

Insulation co-ordination —

Part 2: Application guide

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Contents

	Page
Committees responsible	Inside front cover
National foreword	ii
Foreword	2
Text of EN 60071-2	5
List of references	Inside back cover

National foreword

This Part of BS EN 60071 has been prepared by Technical Committee GEL/28, and is the English language version of EN 60071-2:1997, *Insulation co-ordination — Part 2: Application guide*, published by the European Committee for Electrotechnical Standardization (CENELEC). It is identical with IEC 71-2:1996, published by the International Electrotechnical Commission (IEC). It supersedes BS 5622-2:1979 which is withdrawn.

Cross-references

Publication referred to	Corresponding British Standard
HD 588.1 S1:1991 (IEC 60-1:1989)	BS 923 <i>Guide on high-voltage test techniques</i> Part 1:1990 <i>General</i>
EN 60071-1:1995 (IEC 71-1:1993)	BS EN 60071 <i>Insulation co-ordination</i> Part 1:1996 <i>Definitions, principles and rules</i>
EN 60099-1:1994 (IEC 99-1:1991)	BS EN 60099 <i>Surge arresters</i> Part 1:1994 <i>Non-linear resistor type gapped surge arresters for a.c. systems</i>
EN 60099-4:1993 (IEC 99-4:1991)	Part 4:1993 <i>Metal-oxide surge arresters without gaps for a.c. systems</i>
EN 60507:1993 (IEC 507:1991)	BS EN 60507:1993 <i>Artificial pollution tests on high-voltage insulators to be used on a.c. systems</i>
	BS 7527 <i>Classification of environmental conditions</i> Part 2: <i>Environmental conditions appearing in nature</i> Section 2.3:1991 <i>Air pressure</i>
HD 478.2.3 S1:1990 (IEC 721-2-3:1987)	

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Summary of pages

This document comprises a front cover, an inside front cover, pages i and ii, the EN title page, pages 2 to 106, an inside back cover and a back cover.

This standard has been updated (see copyright date) and may have had amendments incorporated. This will be indicated in the amendment table on the inside front cover.

English version

Insulation co-ordination Part 2: Application guide

(IEC 71-2:1996)

Coordination de l'isolement
Partie 2: Guide d'application
(CEI 71-2:1996)

Isolationskoordination
Teil 2: Anwendungsrichtlinie
(IEC 71-2:1996)

This European Standard was approved by CENELEC on 1996-10-01. CENELEC members are bound to comply with the CEN/CENELEC Internal Regulations which stipulate the conditions for giving this European Standard the status of a national standard without any alteration.

Up-to-date lists and bibliographical references concerning such national standards may be obtained on application to the Central Secretariat or to any CENELEC member.

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European Committee for Electrotechnical Standardization
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Central Secretariat: rue de Stassart 35, B – 1050 Brussels

Foreword

The text of document 28/115/FDIS, future edition 3 of IEC 71-2, prepared by IEC TC 28, Insulation co-ordination, was submitted to the IEC-CENELEC parallel vote and was approved by CENELEC as EN 60071-2 on 1996-10-01.

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The following dates were fixed:

- latest date by which the EN has to be implemented at national level by publication of an identical national standard or by endorsement (dop) 1997-09-01
- latest date by which the national standards conflicting with the EN have to be withdrawn (dow) 1997-09-01

Annexes designated “normative” are part of the body of the standard.

Annexes designated “informative” are given for information only.

In this standard, annexes A and ZA are normative and annexes B to J are informative.

Annex ZA has been added by CENELEC.

Endorsement notice

The text of the International Standard IEC 71-2:1996 was approved by CENELEC as a European Standard without any modification.

Contents

	Page
Foreword	2
1 General	5
1.1 Scope	5
1.2 Normative references	5
1.3 List of symbols and definitions	5
2 Representative voltage stresses in service	10
2.1 Origin and classification of voltage stresses	10
2.2 Characteristics of overvoltage protective devices	10
2.3 Representative voltages and overvoltages	12
3 Co-ordination withstand voltage	23
3.1 Insulation strength characteristics	23
3.2 Performance criterion	27
3.3 Insulation co-ordination procedures	27
4 Required withstand voltage	34
4.1 General remarks	34
4.2 Atmospheric correction	35
4.3 Safety factors	36
5 Standard withstand voltage and testing procedures	37
5.1 General remarks	37
5.2 Test conversion factors	38
5.3 Determination of insulation withstand by type tests	39
6 Special considerations for overhead lines	42
6.1 General remarks	42
6.2 Insulation co-ordination for operating voltages and temporary overvoltages	43
6.3 Insulation co-ordination for slow-front overvoltages	43
6.4 Insulation co-ordination for lightning overvoltages	43
7 Special considerations for substations	44
7.1 General remarks	44
7.2 Insulation co-ordination for overvoltages	45
Annex A (normative) Clearances in air to assure a specified impulse withstand voltage installation	47
Annex B (informative) Determination of temporary overvoltages due to earth faults	49
Annex C (informative) Weibull probability distributions	53

	Page		Page
Annex D (informative) Determination of the representative slow-front overvoltage due to line energization and re-energization	57	Figure B.2 — Relationship between R_0/X_1 and X_0/X_1 for constant values of earth-fault factor k where $R_1 = 0$	51
Annex E (informative) Transferred overvoltages in transformers	65	Figure B.3 — Relationship between R_0/X_1 et X_0/X_1 for constant values of earth-fault factor k where $R_1 = 0,5 X_1$	51
Annex F (informative) Lightning overvoltages	71	Figure B.4 — Relationship between R_0/X_1 et X_0/X_1 for constant values of earth-fault factor k where $R_1 = X_1$	52
Annex G (informative) Calculation of air gap breakdown strength from experimental data	78	Figure B.5 — Relationship between R_0/X_1 et X_0/X_1 for constant values of earth-fault factor k where $R_1 = 2X_1$	52
Annex H (informative) Examples of insulation co-ordination procedure	82	Figure C.1 — Conversion chart for the reduction of the withstand voltage due to placing insulation configurations in parallel	57
Annex J (informative) Bibliography	104	Figure D.1 — Example for bivariate phase-to-phase overvoltage curves with constant probability density and tangents giving the relevant 2 % values	62
Annex ZA (normative) Normative references to international publications with their corresponding European publications	105	Figure D.2 — Principle of the determination of the representative phase-to-phase overvoltage U_{pre}	63
Figure 1 — Range of 2 % slow-front overvoltages at the receiving end due to line energization and re-energization	16	Figure D.3 — Schematic phase-phase-earth insulation configuration	64
Figure 2 — Ratio between the 2 % values of slow-front overvoltages phase-to-phase and phase-to-earth	17	Figure D.4 — Description of the 50 % switching impulse flashover voltage of a phase-phase-earth insulation	64
Figure 3 — Diagram for surge arrester connection to the protected object	22	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	65
Figure 4 — Distributive discharge probability of self-restoring insulation described on a linear scale	30	Figure E.1 — Distributed capacitances of the windings of a transformer and the equivalent circuit describing the windings	70
Figure 5 — Disruptive discharge probability of self-restoring insulation described on a Gaussian scale	31	Figure E.2 — Values of factor J describing the effect of the winding connections on the inductive surge transference	71
Figure 6 — Evaluation of deterministic co-ordination factor K_{cd}	31	Table 1 — Recommended creepage distances	29
Figure 7 — Evaluation of the risk of failure	32	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	39
Figure 8 — Risk of failure of external insulation for slow-front overvoltages as a function of the statistical co-ordination factor K_{cs}	34	Table 3 — Test conversion factors for range II to convert required short-duration power-frequency withstand voltages to switching impulse withstand voltages	39
Figure 9 — Dependence of exponent m on the co-ordination switching impulse withstand voltage	36	Table 4 — Selectivity of test procedures B and C of IEC 60-1	41
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	41		
Figure 11 — Example of a schematic substation layout used for the overvoltage stress location (see 7.1)	44		
Figure B.1 — Earth-fault factor k on a base of X_0/X_1 for $R_1/X_1 = R = 0$	50		

	Page
Table A.1 — Correlation between standard lightning impulse withstand voltages and minimum air clearances	48
Table A.2 — Correlation between standard switching impulse withstand voltages and minimum phase-to-earth air clearances	49
Table A.3 — Correlation between standard switching impulse withstand voltages and minimum phase-to-phase air clearances	49
Table C.1 — Breakdown voltage versus cumulative flashover probability — Single insulation and 100 parallel insulations	55
Table F.1 — Corona damping constant K_{co}	73
Table F.2 — Factor A for various overhead lines	77
Tableau G.1 — Typical gap factors K for switching impulse breakdown phase-to-earth	81
Table G.2 — Gap factors for typical phase-to-phase geometries	82
Table H.1 — Summary of minimum required withstand voltages obtained for example H.1.1	87
Table H.2 — Summary of required withstand voltages obtained for example H.1.2	90
Table H.3 — Values related to the insulation co-ordination procedure for example H.3	103

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.
α_1	(m)	length of the lead connecting the surge arrester to the line.
α_2	(m)	length of the lead connecting the surge arrester to earth.
α_3	(m)	length of the phase conductor between the surge arrester and the protected equipment.
α_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_f^+	(–)	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/ μ s)	steepness of a lightning surge impinging on a substation.
S_e	(kV)	conventional deviation of phase-to-earth overvoltage distribution.
S_p	(kV)	conventional deviation of phase-to-phase overvoltage distribution.
S_{rp}	(kV/ μ s)	representative steepness of a lightning impinging surge.
S_e	(–)	normalized value of the conventional deviation S_e (S_e referred to U_{e50}).
S_p	(–)	normalized value of the conventional deviation S_p (S_p referred to U_{p50}).
T	(μ s)	travel time of a lightning surge.
U	(kV)	amplitude of an overvoltage (or of a voltage).

U^+	(kV)	positive switching impulse component in a phase-to-phase insulation test.
U^-	(kV)	negative switching impulse component in a phase-to-phase insulation test.
U_0	(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 μ s impulse;
- maximum residual voltage at the selected nominal discharge current.

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

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

2.2.2.2 Protection characteristics related to slow-front overvoltages

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

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

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

2.2.3 Metal oxide surge arresters without gaps

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

2.2.3.1 Protection characteristics related to fast-front overvoltages

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

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

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

2.2.3.2 Protection characteristics related to slow-front overvoltages

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

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

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

2.2.4 Spark gaps

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

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

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

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: $\sqrt{2} U_g / \sqrt{3}$):

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

The probability distribution of the overvoltages without surge arrester operation is characterized by its 2 % value, its deviation and its truncation value. Although not perfectly valid, the probability distribution can be approximated by a Gaussian distribution between the 50 % value and the truncation value above which no values are assumed to exist. Alternatively, a modified Weibull distribution may be used (see annex 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]¹⁾.

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

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

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

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

¹⁾ Figures in square brackets refer to the bibliography given in annex J.

As a rough guide, Figure 1 shows the range of the 2 % overvoltage values (in p.u. of $\sqrt{2} U_g / \sqrt{3}$) 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.

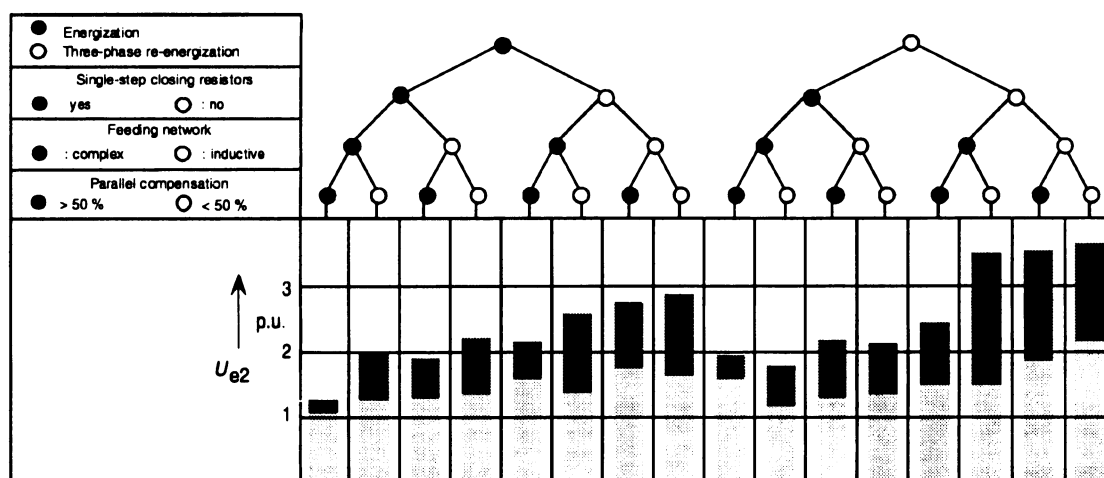
2.3.3.1.2 Phase-to-phase overvoltages

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]:

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

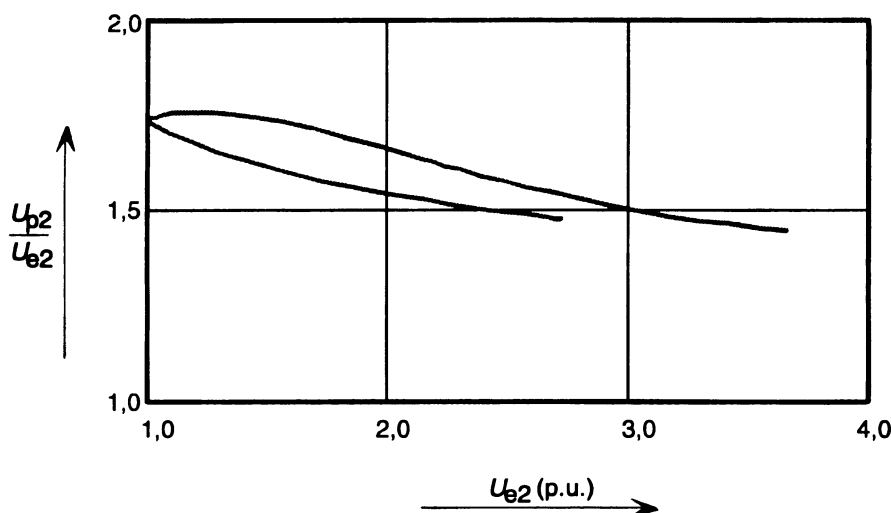
The statistical characteristics of the phase-to-phase overvoltages and the relations between the values belonging to the two instants are described in annex D. It is concluded that for all insulation types except for air clearances in range II, the representative overvoltage between phases is equal to 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.



IEC 1019/96

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



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 $U_{et} = (2k - 1) U_s \sqrt{2}/\sqrt{3}$ (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 μ s, overvoltages with high amplitudes and times-to-crest critical for the insulation do not occur. Slow-front lightning overvoltages, therefore, are of minor importance for insulation co-ordination and are usually neglected.

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 μ s). The representative amplitude is either given as an assumed maximum or by a probability distribution of peak values usually given as the peak value dependent on the overvoltage return rate.

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 lightning overvoltage return rates for different instantaneous values of the operating voltage;
- evaluating the insulation failure probability for the various subdivisions into components. Usually the sum of the two components is the decisive parameter;
- determining the insulation failure rate dependent on the sum of the lightning overvoltage and of the instantaneous value of power-frequency;
- 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 μ s). However, special attention should be paid to equipment with windings because of high inter-turn stresses.

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

- 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 breakers tend to produce multiple transient current interruptions resulting in overvoltages up to 6 p.u. unless appropriate protection measures are taken.

- disconnecter switching: 3 p.u.

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

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.

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

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

where

- U_{pl} is the lightning impulse protective level of the arrester (kV);
- S is the steepness of the impinging surge (kV/ μ s);
- T is the travel time of the lightning surge determined as following:

$$T = L/c \quad (3)$$

where

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

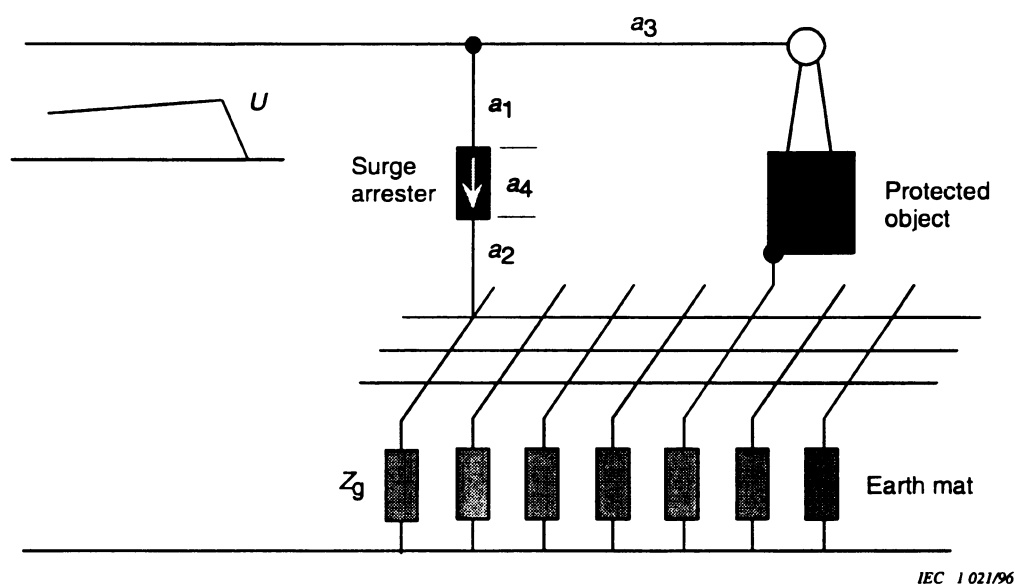
$L = a_1 + a_2 + a_3 + a_4$: distances from Figure 3 (m).

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

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

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

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

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 (1 013 mbar);
- absolute humidity 11 g/m³.

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

For outdoor insulation, the effects of 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 μ s time-to-peak. This means that the use of the withstand voltage of the insulation at the standard voltage shape 250/2 500 μ s results in a conservative insulation design for slow-front overvoltages. For some systems in which slow-front overvoltages have fronts much longer than the standard one, the higher insulation strength at these fronts may be advantageously utilized.

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

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):

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

- 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).

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

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 g must be 4,83 in equation (5). Approximating this value to $g = 5$ does not result in any appreciable errors so that the modified Weibull distribution proposed in this guide is described in equation (6).

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

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

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

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

The influence of weather conditions (refer to 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:

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

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 ^a
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^b — 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^c	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)^c	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^c	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.

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

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

^c 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 $K_{cd} = 1$.

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.

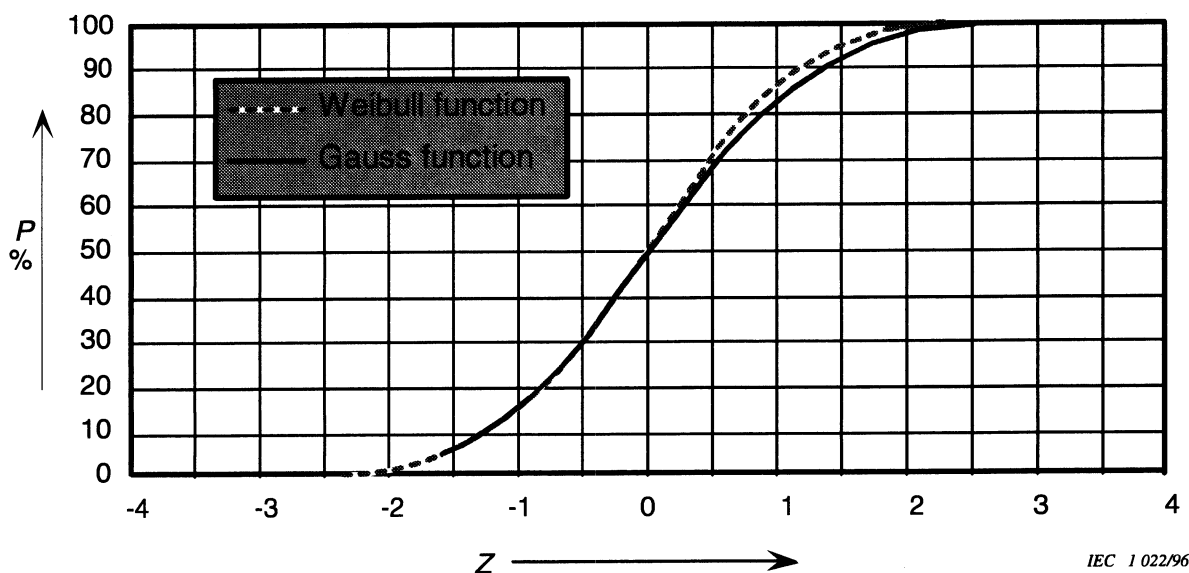


Figure 4 — Distributive discharge probability of self-restoring insulation described on a linear scale