,66	1,35	
	H't/Ht	0,2 - 0,9	0	
$D_1 > D_2$ Longitudinal (Rod-Rod structure)	D_1 / Ht	0,1 - 0,8	0,5	

Table G.2 – Gap factors for typical phase-to-phase geometries

Configuration	$\alpha = 0{,}5$	$\alpha = 0{,}33$
Ring-ring or large smooth electrodes	1,80	1,70
Crossed conductors	1,65	1,53
Rod-rod or conductor-conductor (along the span)	1,62	1,52
Supported busbars (fittings)	1,50	1,40
Asymmetrical geometries	1,45	1,36
NOTE – According to [1] and [4].		

Annex H
(informative)

Examples of insulation co-ordination procedure

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 71-1, 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 this annex. 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.

H.1 Numerical example for a system in range I (with nominal voltage of 230 kV)

The system analysed corresponds to that shown in figure 11. The process of insulation co-ordination is applied to station 1 assumed to be a new station.

For equipment in range I, IEC 71-1 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. This example 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 where no “abnormal” operating condition is considered.

However, as a second part of the example, 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, 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 table 1);
– the altitude is H = 1000 m.

H.1.1 *Part 1: no special operating conditions*

H.1.1.1 *Step 1: determination of the representative overvoltages – values of* U_{rp}

H.1.1.1.1 *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 (r.m.s., phase-to-phase). The system, including compensation, is designed to operate at or below this limit. Obviously, the installed equipment should have a U_m equal to or greater than U_s.

The new station 1 is to be located adjacent to a major thoroughfare where salt, spread on the road in winter, can be expected to lead to heavy pollution. Because of this environment, the performance requirements of external insulation at power-frequency will be met by specifying an artificial pollution test corresponding to pollution level III of table 1. According to the same table, the minimum creepage distance recommended for insulators is 25 mm/kV.

H.1.1.1.2 *Temporary overvoltages*

One source of temporary overvoltages is earth faults (refer to 2.3.2.1) 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 2.3.2.2) 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 2.3.2.5, 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.

H.1.1.1.3 *Slow-front overvoltages*

System studies have confirmed that slow-front overvoltages from remote lightning strokes (refer to 2.3.3.5) 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 2.3.3.2) 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.

Particular surges affecting line entrance equipment (at station 1)

System studies using the phase-peak method (refer to annex D) 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 D:

- $u_{et} = 1,25\ u_{e2} - 0,25$ $\Rightarrow$ u_{et} = 700 kV;
- $u_{pt} = 1,25\ U_{p2} - 0,43$ $\Rightarrow$ u_{pt} = 1039 kV.

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.

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 2.3.3.7), identical to those planned for transformer protection. The rating of these arresters is such that they can sustain the worst temporary overvoltage cycle (amplitude and duration). Their protection characteristics are:

- switching impulse protective level: U_{ps} = 410 kV;
- lightning impulse protective level: U_{pl} = 500 kV.

As explained in 2.3.3.7, 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.

H.1.1.1.4 *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.

H.1.1.2 *Step 2: determination of the co-ordination withstand voltages – values of* U_{cw}

According to clause 3 of the guide, 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).

H.1.1.2.1 *Temporary overvoltages*

For this class of overvoltages, the co-ordination withstand voltage is equal to the representative temporary overvoltage (refer to 3.3.1). 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.

H.1.1.2.2 *Slow-front overvoltages*

The deterministic approach will be used. With such an approach, one must take into account that surge limitation by an arrester distorts the statistical distribution of these surges, creating a significant bulge in the probability distribution of surges at about the arrester protective level (refer to 3.3.2.1). Therefore, small uncertainties related to the arrester protective characteristic or to equipment strength could lead to an abnormally high increase in the failure rate. Figure 4 takes this into account by applying a deterministic co-ordination factor K_{cd} to the arrester protective 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: $U_{cw} = 1,1 \times 410$ ⇒ U_{cw} = 451 kV;
– phase-to-phase: $U_{cw} = 1,0 \times 820$ ⇒ U_{cw} = 820 kV.

For all other equipment:

– phase-to-earth: $U_{cw} = 1,03 \times 410$ ⇒ U_{cw} = 422 kV;
– phase-to-phase: $U_{cw} = 1,0 \times 639$ ⇒ U_{cw} = 639 kV.

H.1.1.2.3 *Fast-front overvoltages*

A statistical approach is used (refer to 3.3.3.2), and more specifically, a simplified statistical approach (refer to F.4). Here, the factor to be applied to U_{rp} is based on experience with particular line construction and on the calculated effect due to the separation between the arrester and the protected equipment.

One determines the length L_a of overhead line with an outage rate equal to the acceptable failure rate R_a. Then, taking account of the separation distance L, the number of lines n entering the station, and the span length L_{sp} ,one calculates the effective protective level of the arrester, which is the desired value U_{cw}.

For this example, the following data are available: many arresters with a lightning protective 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 = 4500 (refer to table F.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 (F.18), the value of L_a = 0,25 km is found. Introducing the value of L_a and other parameters in equation (F.19) the co-ordination withstand voltage is found:

- for internal insulation:
  - $U_{cw} = 500 + [(4500 / 2) \times 30 / (300+250)]$ ⇒ U_{cw} = 622 kV;
- for external insulation:
  - $U_{cw} = 500 + [(4500 / 2) \times 60 / (300+250)]$ ⇒ U_{cw} = 745 kV.

Fast-front overvoltages affect the phase-to-phase and the phase-to-earth insulations in the same way.

H.1.1.3 *Step 3: determination of the required withstand voltages – values of* U_{rw}

The required withstand voltages are obtained by applying to the co-ordination withstand voltages two correction factors (refer to clause 4): factor K_a which takes into account the altitude of the installation, and a safety factor K_s.

H.1.1.3.1 *Safety factor*

The recommended values for the safety factor K_s are defined in 4.3.4. 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.

H.1.1.3.2 *Atmospheric correction factor*

The altitude correction factor K_a is defined in 4.2.2 (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:

⇒ m = 0,5.

For switching impulse withstand, the value of m is a function of the co-ordination withstand voltage according to figure 9:

– phase-to-earth: U_{cw} = 451 kV ⇒ m = 0,94;

– phase-to-phase: U_{cw} = 820 kV ⇒ m = 1,00.

For lightning impulse withstand: ⇒ m = 1,00.

The installation is at an altitude H = 1000 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).

H.1.1.3.3 *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 and K_s and K_a values found in step 3.

For temporary overvoltages:

– external insulation:
  • phase-to-earth ⇒ $U_{rw} = 212 \times 1,05 \times 1,063$ ⇒ U_{rw} = 237 kV,
  • phase-to-phase ⇒ $U_{rw} = 343 \times 1,05 \times 1,063$ ⇒ U_{rw} = 383 kV;
– internal insulation:
  • phase-to-earth ⇒ $U_{rw} = 212 \times 1,15$ ⇒ U_{rw} = 243 kV,
  • phase-to-phase ⇒ $U_{rw} = 343 \times 1,15$ ⇒ U_{rw} = 395 kV.

For slow-front overvoltages:

For line entrance equipment
– external insulation:
  • phase-to-earth ⇒ $U_{rw} = 451 \times 1,05 \times 1,122$ ⇒ U_{rw} = 531 kV,
  • phase-to-phase ⇒ $U_{rw} = 820 \times 1,05 \times 1,13$ ⇒ U_{rw} = 973 kV.

For other equipment
– external insulation:
  • phase-to-earth ⇒ $U_{rw} = 422 \times 1,05 \times 1,122$ ⇒ U_{rw} = 497 kV,
  • phase-to-phase ⇒ $U_{rw} = 639 \times 1,05 \times 1,13$ ⇒ U_{rw} = 758 kV.
– internal insulation:
  • phase-to-earth ⇒ $U_{rw} = 422 \times 1,15$ ⇒ U_{rw} = 485 kV,
  • phase-to-earth ⇒ $U_{rw} = 639 \times 1,15$ ⇒ U_{rw} = 735 kV.

For fast-front overvoltages:

– external insulation:
  • phase-to-earth ⇒ $U_{rw} = 745 \times 1,05 \times 1,13$ ⇒ U_{rw} = 884 kV,
  • phase-to-phase ⇒ $U_{rw} = 745 \times 1,05 \times 1,13$ ⇒ U_{rw} = 884 kV.
– internal insulation:
  • phase-to-earth ⇒ $U_{rw} = 622 \times 1,15$ ⇒ U_{rw} = 715 kV,
  • phase-to-phase ⇒ $U_{rw} = 622 \times 1,15$ ⇒ U_{rw} = 715 kV.

H.1.1.4 *Step 4: conversion to withstand voltages normalized for range I*

In range I, the insulation level is normally described by a set of two values as shown in table 2 of IEC 71-1: a short-duration power-frequency withstand voltage and a lightning impulse withstand voltage. Table 2 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.

H.1.1.4.1 *Conversion to short-duration power-frequency withstand voltage (SDW)*

For line entrance equipment:

– external insulation:
  - phase-to-earth ⇒ SDW = 531 × (0,6 + 531 / 8500) = 352 kV;
  - phase-to-phase ⇒ SDW = 973 × (0,6 + 973 / 12 700) = 658 kV.

For other equipment:

– external insulation:
  - phase-to-earth ⇒ SDW = 497 × (0,6 + 497 / 8500) = 327 kV;
  - phase-to-phase ⇒ SDW = 758 × (0,6 + 758/12 700) = 500 kV;

– internal insulation:
  - phase-to-earth ⇒ SDW = 485 × 0,5 = 243 kV;
  - phase-to-phase ⇒ SDW = 735 × 0,5 = 367 kV.

H.1.1.4.2 *Conversion to lightning impulse withstand voltage (LIW)*

For line entrance equipment:

– external insulation:
  - phase-to-earth ⇒ LIW = 531 × 1,30 = 690 kV;
  - phase-to-phase ⇒ LIW = 973 × (1,05 + 973/9000) = 1127 kV.

For other equipment:

– external insulation:
  - phase-to-earth ⇒ LIW = 497 × 1,30 = 646 kV;
  - phase-to-phase ⇒ LIW = 758 × (1,05 + 758 / 9000) = 860 kV;

– internal insulation:
  - phase-to-earth ⇒ LIW = 485 × 1,10 = 534 kV;
  - phase-to-phase ⇒ LIW = 735 × 1,10 = 808 kV.

H.1.1.5 *Step 5: selection of standard withstand voltage values*

Table H.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 H.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 H.1 – Summary of minimum required withstand voltages obtained for example H.1.1 (part 1, without capacitor switching at remote station (station 2))

Values of U_{rw} : – in kV r.m.s for short-duration power frequency – in kV peak for switching or lightning impulse		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	phase-earth	**237**	352	**237**	327	**243**	243
	phase-phase	**383**	658	**383**	500	**395**	367
Switching impulse	phase-earth	531		497	–	485	–
	phase-phase	973	–	758	–	735	–
Lightning impulse	phase-earth	**884**	690	**884**	646	**715**	534
	phase-phase	884	**1127**	**884**	860	715	**808**

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 H.1 (highest value of minimum withstand required $U_{rw(s)}$ or converted value $U_{rw(c)}$) and standard values proposed in IEC 71-1, 4.6 and 4.7 Normally, specified voltages are chosen in such a way as to correspond to a standard insulation level as defined in 3.33 of IEC 71-1 and shown in table 2 of IEC 71-1.

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 1127 kV minimum withstand value is required. However, in this example, three-phase equipment is not installed at line entrance so that a minimum phase-to-phase clearance can be specified instead of testing. According to table A.1, a clearance of 2,35 m between phases would be required for line entrance equipment, corresponding to a standard lightning impulse withstand voltage of 1175 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 economical issue, are possible (refer to subclause 4.9 of IEC 71-1): specification of a lightning impulse withstand voltage of 850 kV, phase-to-phase and phase-to-earth; or 750 kV phase-to-earth with a special phase-to-phase test at 850 kV. However, the short-duration power-frequency test at a minimum value of 395 kV must 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 71-1.

H.1.2 *Part 2: influence of capacitor switching at station 2*

This second part of the example H.1 deals with an additional slow-front overvoltage possibility originating from capacitor bank switching done at station 2 (remote station). All the other stresses considered in part 1 are present at their same values, with the same arrester implementation at station 1.

Results from system studies show that all equipment at station 1 (including line entrance equipment in normal operating closed condition) is subjected to severe voltage surges due to capacitor bank energization at station 2. These surges propagate and, due to amplification phenomenon (resonance at given frequencies), show the following maximum amplitudes at station 1:

– phase-to-earth:
  - U_{e2} = 500 kV;
  - U_{et} = 575 kV;
– phase-to-phase:
  - U_{p2} = 750 kV;
  - U_{pt} = 852 kV.

For the open-end line entrance equipment, the highest slow-front surges are those related to line re-energization described in part 1. But for all other equipment, the slow-front surges governing the insulation co-ordination procedure are now related to capacitor bank switching in station 2, which are higher than surges originating from local energization and re-energization (described in part 1). Hereafter, we will deal only with this type of stress (new slow-front surges), conclusions for the other types of stress (temporary and fast-front overvoltages) remaining the same as discussed in part 1.

Values of representative slow-front overvoltages U_{rp} are now controlled by the surge arrester protection characteristic because $U_{ps} < U_{et}$ and $2\ U_{ps} < U_{pt}$, so that:

– phase-to-earth: U_{rp} = 410 kV;

– phase-to-phase: U_{rp} = 820 kV.

To obtain the slow-front co-ordination withstand voltages U_{cw}, a deterministic co-ordination factor K_{cd} is applied to U_{rp} values by following the same procedure described in part 1:

– phase-to-earth: $U_{ps}/\ U_{e2}$ =410/500 = 0,82 $\Rightarrow$ K_{cd} = 1,10 $\Rightarrow$ U_{cw} = 451 kV;

– phase-to-phase: 2 $U_{ps}/\ U_{p2}$ =820/750 =1,09 $\Rightarrow$ K_{cd} =1,00 $\Rightarrow$ U_{cw} = 820 kV.

The values for the safety factor K_s and for the atmospheric correction factor K_a keep approximately the same values as in part 1 so that the resulting required withstand voltages U_{rw} are:

– external insulation:
  - phase-to-earth $\Rightarrow$ $U_{rw} = 451 \times 1,05 \times 1,122$ $\Rightarrow$ U_{rw} = 531 kV;
  - phase-to-phase $\Rightarrow$ $U_{rw} = 820 \times 1,05 \times 1,13$ $\Rightarrow$ U_{rw} = 973 kV;
– internal insulation:
  - phase-to-earth $\Rightarrow$ $U_{rw} = 451 \times 1,15$ $\Rightarrow$ U_{rw} = 518 kV;
  - phase-to-phase $\Rightarrow$ $U_{rw} = 820 \times 1,15$ $\Rightarrow$ U_{rw} = 943 kV.

The required withstand voltages for slow-front surges are converted into short-duration power-frequency and lightning impulse withstand voltages (refer to part 1 for detailed information).

Conversion to short-duration power-frequency withstand voltage (SDW):

– external insulation:
  - phase-to-earth ⇒ SDW = 531 × (0,6 + 531 / 8500) = 352 kV;
  - phase-to-phase ⇒ SDW = 973 × (0,6 + 973 / 12 700) = 658 kV;

– internal insulation:
  - phase-to-earth ⇒ SDW = 518 × 0,5 = 259 kV;
  - phase-to-phase ⇒ SDW = 943 × 0,5 = 472 kV.

Conversion to lightning impulse withstand voltage (LIW):

– external insulation:
  - phase-to-earth ⇒ LIW = 531 × 1,30 = 690 kV;
  - phase-to-phase ⇒ LIW = 973 × (1,05 + 973 / 9000) = 1127 kV;

– internal insulation:
  - phase-to-earth ⇒ LIW = 518 × 1,10 = 570 kV;
  - phase-to-phase ⇒ LIW = 943 × 1,10 = 1037 kV.

Table H.2 : Summary of required withstand voltages obtained for example H.1.2 (part 2, with capacitor switching at remote station (station 2))

Values of U_{rw} are: – in kV rms for short-duration power frequency – in kV peak for switching or lightning impulse		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	phase-earth	**237**	352	**237**	352	**243**	259
	phase-phase	**383**	658	**383**	658	**395**	472
Switching impulse	phase-earth	531	–	531	–	518	–
	phase-phase	973	–	973	–	943	–
Lightning impulse	phase-earth	**884**	690	**884**	690	**715**	570
	phase-phase	884	**1127**	884	**1127**	715	**1037**

Table H.2 reflects the minimum withstand (or test) values required to take into account the different overvoltage stresses related to part 2 of example H.1. Minimum values required for the short-duration power-frequency and lightning impulse withstand tests are shown in bold characters.

A comparison between table H.2 and table H.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.

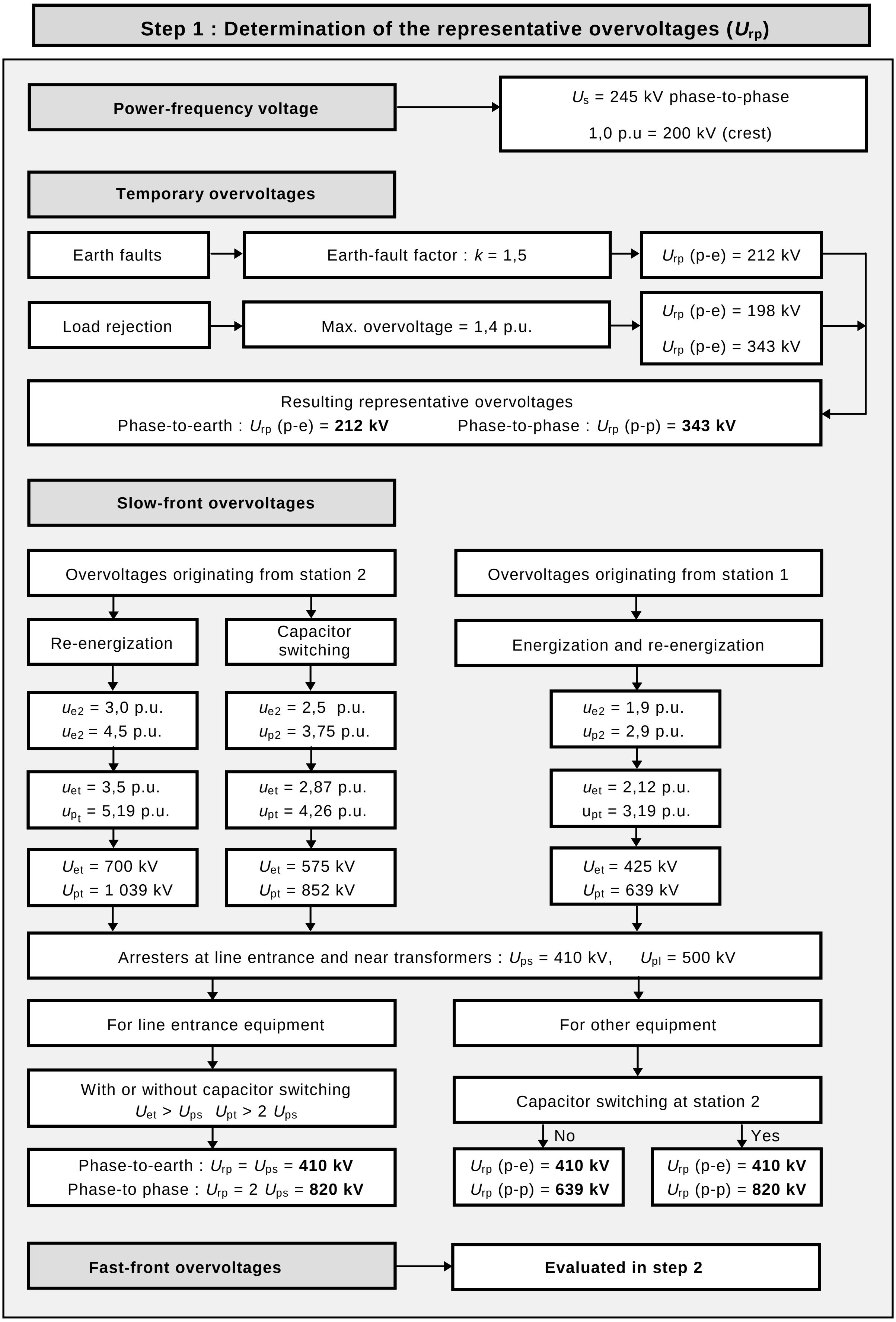
For external insulation, including longitudinal insulation, the same standard insulation level defined in part 1 (395 kV/950 kV) is also applicable here, no phase-to-phase test being required if a 2,35 m phase-to-phase clearance (corresponding to a standard lightning impulse withstand voltage of 1175 kV) is adopted for all external equipment (not only at line entrance as for part 1).

For the internal insulation, a standard insulation level applicable phase-to-phase and phase-to-earth of 460 kV / 1050 kV, corresponding to U_m = 245 kV, can be chosen (refer to table 2 of IEC 71-1). 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 1050 kV would be required.

H.1.3 *Flow charts related to example H.1*

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 2.3.3.6, 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 step 5 of the flow chart), 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-e) = 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_{e2} = 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_{p_t} = 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 : $U_{cw} = K_c \times U_{rp} = 1,0 \times 212 = 212$ kV
Phase-to-phase : $U_{cw} = K_c \times U_{rp} = 1,0 \times 343 = 343$ 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
→

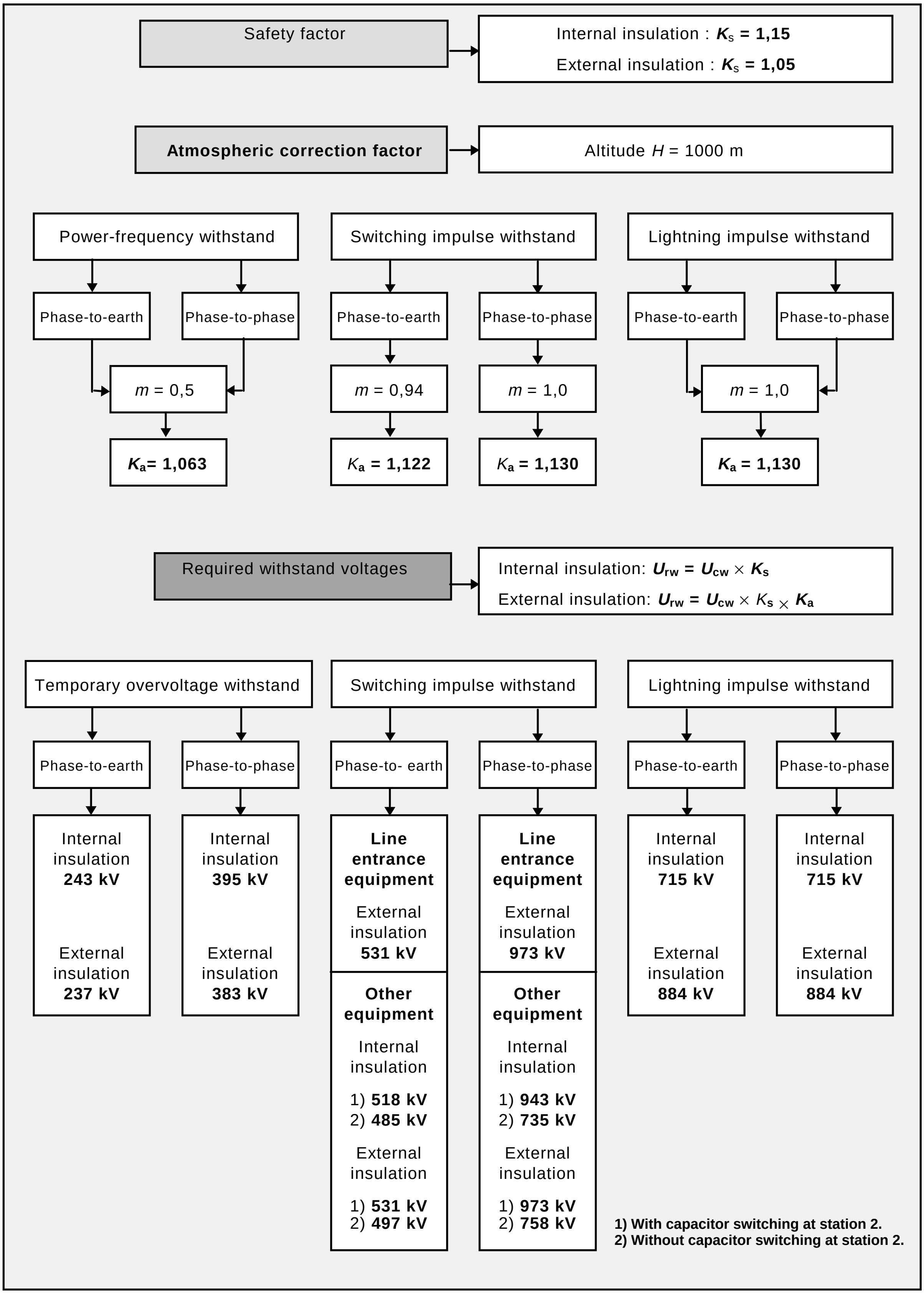
Parameter « A » :	A = 4500
Span length :	L_{sp} = 300 m
Outage rate :	1/100 km. year
Acceptable failure rate :	1/400 years

→ 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
1127 kV

Other equipment

External insulation
- phase-to-earth
1) **690 kV**
2) **646 kV**
- phase-to-phase
1) **1127 kV**
2) **860 kV**

Internal insulation
- phase-to-earth
1) **570 kV**
2) **534 kV**
- phase-to-phase
1) **1037 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 H.1	**With** capacitor switching at remote station. Refer to explanations related with table H.2
Standard insulation level :	395 kV / 950 kV Applicable to any insulation	395 kV / 950 kV External insulation 460 kV / 1050 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	1050 kV

H.2 Numerical example for a system in range II (with nominal voltage of 735 kV)

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 table 1);
- the altitude is: H = 1000 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.

H.2.1 *Step 1: determination of the representative overvoltages – values of U_{rp}*

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 (r.m.s., phase-to-earth);
- slow-front overvoltages: U_{e2} = 1200 kV (peak, phase-to-earth; phase-peak method).

H.2.1.1 *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 of this example.

H.2.1.2 *Slow-front overvoltages*

The slow-front overvoltage is related to line reclosing and is limited to about 2,0 p.u. by the use of closing resistors implemented on line circuit breakers.

The surge arrester rating is also determined from these same system studies (normally from the temporary overvoltage characteristics: amplitude and duration) and, for the particular case of this example, the following protection levels were determined:

- switching impulse protective level: U_{ps} = 1300 kV (peak value);
- lightning impulse protective level: U_{pl} = 1500 kV (peak value).

H.2.1.3 *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 H.2.6).

H.2.2 *Step 2: determination of the co-ordination withstand voltages – values of* U_{cw}

The co-ordination withstand voltage is obtained by applying a co-ordination factor (K_c) to the representative overvoltages, this factor being either K_{cd} for the deterministic method or K_{cs} for the statistical method. Thus the determination of the co-ordination withstand voltages must be carried out for internal insulation (such as transformers) and external insulation separately.

H.2.2.1 U_{cw} *for internal insulation*

In this step, the determination of U_{cw} for internal insulation is carried out for power-frequency, slow-front and fast-front overvoltages.

H.2.2.1.1 U_{cw} *for temporary overvoltages*

For this class of overvoltages, the co-ordination withstand voltage is equal to the representative temporary overvoltage (refer to 3.3.1). In other words the co-ordination factor K_c = 1. Therefore:

– phase-to-earth: U_{cw} = 660 kV.

H.2.2.1.2 U_{cw} *for slow-front overvoltages*

For equipment protected by surge arresters, the maximum slow-front overvoltage (and thus the slow-front representative overvoltage) is equal to the switching-impulse protective level of the surge arrester, namely 1300 kV.

This value of 1300 kV must 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 3.3.2.1. It can be seen from figure 4 that for a ratio of U_{ps} / U_{e2} = 1,08 (1300/1200) the value of K_{cd} is 1,03. Hence, the co-cordination withstand voltage for slow-front surges is 1340 kV:

– representative slow-front overvoltage: U_{rp} = 1300 kV;
– deterministic co-ordination factor: K_{cd} = 1,03 kV;
– co-ordination withstand voltage: U_{cw} = 1340 kV.

H.2.2.1.3 U_{cw} *for fast-front overvoltages*

For equipment protected by surge arresters, the maximum fast-front overvoltage (and thus the fast-front representative overvoltage) is equal to the lightning-impulse protective level of the surge arrester, namely 1500 kV.

However, to this value of 1500 kV, one must add a voltage equal to $AL/(n\ (L_{sp} + L_a))$ according to equation (F.19) to take into account the separation distance L between the surge arrester and the protected equipment, as explained in 2.3.4.5.

The parameters are obtained as follows:

– A: from table F.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} = 1500 kV.
– Correction value for separation: 130 kV.
– Co-ordination withstand voltage: U_{cw} = 1630 kV.

H.2.2.2 U_{cw} *for external insulation*

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 H.2.2.2.2 below.

H.2.2.2.1 U_{cw} *for temporary overvoltages*

These are the same as for the internal insulation (H.2.2.1.1).

H.2.2.2.2 U_{cw} *for slow-front overvoltages*

The value of the statistical co-ordination factor K_{cs} comes from choosing a risk of failure of the insulation that has been proven from experience to be acceptable. The relation between the risk of failure R and K_{cs} is shown in figure 8 and, for a usually acceptable value of R in the range of 10^{-4}, the value of K_{cs} is 1,15. Hence the co-ordination withstand voltage is U_{cw} = 1200 kV × 1,15 = 1380 kV:

- statistical overvoltage: U_{e2} = 1200 kV;
- statistical co-ordination factor: K_{cs} = 1,15;
- co-ordination withstand voltage: U_{cw} = 1380 kV.

H.2.2.2.3 U_{cw} *for fast-front overvoltages*

The determination of the co-ordination withstand voltage for fast-front overvoltage is not necessary since the lightning impulse withstand voltage of the minimum clearances that result from the switching impulse withstand voltage will be far in excess of those that should be determined solely by the lightning impulse withstand voltage required for the non-self-restoring insulation.

This is demonstrated at the end of this example when the question of air clearance to ground is discussed.

H.2.3 *Step 3: determination of the required withstand voltages – values of* U_{rw}

The required withstand voltage is obtained by applying a safety factor K_s to the co-ordination withstand voltage as explained in 4.3.4. 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 H.2.3.2 below).

H.2.3.1 U_{rw} *for internal insulation*

- 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} = 1340 kV;
- Safety factor: K_s = 1,15;
- U_{rw} for slow-front overvoltages: U_{rw} = 1540 kV;
- U_{cw} for fast-front overvoltages: U_{cw} = 1630 kV;
- Safety factor: K_s = 1,15;
- U_{rw} for fast-front overvoltages: U_{rw} = 1875 kV.

H.2.3.2 *U_{rw} for external insulation*

For power-frequency we will determine the atmospheric correction factor assuming we require a short-duration power-frequency test on polluted insulators, for which $m = 0,5$ and assuming $H = 1000$ m, $K_a = 1,063$.

Hence $U_{rw} = 660 \times 1,063 \times 1,05 = 737$ kV:

- U_{cw} for temporary overvoltages: U_{cw} = 660 kV;
- atmospheric correction factor: K_a = 1,063;
- safety factor: K_s = 1,05;
- U_{rw} for temporary overvoltage: U_{rw} = 737 kV.

The atmospheric correction factor K_a for slow-front overvoltages is based on the assumed altitude as explained in 4.2.2 and equation (11). For $H = 1000$ m and $m = 0,6$ (from figure 9), then $K_a = e^{0,07} = 1,07$. Hence $U_{rw} = 1380$ kV $\times 1,07 \times 1,05 = 1550$ kV:

- U_{cw} for slow-front overvoltages: U_{cw} = 1380 kV;
- atmospheric correction factor: K_a = 1,07;
- safety factor: K_s = 1,05;
- U_{rw} for slow-front overvoltages: U_{rw} = 1550 kV.

H.2.4 *Step 4: conversion to switching impulse withstand voltages (SIW)*

Referring to clause 5.1, the required short-duration power-frequency withstand voltages are converted to an equivalent switching impulse withstand voltage (SIW), according to table 3.

- For internal insulation: SIW = $759 \times 2,3 = 1746$ kV.
- For external insulation: SIW = $737 \times 1,7 = 1253$ kV.

H.2.5 *Step 5: selection of standard insulation levels*

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 71-1.

H.2.5.1 *U_w for internal insulation*

For the temporary overvoltage stresses, a switching withstand voltage of 1750 kV would be required according to step 4. Considering this last requirement, many options are available. At first, a value of 1750 kV is not standardized in IEC 71-1, the highest one being 1550 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 71-1, 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 7200 periods followed by 1,5 p.u. for 1 h).

- U_{rw} for slow-front overvoltages: $U_{rw} = 1540$ kV.
- Standard switching-impulse withstand voltage: $U_w = 1550$ kV.
- U_{rw} for fast-front overvoltages: $U_{rw} = 1875$ kV.
- Standard lightning impulse withstand voltage: $U_w = 1950$ kV.

H.2.5.2 *U_w for external insulation*

The lightning impulse withstand voltage of 1950 kV would apply to the external insulation of equipment protected by arresters, such as transformers and shunt reactors.

In the case of equipment remotely located from the surge arresters such as current transformers, circuit-breakers, disconnectors and buswork, the separation distance (see 2.3.4.5) 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 = 2100 kV.

- U_{rw} for slow-front overvoltages : U_{rw} = 1550 kV.
- Standard switching impulse withstand voltage: U_w = 1550 kV.
- Standard lightning impulse withstand voltage (protected equipment): U_w = 1950 kV.
- Standard lightning impulse withstand voltage (unprotected equipment): U_w = 2100 kV.

The standard switching impulse withstand voltage of 1550 kV is more than sufficient to cover the required switching impulse withstand voltage of 1253 kV converted from the power-frequency requirements (external insulation).

H.2.6 *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 D.4. Based on this subclause, 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 = tg ϕ) comes from figure D.5 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} = 1200 kV;
- phase-to-phase slow-front overvoltage: U_{p2} = 2040 kV.

The phase-to-earth slow-front overvoltage was determined in H.2.1. 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} = 2040 kV. Equation (D.14) gives the phase-to-phase representative overvoltage:

$$U_{p2\text{-}re} = 2 \ (F_1 \ U_{p2} + F_2 \ U_{e2}) = 2067 \text{ kV.}$$

The co-ordination phase-to-phase withstand voltage is obtained applying a co-ordination factor K_{cs} = 1,15:

$$U_{p\text{-}cw} = K_{cs} \ U_{p2\text{-}re} = 2377 \text{ kV.}$$

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 H.2.3):

$$U_{p\text{-}rw} = K_a \ K_s \ U_{p\text{-}cw} = 2670 \text{ kV.}$$

Test values are thus specified as ± 1335 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 1143 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 : $U_{rw} = 1143 \times 1{,}15 = 1314$ kV;
- external insulation : $U_{rw} = 1143 \times 1{,}063 \times 1{,}05 = 1276$ kV.

These are converted into phase-to-phase switching impulse withstand voltages (SIW):

- internal insulation : SIW = 1314 × 2,3 = 3022 kV;
- external insulation : SIW = 1276 × 1,7 = 2169 kV.

The previously determined switching impulse test voltage of 2670 kV is adequate to cover the external insulation power-frequency requirement but not the internal insulation. Special measures as described in H.2.5.1 would be required.

H.2.7 *Phase-to-earth clearances*

The required phase-to-earth clearance for switching impulses can be obtained from table A.2 and a standard switching impulse withstand voltage of 1550 kV.

For the conductor-structure configuration (slow-front gap factor K = 1,35), the minimum clearance is 4900 mm. For the rod-structure configuration (slow-front gap factor K < 1,15), the minimum clearance is 6400 mm. The lightning impulse withstand voltage of such clearances can be estimated from the formulae given in annex G. Using equation (G.7) to obtain the equivalent fast-front gap factors, we obtain:

- conductor-structure: $K_{ff}^{+} = 0{,}74 + 0{,}26 \times 1{,}35 = 1{,}05$;
- rod-structure: $K_{ff}^{+} = 0{,}74 + 0{,}26 \times 1{,}15 = 1{,}04$.

Using K_{ff}^{+} = 1,04 to be conservative, we obtain from equations (G.6) and (7):

- $U_{50RP} = K_{ff}^{+}\ 530\ d = 1{,}04 \times 530 \times 4{,}9 = 2700$ kV and
- LIW = $U_{50RP} - 1{,}3\ Z = U_{50RP}\ (1 - 1{,}3\ z) = 2700\ (1 - 1{,}3 \times 0{,}03) = 2595$ kV,

which is well above the standard lightning impulse withstand voltage of 2100 kV from H.2.5.2.

H.2.8 *Phase-to-phase clearances*

The required phase-to-phase clearance can be obtained from equation (D.12) which states that $U_0^+ = U^+ + BU^-$ where U_0^+ is an equivalent phase-to-earth voltage that represents the effect of a positive voltage on one phase (U^+) and a negative voltage on the other phase (U^-). From the work carried out in H.2.6, with the values of $U^+ = U^- = 1335$ kV and with B = 0,6, one can find U_0^+ as:

$$U_0^+ = 1335 \times 1{,}6 = 2136 \text{ kV}$$

The corresponding value of U_{50} is given by $U_{50} = U_{10}$ / 0,922 = 2317 kV; d is obtained from equations (G.3) and (G.5) and for gap factors K = 1,62 (parallel conductor configuration) and K = 1,45 (rod-conductor configuration):

$$2317 = K\ 1080 \ln (0{,}46\ d + 1)$$

from which phase-to-phase clearances are:

- conductor-conductor: d = 6,0 m;
- rod-conductor: d = 7,4 m.

From table A.3, a standard phase-to-earth switching impulse withstand voltage of 1550 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.

H.3 Numerical example for substations in distribution systems with U_m up to 36 kV in range I

For equipment in this voltage range, IEC 71-1 specifies standard rated short-duration power-frequency and lightning impulse withstand voltages. The selection of these values is illustrated in table H.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 = 1000 m.

The altitude level here is assumed to cover all possible locations.

H.3.1 *Step 1: determination of the representative overvoltages – values of* U_{rp}

H.3.1.1 *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.

H.3.1.2 *Slow-front overvoltages*

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 H.3 are selected according to annex D 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 formulae of annex D 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.

H.3.1.3 *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 F.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 H.3.

H.3.2 *Step 2: determination of the co-ordination withstand voltages – values of* U_{cw}

H.3.2.1 *Temporary overvoltages*

As the previously defined representative temporary overvoltages correspond to the maximum assumed voltage stresses, the deterministic insulation co-ordination procedure is applicable (see clause 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} ($U_{cw} = K_c\ U_{rp} = U_{rp}$).

H.3.2.2 *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 3.3.2.1). 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.

H.3.2.3 *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 F.2, the corresponding value for the factor A is 2700;

– 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 (F.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 (F.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.

H.3.3 *Step 3: determination of required withstand voltages – values of U_{rw}*

The required withstand voltages are obtained by applying the recommended safety factors (see 4.3.4) and the altitude correction (see 4.2.2). For the example given, it is assumed that substations of the same design shall be used up to altitudes of 1000 m.

H.3.3.1 *Safety factors*

The recommended safety factors from 4.3.4 are:

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

H.3.3.2 *Altitude correction factor*

The altitude correction factor is defined in 4.2.2. 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 1200 kV phase-to-phase, m = 1,0.
- For lightning impulse withstand, m = 1,0 and K_a = 1,13.

H.3.3.3 *Temporary overvoltage*

- Phase-to-earth:
  - internal insulation ⇒ $U_{rw} = U_{cw} \times 1{,}15 = 24 \times 1{,}15 = 28$ kV;
  - external insulation ⇒ $U_{rw} = U_{cw} \times 1{,}05 \times 1{,}13 = 24 \times 1{,}05 \times 1{,}13 = 28$ kV.
- Phase-to-phase:
  - internal insulation ⇒ $U_{rw} = U_{cw} \times 1{,}15 = 28 \times 1{,}15 = 32$ kV;
  - external insulation ⇒ $U_{rw} = U_{cw} \times 1{,}05 \times 1{,}13 = 28 \times 1{,}05 \times 1{,}13 = 33$ kV.

H.3.3.4 *Slow-front overvoltage*

- Phase-to-earth:
  - internal insulation ⇒ $U_{rw} = U_{cw} \times 1{,}15 = 59 \times 1{,}15 = 68$ kV;
  - external insulation ⇒ $U_{rw} = U_{cw} \times 1{,}05 \times 1{,}13 = 59 \times 1{,}05 \times 1{,}13 = 70$ kV.
- Phase-to-phase:
  - internal insulation ⇒ $U_{rw} = U_{cw} \times 1{,}15 = 86 \times 1{,}15 = 99$ kV;
  - external insulation ⇒ $U_{rw} = U_{cw} \times 1{,}05 \times 1{,}13 = 86 \times 1{,}05 \times 1{,}13 = 102$ kV.

H.3.3.5 *Fast-front overvoltage*

- internal insulation: ⇒ $U_{rw} = U_{cw} \times 1{,}15 = 95 \times 1{,}15 = 109$ kV;
- external insulation: ⇒ $U_{rw} = U_{cw} \times 1{,}05 \times 1{,}13 = 95 \times 1{,}05 \times 1{,}13 = 125$ kV.

H.3.4 *Step 4: conversion to standard short-duration power-frequency and lightning impulse withstand voltages*

For the selection of the standard withstand voltages in table 2 of IEC 71-1, 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).

H.3.4.1 *Conversion to short-duration power-frequency withstand voltage (SDW)*

– Phase-to-earth:
  - internal insulation ⇒ SDW = $U_{rw} \times 0,5 = 68 \times 0,5 = 34$ kV;
  - external insulation ⇒ SDW = $U_{rw} \times 0,6 = 70 \times 0,6 = 42$ kV.

– Phase-to-phase:
  - internal insulation ⇒ SDW = $U_{rw} \times 0,5 = 99 \times 0,5 = 50$ kV;
  - external insulation ⇒ SDW = $U_{rw} \times 0,6 = 102$ x $0,6 = 61$ kV.

H.3.4.2 *Conversion to lightning impulse withstand voltage (LIW)*

– Phase-to-earth:
  - internal insulation ⇒ LIW = $U_{rw} \times 1,10 = 68 \times 1,1 = 75$ kV;
  - external insulation ⇒ LIW = $U_{rw} \times 1,06 = 70 \times 1,06 = 74$ kV.

– Phase-to-phase:
  - internal insulation ⇒ LIW = $U_{rw} \times 1,10 = 99 \times 1,1 = 109$ kV;
  - external insulation ⇒ LIW = $U_{rw} \times 1,06 = 102 \times 1,06 = 108$ kV.

H.3.5 *Step 5: selection of standard withstand voltages*

Table 2 of IEC 71-1 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 71-1 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.

H.3.6 *Summary of insulation co-ordination procedure for example H.3*

Table H.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 H.3 – Values related to the insulation co-ordination procedure for example H.3

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	Values of K_c or K_{cd} :	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	—	—
Co-ordination withstand voltages	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	Safety factor K_s :	1,15	1,05	1,15	1,05	1,15	1,05	1,15	1,05	1,15	1,05
Required withstand voltages	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	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		
Standard withstand voltages	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 J
(informative)

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- ☐ product demonstration
- ☐ other................................

9.

In what medium of standard does your organization maintain most of its standards (check one):

- ☐ paper
- ☐ microfilm/microfiche
- ☐ mag tapes
- ☐ CD-ROM
- ☐ floppy disk
- ☐ on line

9A.

If your organization currently maintains part or all of its standards collection in electronic media please indicate the format(s):

- ☐ raster image
- ☐ full text

10.

In what medium does your organization intend to maintain its standards collection in the future (check all that apply):

- ☐ paper
- ☐ microfilm/microfiche
- ☐ mag tape
- ☐ CD-ROM
- ☐ floppy disk
- ☐ on line

10A.

For electronic media which format will be chosen (check one)

- ☐ raster image
- ☐ full text

11.

My organization is in the following sector (e.g. engineering, manufacturing)

....

12.

Does your organization have a standards library:

- ☐ yes
- ☐ no

13.

If you said yes to 12 then how many volumes:

....

14.

Which standards organizations published the standards in your library (e.g. ISO, DIN, ANSI, BSI, etc.):

....

15.

My organization supports the standards-making process (check as many as apply):

- ☐ buying standards
- ☐ using standards
- ☐ membership in standards organization
- ☐ serving on standards development committee
- ☐ other...............................

16.

My organization uses (check one)

- ☐ French text only
- ☐ English text only
- ☐ Both English/French text

17.

Other comments:

....

....

....

....

....

....

18.

Please give us information about you and your company

name: ....

job title:..

company: ....

address:...

....

....

....

No. employees at your location:.........

turnover/sales:.................................

Publications de la CEI préparées par le Comité d’Etudes n° 28

71: — Coordination de l'isolement.

71-1 (1993)	Partie 1: Définitions, principes et règles.
71-2 (1996)	Partie 2: Guide d'application.
72-3 (1982)	Troisième partie: Coordination de l'isolement entre phases. Principes, règles et guide d'application.

664: — Coordination de l'isolement des matériels dans les systèmes (réseaux) à basse tension.

664-1 (1992)	Partie 1: Principes, prescriptions et essais.
664-3 (1992)	Partie 3: Utilisation de revêtements pour réaliser la coordination de l'isolement des cartes imprimées équipées.

IEC publications prepared by Technical Committee No. 28

71: — Insulation co-ordination.

71-1 (1993)	Part 1: Definitions, principles and rules.
71-2 (1996)	Part 2: Application guide.
71-3 (1982)	Part 3: Phase-to-phase insulation co-ordination. Principles, rules and application guide.

664: — Insulation coordination for equipment within low-voltage systems.

664-1 (1992)	Part 1: Principles, requirements and tests.
664-3 (1992)	Part 3: Use of coatings to achieve insulation coordination of printed board assemblies.

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