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Part 2: Application guide

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

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INSULATION CO-ORDINATION –

Part 2: Application guide

FOREWORD

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

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

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

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

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

Annex A forms an integral part of this standard.

Annexes B to J are for information only.

INSULATION CO-ORDINATION –

Part 2: Application guide

1 General

1.1 *Scope*

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

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

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

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

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

The content of this guide strictly follows the flow chart of the insulation co-ordination process presented in figure 1 of IEC 71-1. Clauses 2 to 5 correspond to the squares in this flow chart and give detailed information on the concepts governing the insulation co-ordination process which leads to the establishment of the required withstand levels.

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

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

1.2 *Normative references*

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

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

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

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

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

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

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

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

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

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

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

1.3 *List of symbols and definitions*

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

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

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

c_f	(p.u.)	coupling factor of voltages between earth wire and phase conductor of overhead lines.
E_0	(kV/m)	soil ionization gradient.
F		function describing the cumulative distribution of overvoltage amplitudes, where $F(U) = 1 - P(U)$. See annex C.3.
f		function describing the probability density of overvoltage amplitudes.
g	(-)	ratio of capacitively transferred surges.
H	(m)	altitude above sea-level.
h	(-)	power-frequency voltage factor for transferred surges in transformers.
Ht	(m)	height above ground.
I	(kA)	lightning current amplitude.
I_g	(kA)	limit lightning current in tower footing resistance calculation.
J	(-)	winding factor for inductively transferred surges in transformers.
K	(-)	gap factor taking into account the influence of the gap configuration on the strength.
K_a	(-)	atmospheric correction factor. [3.28 of IEC 71-1]
K_c	(-)	co-ordination factor. [3.25 of IEC 71-1]
K_s	(-)	safety factor. [3.29 of IEC 71-1]
K_{cd}	(-)	deterministic co-ordination factor.
K_{co}	(µs/(kVm))	corona damping constant.
K_{cs}	(-)	statistical co-ordination factor.
K^{+}_{ff}	(-)	gap factor for fast-front impulses of positive polarity.
K^{-}_{ff}	(-)	gap factor for fast-front impulses of negative polarity.
k	(-)	earth-fault factor. [3.15 of IEC 71-1]
L	(m)	separation distance between surge arrester and protected equipment.
L_a	(m)	overhead line length yielding to an outage rate equal to the acceptable one (related to R_a).
L_t	(m)	overhead line length for which the lightning outage rate is equal to the adopted return rate (related to R_t).
L_{sp}	(m)	span length.
M	(-)	number of insulations in parallel considered to be simultaneously stressed by an overvoltage.
m	(-)	exponent in the atmospheric correction factor formula for external insulation withstand.
N	(-)	number of conventional deviations between U_{50} and U_0 of a self-restoring insulation.
n	(-)	number of overhead lines considered connected to a station in the evaluation of the impinging surge amplitude.
P	(%)	probability of discharge of a self-restoring insulation.
P_w	(%)	probability of withstand of self-restoring insulation.
q	(-)	response factor of transformer windings for inductively transferred surges.
R	(-)	risk of failure (failures per event).
R_a	(1/a)	acceptable failure rate for apparatus. For transmission lines, this parameter is normally expressed in terms of (1/a)/100 km.

R_{hc}	(Ω)	high current value of the tower footing resistance.
R_{km}	(1/(m.a))	overhead line outage rate per year for a design corresponding to the first kilometre in front of the station.
R_{lc}	(Ω)	low current value of the tower footing resistance.
R_p	(1/a)	shielding penetration rate of overhead lines.
R_{sf}	(1/a)	shielding failure flashover rate of overhead lines.
R_t	(1/a)	adopted overvoltage return rate (reference value).
R_u	(kV)	radius of a circle in the U^+/U^- plane describing the phase-phase-earth slow-front overvoltages.
R_0	(Ω)	zero sequence resistance.
R_1	(Ω)	positive sequence resistance.
R_2	(Ω)	negative sequence resistance.
S	(kV/µs)	steepness of a lightning surge impinging on a substation.
S_e	(kV)	conventional deviation of phase-to-earth overvoltage distribution.
S_p	(kV)	conventional deviation of phase-to-phase overvoltage distribution.
S_{rp}	(kV/µs)	representative steepness of a lightning impinging surge.
s_e	(-)	normalized value of the conventional deviation S_e (S_e referred to U_{e50}).
s_p	(-)	normalized value of the conventional deviation S_p (S_p referred to U_{p50}).
T	(µs)	travel time of a lightning surge.
U	(kV)	amplitude of an overvoltage (or of a voltage).
U^+	(kV)	positive switching impulse component in a phase-to-phase insulation test.
U^-	(kV)	negative switching impulse component in a phase-to-phase insulation test.
U_0	(kV)	truncation value of the discharge probability function $P(U)$ of a self-restoring insulation: $P(U \leq U_0) = 0$.
U_0^+	(kV)	equivalent positive phase-to-earth component used to represent the most critical phase-to-phase overvoltage.
U_{1e}	(kV)	temporary overvoltage to earth at the neutral of the primary winding of a transformer.
U_{2e}	(kV)	temporary overvoltage to earth at the neutral of the secondary winding of a transformer.
U_{2N}	(kV)	rated voltage of the secondary winding of a transformer.
U_{10}	(kV)	value of the 10 % discharge voltage of self-restoring insulation. This value is the statistical withstand voltage of the insulation defined in 3.23 b) of IEC 71-1.
U_{16}	(kV)	value of the 16 % discharge voltage of self-restoring insulation.
U_{50}	(kV)	value of the 50 % discharge voltage of self-restoring insulation.
U_{50M}	(kV)	value of the 50 % discharge voltage of M parallel self-restoring insulations.
U_{50RP}	(kV)	value of the 50 % discharge voltage of a rod-plane gap.
U_c^+	(kV)	positive component defining the centre of a circle which describes the phase-phase-earth slow-front overvoltages.
U_c^-	(kV)	negative component defining the centre of a circle which describes the phase-phase-earth slow-front overvoltages.

U_{cw} (kV) co-ordination withstand voltage of equipment. [3.24 of IEC 71-1]

U_e (kV) amplitude of a phase-to-earth overvoltage.

U_{et} (kV) truncation value of the cumulative distribution $F(U_e)$ of the phase-to-earth overvoltages: $F(U_e \geq U_{et}) = 0$; see annex C.3.

U_{e2} (kV) value of the phase-to-earth overvoltage having a 2 % probability of being exceeded: $F(U_e \geq U_{e2}) = 0{,}02$; see annex C.3.

U_{e50} (kV) 50 % value of the cumulative distribution $F(U_e)$ of the phase-to-earth overvoltages; see annex C.3.

U_l (kV) amplitude of the impinging lightning overvoltage surge.

U_m (kV) highest voltage for equipment. [3.10 of IEC 71-1]

U_p (kV) amplitude of a phase-to-phase overvoltage.

U_{p2} (kV) value of the phase-to-phase overvoltage having a 2 % probability of being exceeded: $F(U_p \geq U_{p2}) = 0{,}02$; see annex C.3.

U_{p50} (kV) 50 % value of the cumulative distribution $F(U_p)$ of the phase-to-phase overvoltages; see annex C.3.

U_s (kV) highest voltage of a system. [3.9 of IEC 71-1]

U_w (kV) standard withstand voltage.

U_{pl} (kV) lightning impulse protective level of a surge arrester. [3.21 of IEC 71-1]

U_{ps} (kV) switching impulse protective level of a surge arrester. [3.21 of IEC 71-1]

U_{pt} (kV) truncation value of the cumulative distribution $F(U_p)$ of the phase-to-phase overvoltages: $F(U_p \geq U_{pt}) = 0$; see annex C.3.

U_{rp} (kV) amplitude of the representative overvoltage. [3.19 of IEC 71-1]

U_{rw} (kV) required withstand voltage. [3.27 of IEC 71-1]

U_{T1} (kV) overvoltage applied at the primary winding of a transformer which produces (by transference) an overvoltage on the secondary winding.

U_{T2} (kV) overvoltage at the secondary winding of a transformer produced (by transference) by an overvoltage applied on the primary winding.

u (p.u.) per unit value of the amplitude of an overvoltage (or of a voltage) referred to $U_s \sqrt{2}/\sqrt{3}$.

w (-) ratio of transformer secondary to primary phase-to-phase voltage.

X (m) distance between struck point of lightning and substation.

X_p (km) limit overhead line distance within which lightning events have to be considered.

X_T (km) overhead line length to be used in simplified lightning overvoltage calculations.

X_0 (Ω) zero sequence reactance of a system.

X_1 (Ω) positive sequence reactance of a system.

X_2 (Ω) negative sequence reactance of a system.

x (-) normalized variable in a discharge probability function $P(U)$ of a self-restoring insulation.

x_M (-) normalized variable in a discharge probability function $P(U)$ of M parallel self-restoring insulations.

Z (kV) conventional deviation of the discharge probability function $P(U)$ of a self-restoring insulation.

Z_0 (Ω) zero sequence impedance.

Z_1 (Ω) positive sequence impedance.

Z_2 (Ω) negative sequence impedance.

Z_e (Ω) surge impedance of the overhead line earth wire.

Z_l (Ω) surge impedance of the overhead line.

Z_M (kV) conventional deviation of the discharge probability function $P(U)$ of M parallel self-restoring insulations.

Z_s (Ω) surge impedance of the substation phase conductor.

z (-) normalized value of the conventional deviation Z referred to U_{50}.

α (-) ratio of the negative switching impulse component to the sum of both components (negative + positive) of a phase-to-phase overvoltage.

β (kV) scale parameter of a Weibull cumulative function.

δ (kV) truncation value of a Weibull cumulative function.

Φ Gaussian integral function.

ϕ (-) inclination angle of a phase-to-phase insulation characteristic.

γ (-) shape parameter of a Weibull-3 cumulative function.

σ (p.u.) per unit value of the conventional deviation (S_e or S_p) of an overvoltage distribution.

ρ (Ωm) soil resistivity.

τ (µs) tail time constant of a lightning overvoltage due to back-flashovers on overhead lines.

2 Representative voltage stresses in service

2.1 *Origin and classification of voltage stresses*

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

– continuous (power-frequency) voltages: originate from the system operation under normal operating conditions;

– temporary overvoltages: they can originate from faults, switching operations such as load rejection, resonance conditions, non-linearities (ferroresonances) or by a combination of these;

– slow-front overvoltages: they can originate from faults, switching operations or direct lightning strokes to the conductors of overhead lines;

– fast-front overvoltages: they can originate from switching operations, lightning strokes or faults;

– very-fast-front overvoltages: they can originate from faults or switching operations in gas-insulated substations (GIS);

– combined overvoltages: they may have any origin mentioned above. They occur between the phases of a system (phase-to-phase), or on the same phase between separated parts of a system (longitudinal).

All the preceding overvoltage stresses except combined overvoltages are discussed as separate items under 2.3. Combined overvoltages are discussed where appropriate within one or more of these items.

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

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

2.2 *Characteristics of overvoltage protective devices*

2.2.1 *General remarks*

Two types of standardized protective devices are considered:

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

– metal-oxide surge arresters without gaps.

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

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

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

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

2.2.2.1 *Protection characteristics related to fast-front overvoltages*

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

– the sparkover voltage for a standard full lightning impulse;

– the residual voltage at the selected nominal discharge current;

– the front-of-wave sparkover voltage.

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

– maximum sparkover voltage with 1,2/50 µs impulse;

– maximum residual voltage at the selected nominal discharge current.

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

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

2.2.2.2 *Protection characteristics related to slow-front overvoltages*

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

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

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

2.2.3 *Metal oxide surge arresters without gaps*

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

2.2.3.1 *Protection characteristics related to fast-front overvoltages*

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

– the residual voltage at the selected nominal discharge current;

– the residual voltage at steep current impulse.

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

2.2.3.2 *Protection characteristics related to slow-front overvoltages*

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

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

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