Chapter 3

Insulation Coordination Design

Content

a) Overvoltages in power systems – a review

b) Insulation coordination design for transmission networks

  1. **What is Insulation Coordination?**
  2. **Insulation Coordination - Principles**
  3. **Insulation Coordination According to Standards**
  4. **Procedure for Insulation Coordination – General**
  5. **Procedure for Insulation Coordination – in 4 Steps**

c) Introduction to CDEGS

Content

1. **Review**

1 STANDARD ATMOSPHERIC CONDITIONS

All specifications of strength are based on the following atmospheric conditions:

1. Ambient temperature: 20°C
2. Air pressure: 101.3 kPa or 760mm Hg
3. Absolute humidity: 11 grams of water/m^3 of air
4. For wet tests: 1 to 1.5 mm of water/minute

2 TYPES OF INSULATION

Insulation may be classified as **internal** or **external** and also as **self-restoring** and **nonself-restoring.**

Per ANSI C92.l (IEEE 13 13.1)

2.1 External Insulation

External insulation is the **distances** in **open air** or **across the surfaces of solid insulation in contact with open air** that are **subjected to dielectric stress** and to the **effects of the atmosphere**.

Examples of external insulation are the **porcelain shell of a bushing**, **bus support insulators**, and **disconnecting switches**.

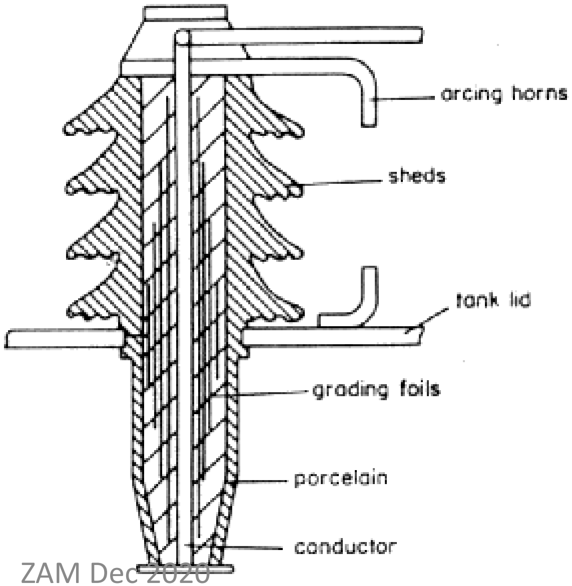
2.2 Internal Insulation

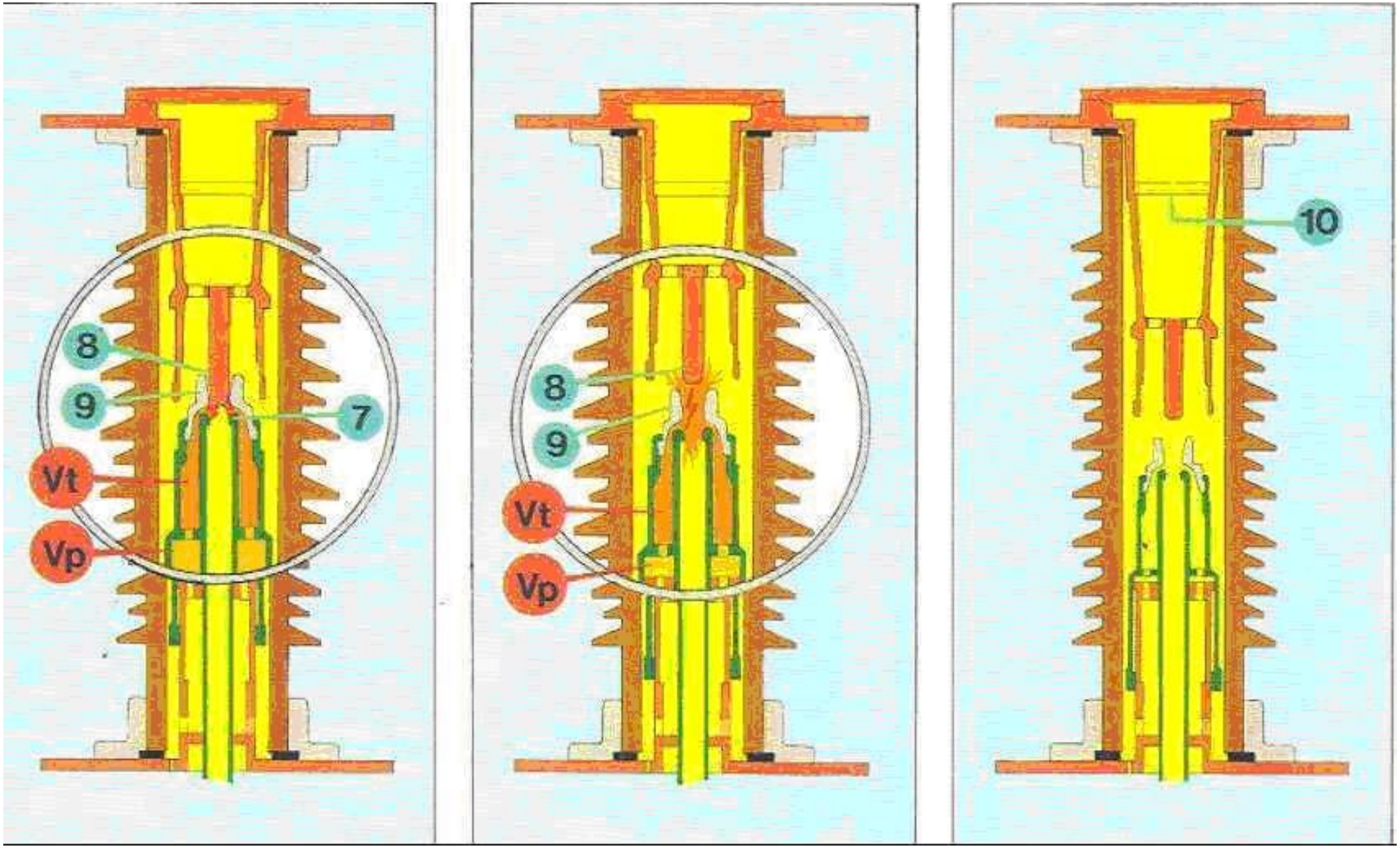
Internal insulation is the **<u>internal</u> solid**, **liquid**, or **gaseous parts** of the insulation of equipment that are **protected by the equipment enclosures from the effects of the atmosphere**.

Examples are **transformer insulation** and the **internal insulation of bushings**.

Equipment may be a **<u>combination</u>** of internal and external insulation.

Examples are a **bushing <u>and a circuit breaker</u>**.





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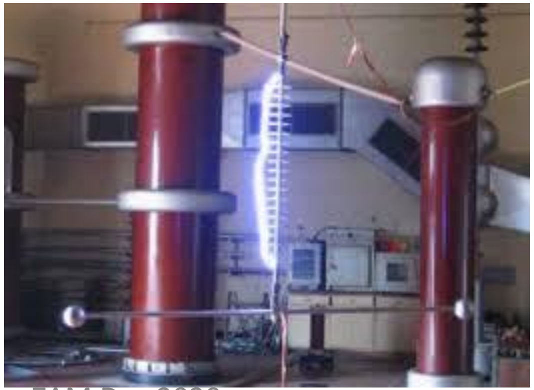
2.3 Self-Restoring (SR) Insulation

Insulation that **completely recovers** insulating properties after a disruptive discharge (flashover) caused by the application of a voltage is called self-restoring insulation.

This type of insulation is generally **<u>external</u>** insulation.



2.4 Non-Self-Restoring (NSR) Insulation

This is the opposite of self-restoring insulators, insulation that **loses insulating properties** or does not recover completely after a disruptive discharge caused by the application of a voltage.

This type of insulation is generally **internal** insulation.

3 DEFINITIONS OF APPARATUS STRENGTH, THE BIL AND THE BSL

3.1 BIL-Basic Lightning Impulse Insulation Level

The BIL or **basic lightning impulse insulation level** is the electrical strength of insulation expressed in terms of the **crest** value of the "standard lightning impulse.“

That is, the BIL is tied to a specific waveshape in addition being tied to standard atmospheric conditions.

Standard Waveshapes

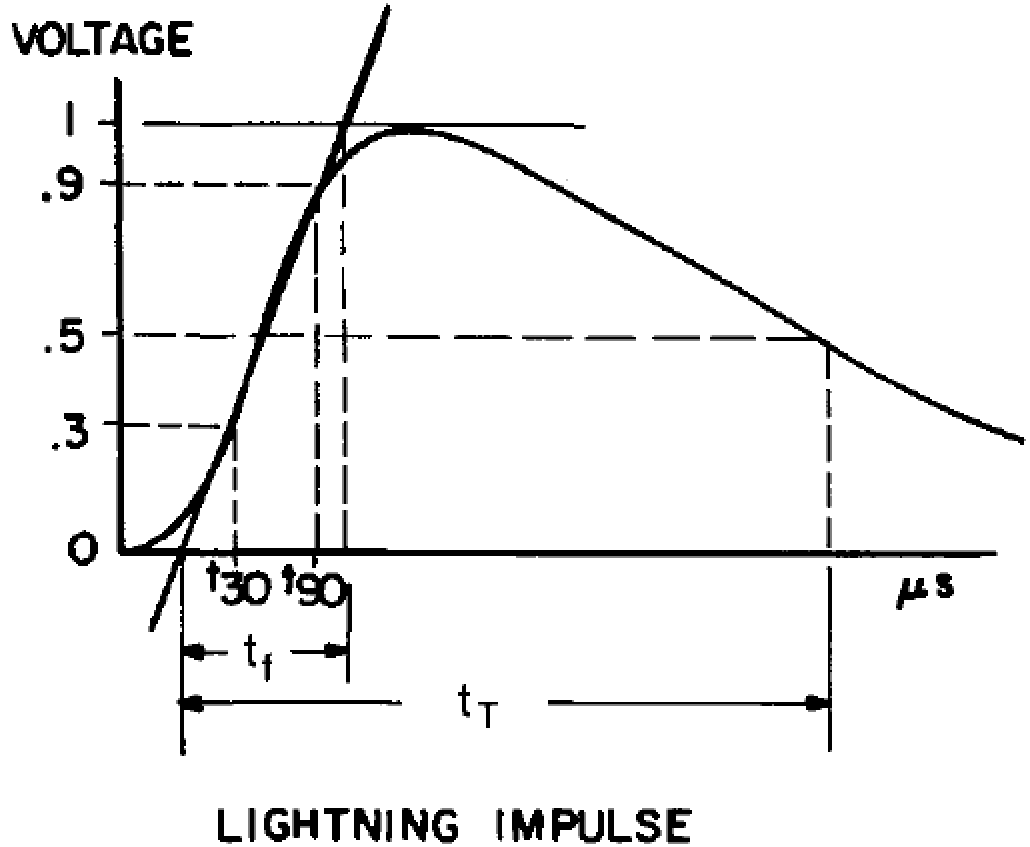


Figure 1 Lightning impulse wave shape.

The BIL may be either a **statistical** BIL or a **conventional** BIL.

The **statistical** BIL is applicable only to **self-restoring** insulations, whereas the **conventional** BIL is applicable to **non-self-restoring** insulations.

BILs are universally for **dry** conditions.

The **statistical** BIL is the crest value of standard lightning impulse for which the insulation exhibits a **90% probability of withstand**, a **10% probability of failure.**

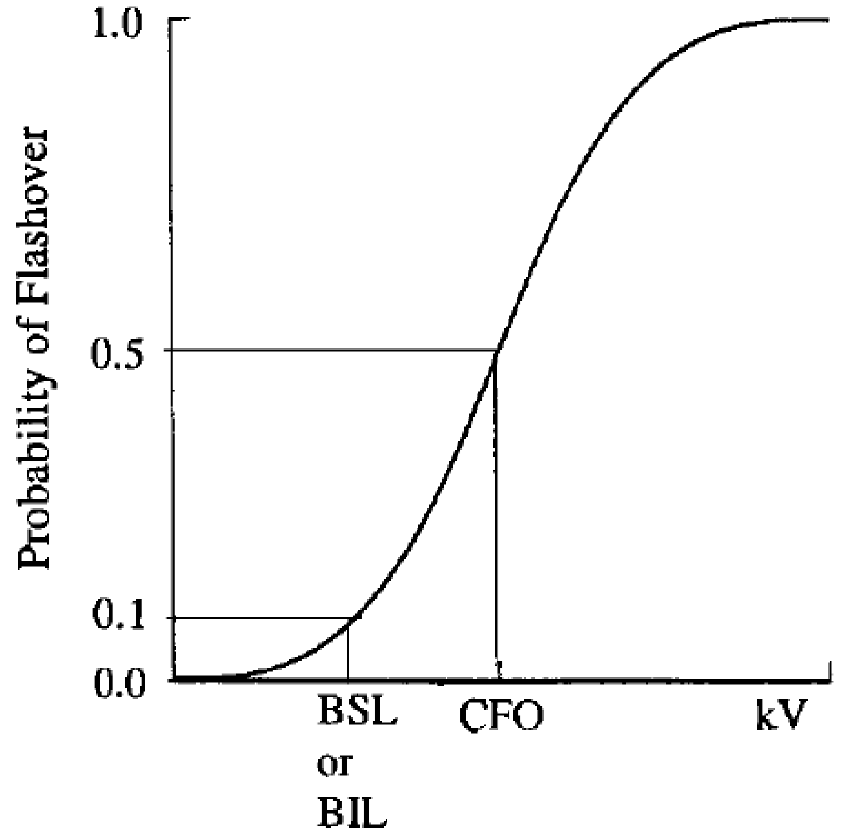


Figure 3 Insulation strength characteristic for self-restoring insulation.

The **conventional** BIL is the crest value of a standard lightning impulse for which the insulation **does not** exhibit disruptive discharge when subjected to a specific number of applications of this impulse.

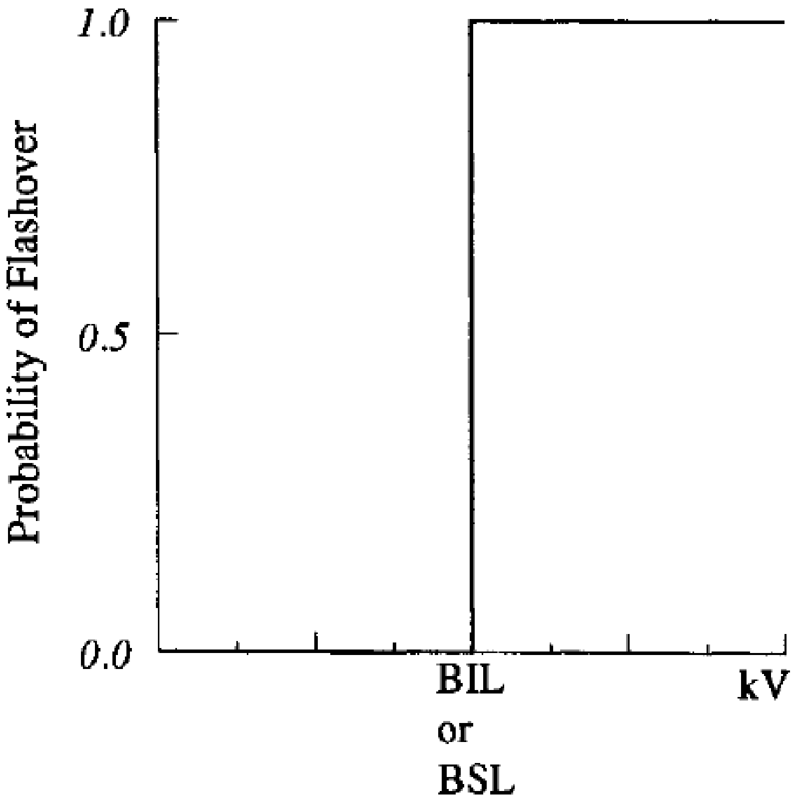


Figure 4 Insulation strength characteristic for non-self-restoring insulation.

In **IEC Publication 60071** [3], the BIL is known as the **lightning impulse withstand voltage**.

That is, it is defined the same but known by a different name.

However, in **IEC**, it is **not** divided into conventional and statistical definitions.

3.2 BSL-Basic Switching Impulse Insulation Level

The BSL is the electrical strength of insulation expressed in terms of the crest value of a **standard switching impulse**.

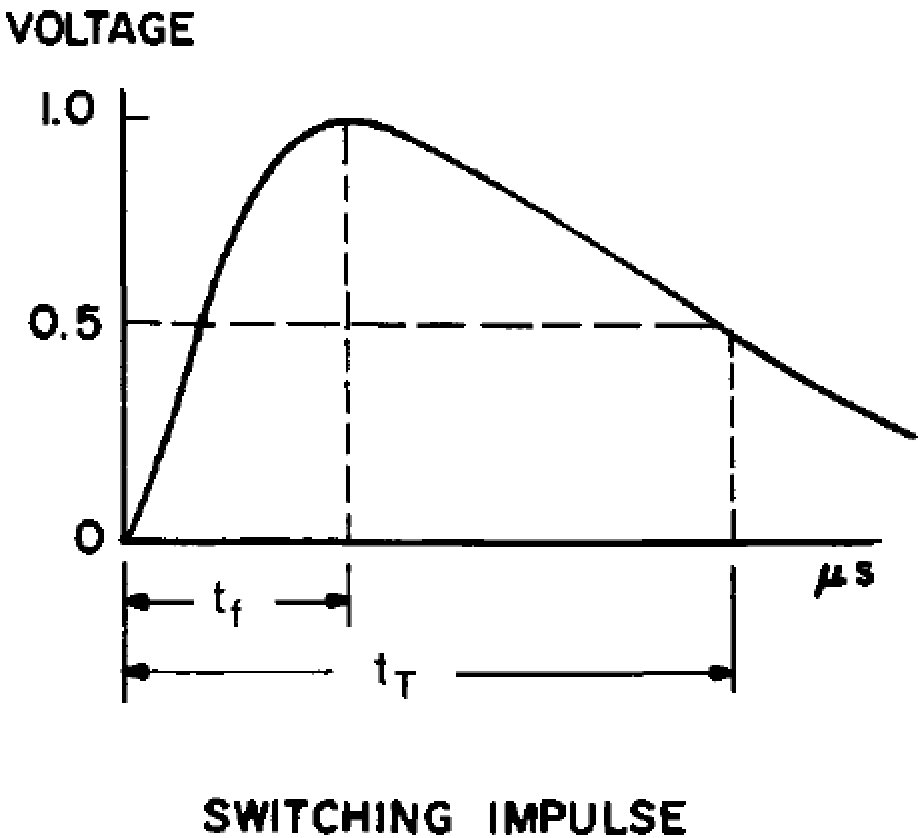


Figure 2 Switching impulse wave shape.

The BSL may be either a **statistical** BSL or a **conventional** BSL.

As with the BIL, the **statistical** BSL is applicable only to **selfrestoring** insulations while the **conventional** BSL is applicable to **non-self-restoring** insulations.

BSLs are universally for **wet** conditions.

The **statistical** BSL is the crest value of a standard switching impulse for which the insulation exhibits a 90% probability of withstand, a 10% probability of failure.

The **conventional** BSL is the crest value of a standard switching impulse for which the insulation does not exhibit disruptive discharge when subjected to a

specific number of applications of this impulse.

In IEC Publication 60071, the BSL is called the switching impulse withstand voltage and the definition is the same. However, as with the lightning impulse withstand voltage, it is **not** segregated into conventional and statistical.

3.4 Statistical vs. Conventional BIL/BSL

As noted, the statistical BIL or BSL is defined statistically or probabilistically.

For every application of an impulse having the standard waveshape and whose crest is equal to the BIL or BSL, the probability of a flashover or failure is 10%.

In general, the insulation strength characteristic may be represented by a cumulative Gaussian distribution as portrayed in Fig. 3.

The mean of this distribution or characteristic is defined as the critical flashover voltage or CFO. Applying the CFO to the insulation results in a 50% probability of flashover, i.e., half the impulses flashover.

Locating the BIL or BSL at the 10% point results in the definition that the BIL or BSL is 1.28 standard deviations, of, below the CFO.

In equation form

$$BIL = CFO\left(1 - 1.28\frac{\sigma_f}{CFO}\right)$$

$$BSL = CFO\left(1 - 1.28\frac{\sigma_f}{CFO}\right)$$

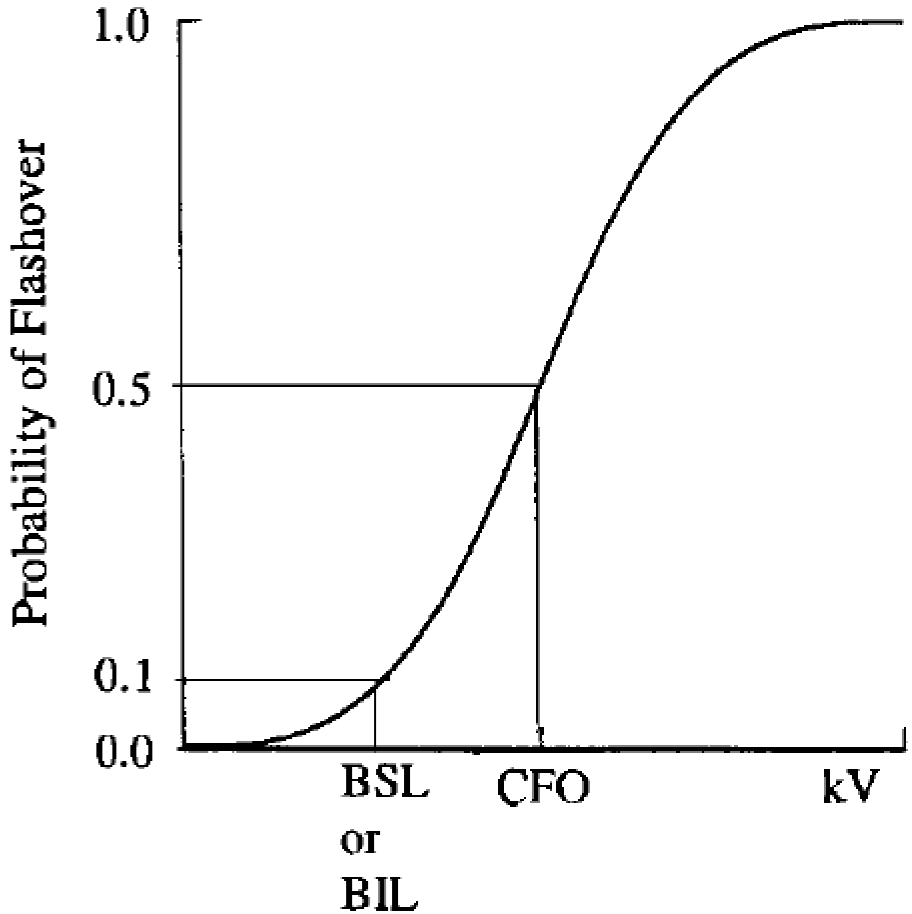


Figure 3 Insulation strength characteristic for self-restoring insulation.

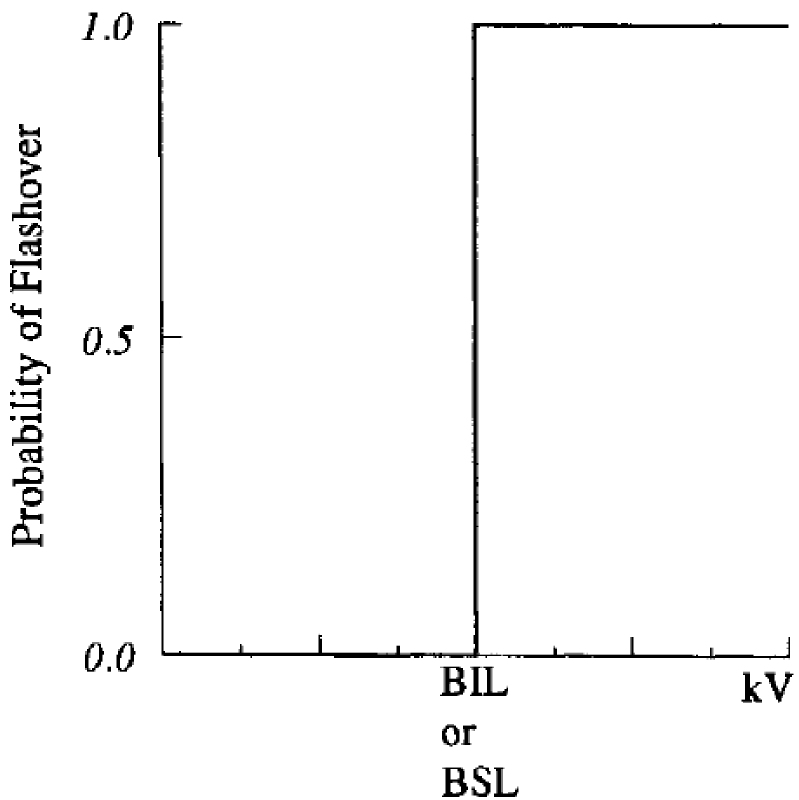


Figure 4 Insulation strength characteristic for non-self-restoring insulation.

3.5 Tests to "Prove" the BIL and BSL

Tests to establish the BIL or BSL must be divided between the conventional and the statistical.

Since the **conventional** BIL or BSL is tied to **non-self-restoring insulation**, it is more than highly desirable that the test be **nondestructive**.

Therefore the test is simply to apply one or more impulses having a standard impulse waveshape whose crest is equal to the BIL or BSL. If no failure occurs, the test is passed. While it is true that some failures on the test floor do occur, the failure rate is extremely low. That is, a manufacturer cannot afford to have failure rates, for example on power transformers, that exceed about 1%.

If this occurs, production is stopped and all designs are reviewed.

Considering the establishment of a statistical BIL or BSL, theoretically no test can conclusively prove that the insulation has a 10% probability of failure.
Also since the insulation is self-restoring, flashovers of the insulation are permissible.
Several types of tests are possible to establish an estimate of the BIL and BSL.
Theoretically the entire strength characteristic could be determined as illustrated in Fig. 3, from which the BIL or BSL could be obtained. However, these tests are not made except perhaps in the equipment design stage.
Rather, for standardization, two types of tests exist, which are n/m (m impulses applied) and n+m (n impulses applied).

n/m (m impulses applied)

1. m impulses are applied.
2. The test is passed if no more than n result in flashover.
3. The preferred test presently in IEC standards is the 2/15 test. That is, 15 impulses having the standard shapes and whose crest voltage is equal to the BIL or BSL are applied to the equipment. If two or fewer impulses result in flash-over, the test is passed, and the equipment is said to have the designated BIL or BSL.

n+m (n impulses applied)

1. n impulses are applied.
2. If none result in flashover, the test is passed.
3. If there are two or more flashovers, the test is failed. If only one flashover occurs, m additional impulses are applied and the test is passed if none of these results in a flashover.
4. The present test on circuit-breakers is the 3+3 test. In IEC standards, an alternate but less preferred test to the 2/15 test is the 3 + 9 test.

The equations for these curves, where P is the probability of passing, p is the probability of flashover on application of a single impulse, and q is (1-p), are

For the 2/15 test $P = q^{15} + 15pq^{14} + 105p^2q^{13}$

For the 3 +3 test $P = q^3 + 3pq^5$

For the 3+9 test $P = q^3 + 9pq^{11}$

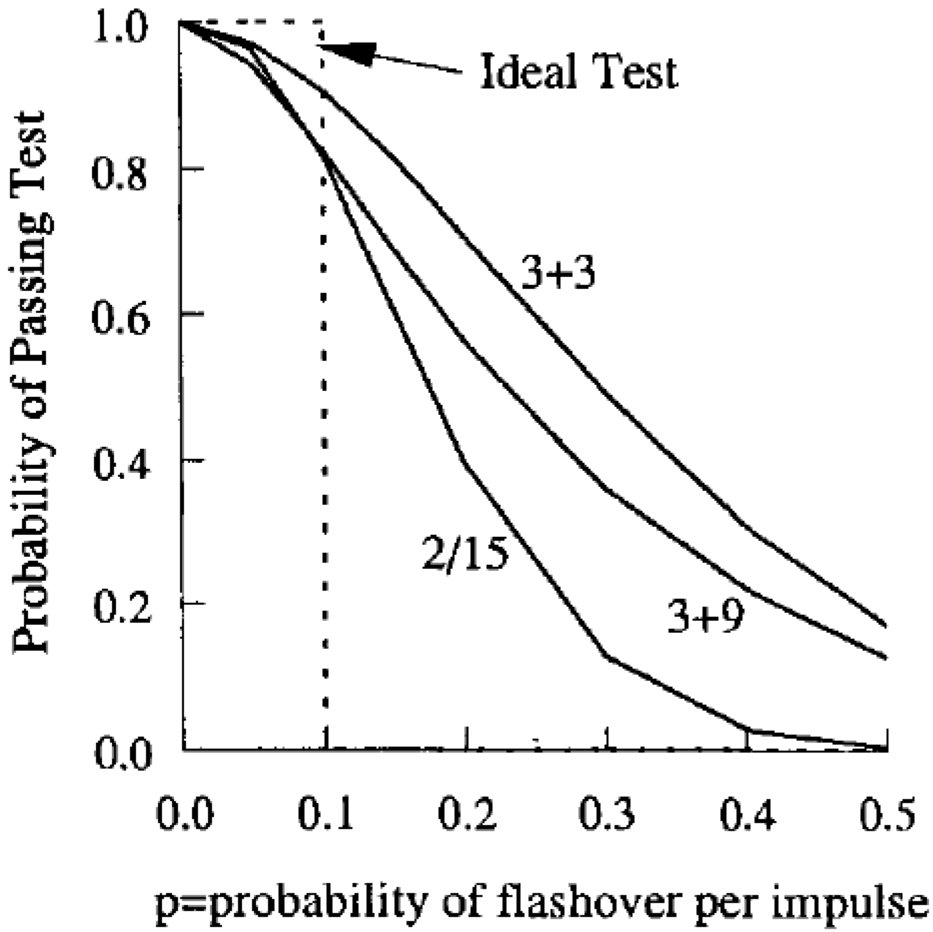


Figure 5 Characteristics for alternate test series.

In general then, as illustrated in Fig. 6, there is manufacturer's risk of having acceptable equipment and not passing the test and a user's risk of having unacceptable equipment and passing the test.

A desired characteristic is that of discrimination, discriminating between "good" and "bad."

The best test would have a steep slope around the 0.10 probability of flashover. As is visually apparent, the 2/15 is the best of the 3 is the worst. Therefore it is little wonder that the IEC preferred 9 test is a compromise between the 3 + 3 and the 2/15 tests included in the IEC Standard at the request of the ANSI circuit breaker group. The 9 test.

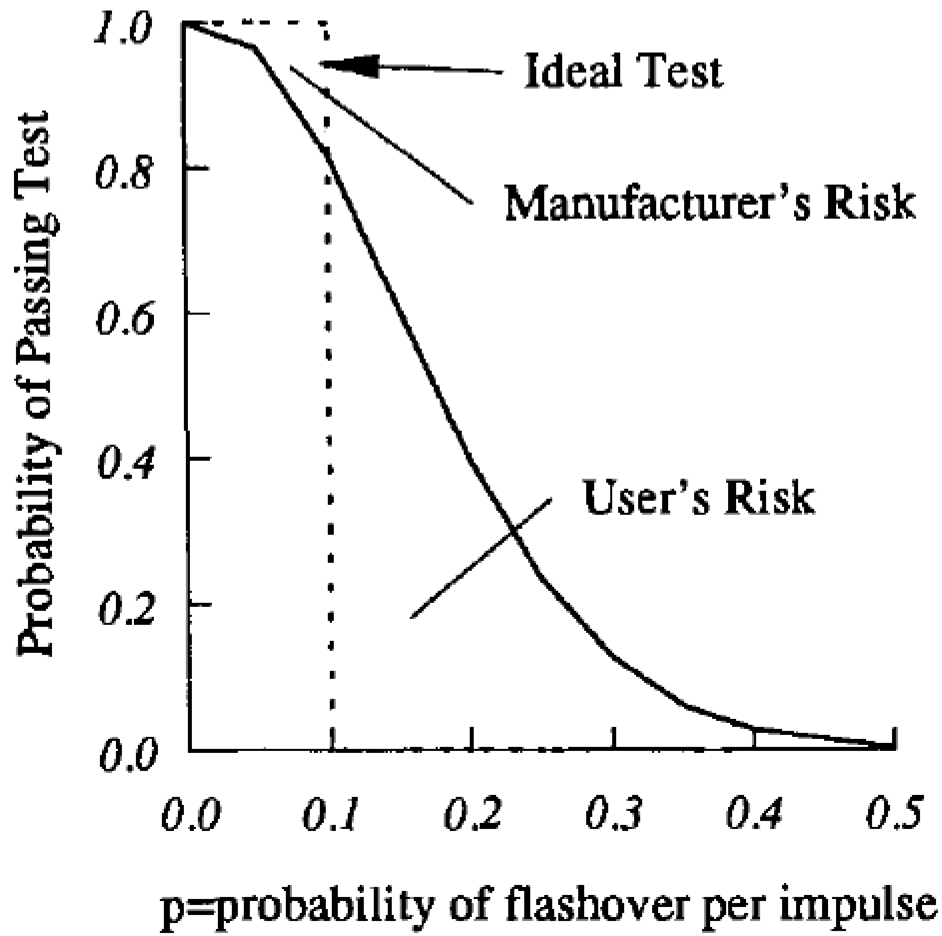


Figure 6 Manufacturer's and user's risk.

Table 2 Standard Values of BIL and BSL per ANSI C92, IEEE 1313.1

30	300	825	1925
45	350	900	2050
60	400	975	2175
75	450	1050	2300
95	500	1175	2425
110	550	1300	2550
125	600	1425	2675
150	650	1550	2800
200	700	1675	2925
250	750	1800	3050

Source: Ref. 7.

Table 3 Standard Values of BIL and BSL per IEC 71.1

20	325	1300	2550
40	450	1425	2700
60	550	1550	2900
75	650	1675	
95	750	1800	
125	850	1950	
145	950	2100	
170	1050	2250	
250	1175	2400	

Source: Ref. 5.

Table 4 Transformer and Bushings BILs and BSLs

System nominal/ max system voltage, kV	Transformers BIL, kV	Transformers BSL, kV	Transformer bushings BIL, kV	Transformer bushings BSL, kV
1.2/-	30, 45		45	
2.5/-	45, 60		60	
5.0/-	60, 75		75	
8.7/-	75, 95		95	
15.0/-	95, 110		110	
25.0/-	150		150	
34.5/-	200		200	
46/48.3	200, 250		250	
69/72.5	250, 350		350	
115/121	350	280	450	
	*450	375	50	
	550	460		
138/145	450	375	450	
	*550	460	550	
	650	540	650	
161/169	550	460	550	
	*650	540	650	
	750	620	750	
230/242	650	540	650	
	*750	620	750	
	825	685	825	
	900	745	900, 1050	
345/362	900	745	900	700
	*1050	870	1050	825
	1175	975	1175, 1300	825
500/550	1300	1080	1300	1050
	*1425	1180	1425	1110
	1550	1290	1550	1175
	1675	1390	1675	1175
765/800	1800	1500	1800	1360
	1925	1600	1925	—
	2050	1700	2050	—

* Commonly used.
Source: Ref. 7, 8.

Table 5 Insulation Levels for Outdoor Substations and Equipment

	NEMA Std, 6, outdoor substations		Circuit breakers		Disconnect switches	
Rated max voltage, kV	BIL, kV	10s power frequency voltage, kV	BIL, kV	BSL, kV	BIL, kV	BSL, kV estimate
8.25	95	30	95		95	
15.5	110	45	110		110	
25.8	150	60	150		125	
					150	
38.0	200	80	200		150	
					200	
48.3	250	100	250		250	
72.5	350	145	350		350	
121	550	230	550		550	
145	650	275	650		650	
169	750	315	750		750	
242	900	385	900		900	
	1050	455			1050	
362	1050	455	1300	825	1050	820
	1300	525		900	1300	960
550	1550	620	1800	1175	1550	1090
	1800	710		1300	1800	1210
800	2050	830	2050	1425	2050	1320
				1500		

Source: Ref. 5, 9.

Table 6 BILs/BSLs of Gas Insulated Stations

Max system voltage, kV		IEC [10]		ANSI [11]	
IEC	ANSI	BIL, kV	BSL, kV	BIL, kV	BSL, kV
72.5	72.5	325	—	300, 350	—
100		450	—		
123	121	550	—	450, 550	—
145	145	650	—	550, 650	—
170	169	750	—	650, 750	—
245	242	950	—	750, 900	—, 720
300		1050	850		
362	362	1175	950	900, 1050	720, 825
420		1300	1050		
525	550	1425	1175	1300, 1550	1050, 1175
765	800	1800	1425	1800	1425

Table 7 BILs of Cables (No BSLs provided), AEIC C54-79

Rated voltage, kV	BIL, kV
115, 120, & 130	550
138	650
161	750
230	1050
345	1300
500	1800

Source: Ref. 12.

Table 8 IEC 71.1: BILs are Tied to Max. System Voltages for Max. System Voltage from 1 to 245 kV

Max system voltage, kV	BILs, kV	Max system voltage, kV	BILs, kV
3.6	20 or 40	52	250
7.2	40 or 60	72.5	325
12	60, 75 or 95	123	450 or 550
17.7	75 or 95	145	450, 550, or 650
24	95, 125 or 145	170	550, 650, or 750
36	145 or 170	245	650, 750, 850, 950, or 1050

Source: Ref. 3.

Table 9 IEC BIL/BSLs, from IEC Publication 71.1

Max. system voltage, kV	Phase–ground BSL, BSL_g, kV	Ratio BSL_p/BSL_g	BIL, kV
300	750	1.50	850 or 950
	850	1.50	950 or 1050
362	850	1.50	950 or 1050
	950	1.50	1050 or 1175
420	850	1.60	1050 or 1175
	950	1.50	1175 or 1300
	1050	1.50	1300 or 1425
550	950	1.70	1175 or 1300
	1050	1.60	1300 or 1425
	1175	1.50	1425 or 1550
800	1300	1.70	1675 or 1800
	1425	1.70	1800 or 1950
	1550	1.60	1950 or 2100

Source: Ref. 3.

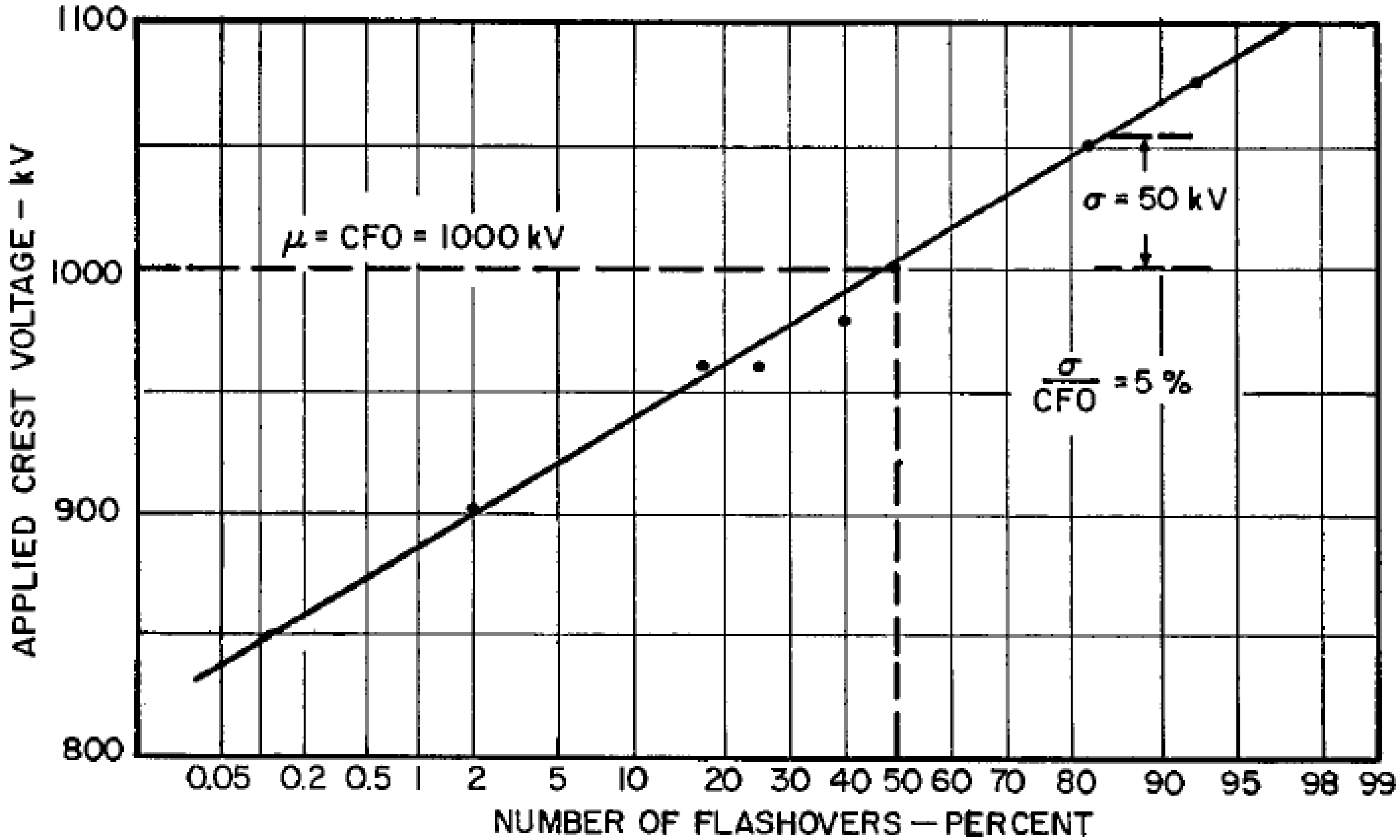


Figure 7 Insulation strength characteristic plotted on Gaussian probability paper.

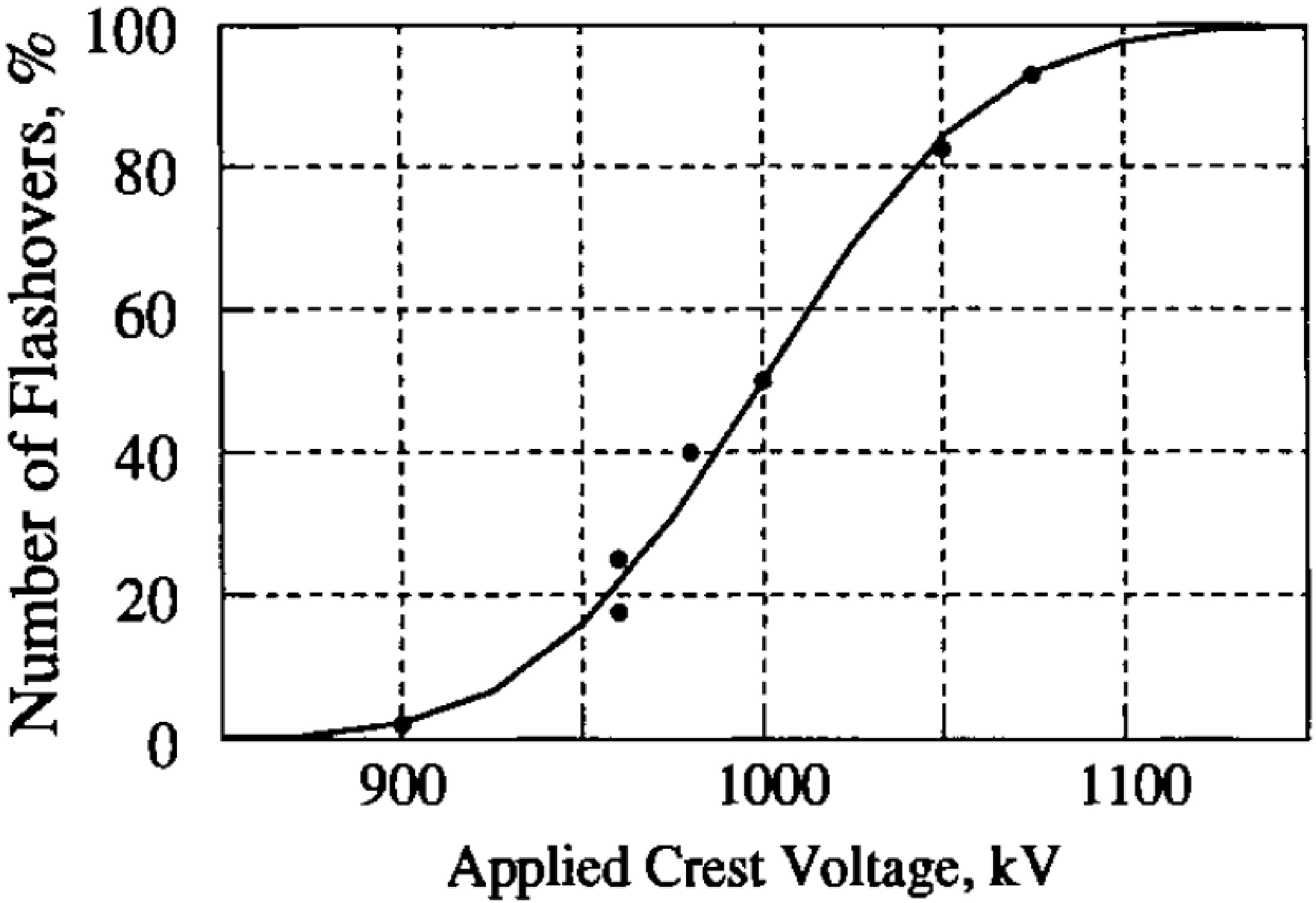


Figure 8 Data plotted on linear paper.

3.9 Chopped Wave Tests or Time-Lag Curves

In general, in addition to the tests to establish the BIL, apparatus are also given chopped wave lightning impulse tests.
The test procedures is to apply a standard lightning impulse waveshape whose crest value exceeds the BIL.
A gap in front of the apparatus is set to flashover at either 2 or 3 us, depending on the applied crest voltage.
The apparatus must "withstand" this test, i.e., no flashover or failure may occur.
The test on the power transformers consists of an applied lightning impulse having a crest voltage of 1.10 times the BIL, which is chopped at 3 us.

For distribution transformers, the crest voltage is a minimum of 1.15 times the BIL, and the time to chop varies from 1 to 3 us.

For a circuit breaker, two chopped wave tests are used: (1) 1.29 times the BIL chopped at 2 us and (2) 1.15 times the BIL at 3 us.

Bushings must withstand a chopped wave equal to 1.15 times the BIL chopped at 3 us.

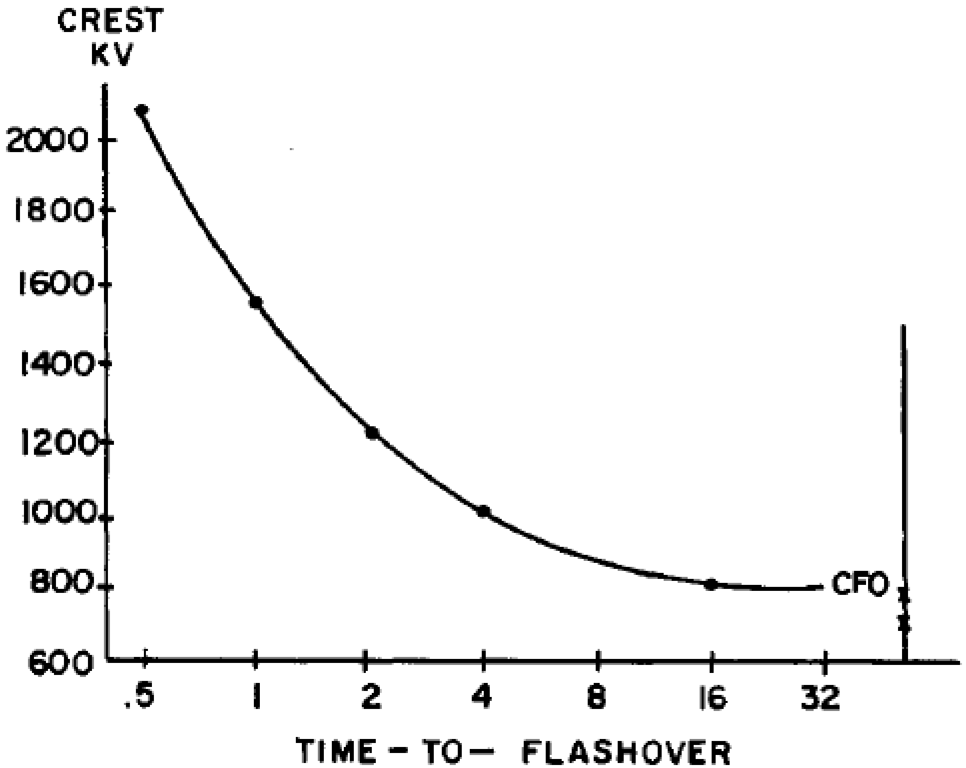


Figure 9 A sample time-lag curve.

Crest Voltage kV	Time to Flashover µs
700	no flashover
780	no flashover
800	16
1000	4
1200	2
1550	1
2050	0.5

Content

2. What is Insulation Coordination?

What is Insulation Coordination?

Definition in IEC 60071-1

Selection of the dielectric strength of equipment in relation to the operating voltages
and overvoltages which can appear on the system for which the equipment is intended and taking into account the service environment and characteristics of the available preventing and protective devices

Definition in IEEE 1313.1

The selection of insulation strength consistent with expected overvoltages to obtain an acceptable risk of failure

"strength vs. stress"

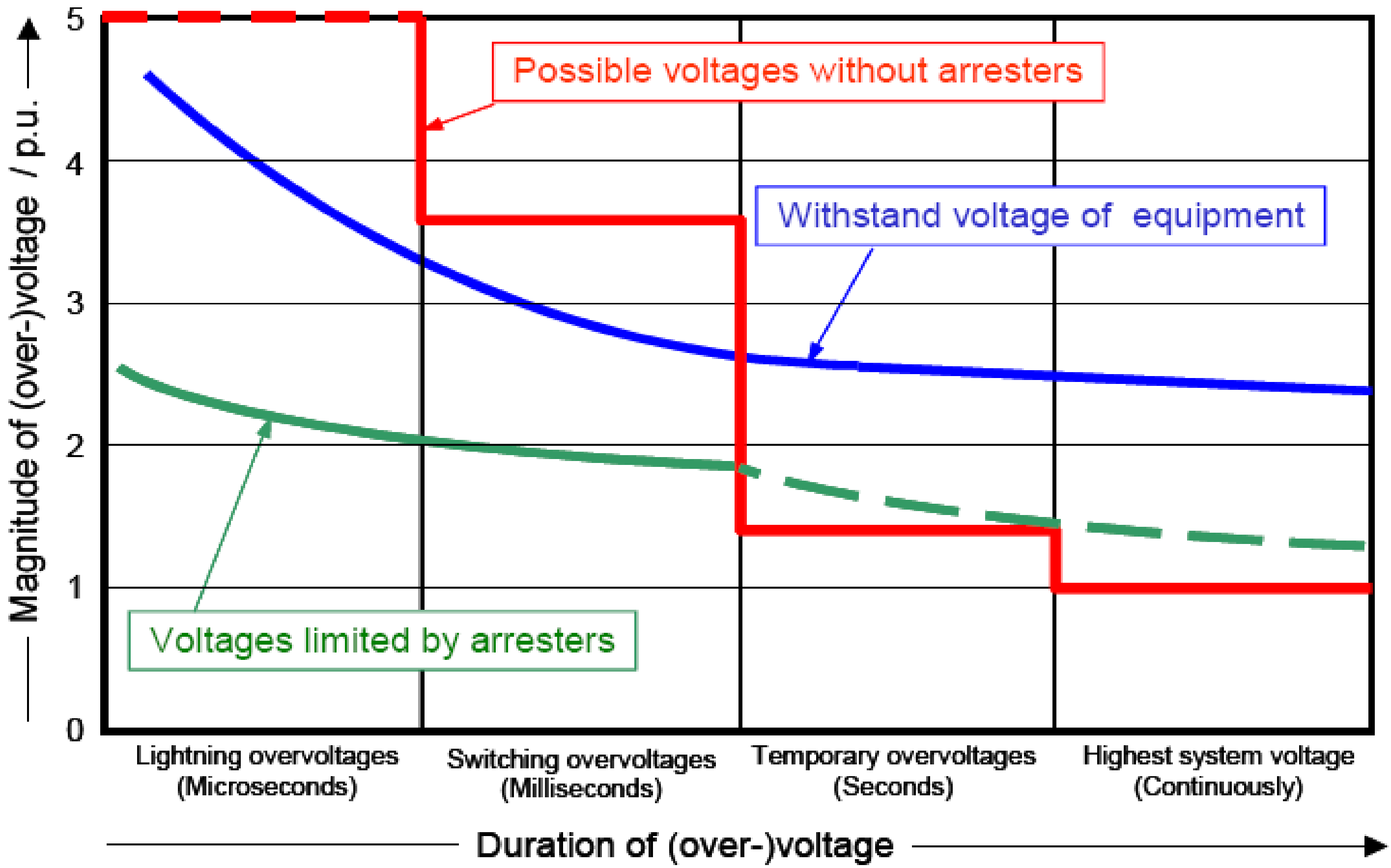


Fig. 1: Schematic representation of the magnitude of voltages and overvoltages in a high-voltage electrical power system versus duration of their appearance (1 p.u. = $\sqrt{2} \cdot U_s / \sqrt{3}$)

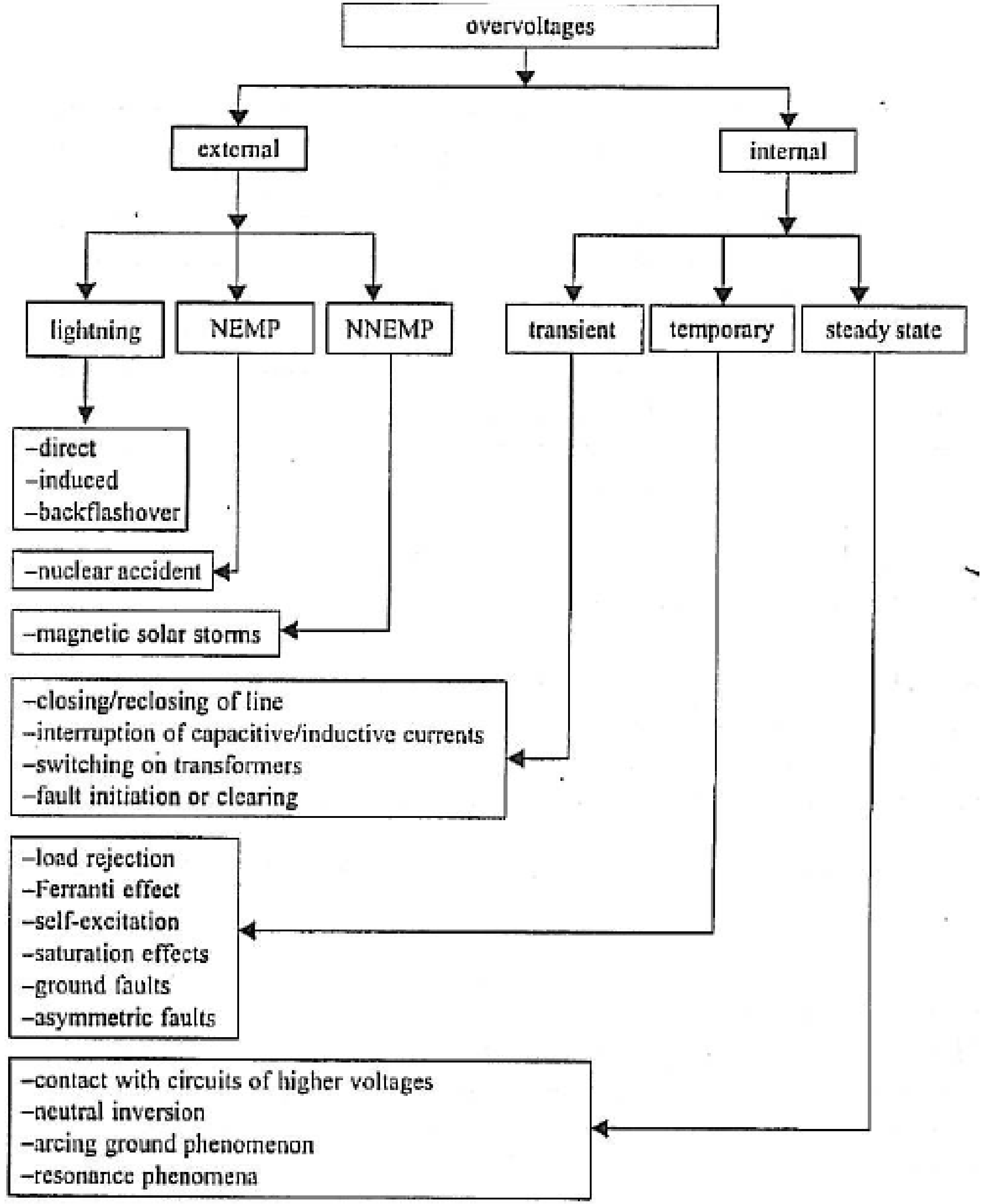


Figure 7.3 Classification of overvoltages

Table 7.1 Summary of important TOV causes and characteristics [21]

Temporary overvoltage phenomena	Important parameters	Overvoltage magnitudes	Typical durations	Methods of control
Common causes				
fault application	fault location system X_0/X_1 ratio fault current magnitude	1.0–1.4 p.u.	2–10 cycles	usually not necessary
load rejection	power flow system short circuit MVA system capacitance machine automatic voltage regulators	1.0–1.6 p.u.	seconds	switched reactors SVS generator controls
line energising	line capacitance system short circuit MVA	1.0–1.2 p.u.	seconds	switched reactors SVS generator controls

Temporary overvoltage phenomena	Important parameters	Overvoltage magnitudes	Typical durations	Methods of control
line dropping/ fault clearing	fault conditions line capacitance shunt reactors breaker opening sequence	1.0–1.5 p.u.	<1 second	shunt reactors relaying SVS
reclosing	line capacitance shunt reactors trapped charge levels fault conditions	1.0–1.5 p.u.	seconds	shunt reactors relaying SVS
transformer energising	system short circuit MVA transformer saturation characteristics frequency response characteristics system voltage level	1.0–1.5 p.u.	0–2 seconds	switched reactors SVS harmonic filters breaker closing res.
Special cases				
parallel line resonance	coupling capacitance between circuits shunt reactor values and saturation line corona losses	1.0–2.0 p.u.	steady state	neutral reactors switched reactors
uneven breaker poles	circuit capacitance shunt reactor values and saturation line corona losses	1.0–2.0 p.u.	steady state	neutral reactors switched reactors
ferroresonance	circuit capacitance transformer saturation transformer characteristics	1.0–1.5 p.u.	steady state	operating procedures
backfeeding	cable or line capacitance system short circuit MVA frequency response characteristics	1.0–2.0 p.u.	seconds	operating procedures shunt motors

What is Insulation Coordination?

Procedure of insulation coordination [THI-01]

Three elements are involved in the insulation coordination discipline, namely:

- the study of the **"stresses"**, both electrical and environmental, acting on the equipment insulation. This is usually performed by calculations or field measurements;

- the study of the **"strength"** (dielectric withstand characteristics) of the insulation (both new and aged) when submitted to such stresses, taking into account, when applicable, the effect of the environmental stresses (pollution, rain, snow, ice, atmospheric conditions at large altitudes), including the study of the "test and measurement techniques" which are employed to assess such strength. The strength is determined by calculations, based on suitable discharge models, and/or by laboratory/factory tests, on-site tests and in-service measurements (diagnostics);

- the assessment of the insulation performance (usually expressed in terms of risk of failure) in the considered situation of stresses and strength, including the selection and application of "protective devices and techniques", to establish the final insulation design fulfilling the specified requirements. This may be based on "deterministic" or "statistical" approach.

IEC 60071-1, Edition 8.0 (2006-01)
Insulation co-ordination – Part 1: Definitions, principles and rules

IEC 60071-2, Third Edition (1996-12)
Insulation co-ordination – Part 2: Application guide

IEC/TR 60071-4, First Edition (2004-06)
Insulation co-ordination - Part 4: Computational guide to insulation co-ordination and modelling of electrical networks

IEC 60099-4, Ed. 2.1, 2006-07
Surge arresters – Part 4: Metal-oxide surge arresters without gaps for a.c. systems

IEC 60099-5, Ed. 1.1, 2000-03
Surge arresters – Part 5: Selection and application recommendations

IEEE 1313.1-1996
IEEE Standard for Insulation Coordination—Definitions, Principles, and Rules

IEEE 1313.2-1999
IEEE Guide for the Application of Insulation Coordination

IEEE C62.11-2005
IEEE Standard for Metal-Oxide Surge Arresters for AC Power Circuits (> 1 kV)

IEEE C62.22-1997
IEEE Guide for the Application of Metal-Oxide Surge Arresters for Alternating-Current Systems

Recap on Voltage Stresses:

- **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**

Recap on Voltage Stresses:

- **Fast-front overvoltages: they can originate from switching operations, lightning strokes or faults**

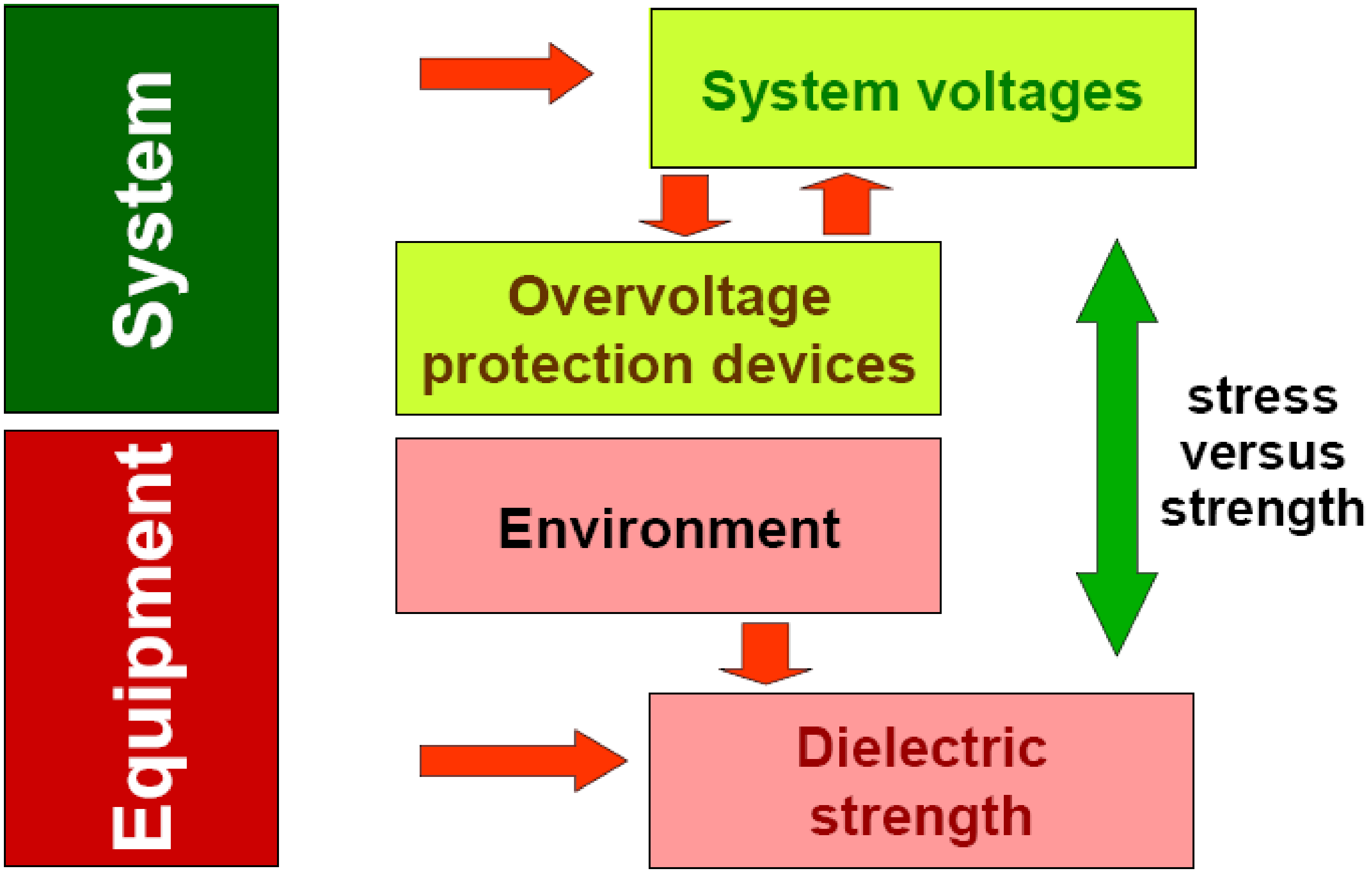
- **Very-fast-front overvoltages: they can originate from faults or switching operations in gas-insulated substations (GIS)**

- **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).**

Content

3. **Insulation Coordination - Principles**

Insulation Coordination - Principles



Insulation Coordination - Principles

- **Voltages of the system**
  - Nominal voltage U_n
    - » **rounded value for characterizing the system**
    - » **10 kV - 20 kV - 110 kV - 220 kV - 380 kV**
  - System voltage
    - » **voltage at which the system is being operated**
    - » **around the nominal value, but not constant**
  - Highest system voltage U_s
    - » **highest operating voltage between phases under normal conditions**
    - » 12 kV - 24 kV - 123 kV - 245 kV - 420 kV (IEC 60038)
- **Voltages of equipment**
  - Highest voltage for equipment U_m
    - » **highest voltage between phases for which the insulation is designed**
    - » 12 kV - 24 kV - 123 kV - 245 kV - 420 kV (IEC 60071-1)

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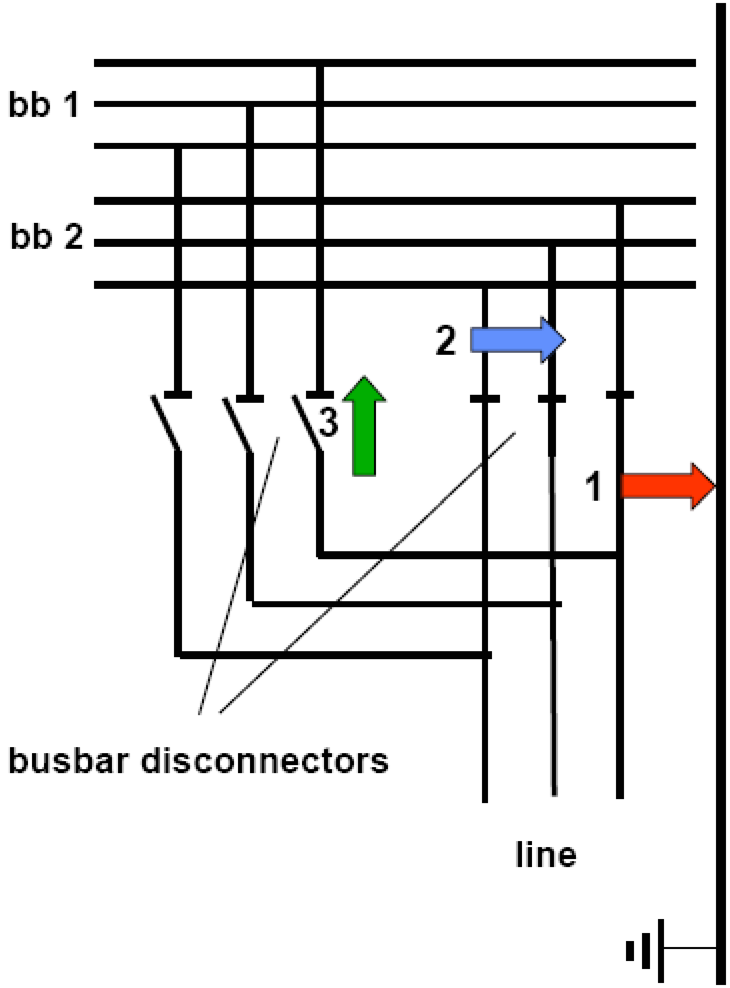
Insulation Coordination - Principles

- **Overvoltages**
  - voltages exceeding the peak value of the highest system voltage
  - various amplitudes and shapes depending on
    - » **system configuration (grid size, degree of meshing, etc.)**
    - » **origin of overvoltage (failure, switching, lightning strike etc.)**
- **Dielectric strength of insulation**
  - verified by type test in the laboratory with the help of
    - » **standardized test voltages (shape, amplitude)**
    - » **specified test setups**
    - » **specified environmental conditions**
- **Insulation coordination**
  - **Determination of interdependence** between voltages and overvoltages of the system and necessary test voltages for the equipment in the laboratory

Equipment in the system		Equipment in the laboratory
Variety of amplitudes and shapes of overvoltages	↔	Standardized amplitudes and shapes of test voltages
Variety of operating conditions and age	↔	Standardized setups and conditions
Variety of environmental conditions	↔	Standardized environmental conditions



Insulation phase - ground
stressed by voltages between one phase and ground

1

Insulation phase - phase
stressed by voltages between two phases

2

Longitudinal insulation
stressed by voltages between same phases of two different systems

3

Content

4. Insulation Coordination According to Standards

Insulation Coordination according to IEC 60071-1 (and 60071-2)

NORME INTERNATIONALE — CEI

INTERNATIONAL STANDARD — IEC

60071-1

Huitième édition
Eighth edition
2006-01

Coordination de l'isolement –

Partie 1:
Définitions, principes et règles

Insulation co-ordination –

Part 1:
Definitions, principles and rules

Insulation Coordination according to IEC 60071-1 (and 60071-2)

1 Scope

This part of IEC 60071 applies to three-phase a.c. systems having a highest voltage for equipment above 1 kV. It specifies the procedure for the selection of the rated withstand voltages for the phase-to-earth, phase-to-phase and longitudinal insulation of the equipment and the installations of these systems. It also gives the lists of the standard withstand voltages from which the rated withstand voltages should be selected.

This standard recommends that the selected withstand voltages should be associated with the highest voltage for equipment. This association is for insulation co-ordination purposes only. The requirements for human safety are not covered by this standard.

Although the principles of this standard also apply to transmission line insulation, the values of their withstand voltages may be different from the standard rated withstand voltages.

The apparatus committees are responsible for specifying the rated withstand voltages and the test procedures suitable for the relevant equipment taking into consideration the recommendations of this standard.

NOTE In IEC 60071-2, Application Guide, all rules for insulation co-ordination given in this standard are justified in detail, in particular the association of the standard rated withstand voltages with the highest voltage for equipment. When more than one set of standard rated withstand voltages is associated with the same highest voltage for equipment, guidance is provided for the selection of the most suitable set.

Insulation Coordination according to IEC 60071-1 (and 60071-2)

60071-1 © IEC:2006 – 3 –

CONTENTS

...39 pages in sum

Procedure for insulation coordination = 10 pages!

Insulation Coordination according to IEC 60071-1 (and 60071-2)

NORME INTERNATIONALE

INTERNATIONAL STANDARD

CEI
IEC
71-2

Troisième édition
Third edition
1996-12

Coordination de l'isolement –

Partie 2:
Guide d'application

Insulation co-ordination –

Part 2:
Application guide

Insulation Coordination according to IEC 60071-1 (and 60071-2)

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.

Insulation Coordination according to IEC 60071-1 (and 60071-2)

CONTENTS

Insulation Coordination according to IEC 60071-1 (and 60071-2)

Tables

Insulation Coordination according to IEC 60071-1 (and 60071-2)

Figures

Insulation Coordination according to IEC 60071-1 (and 60071-2)

71-2 © IEC: 1996 – 7 –

Annexes

...125 pages in sum

Content

5. Procedure for Insulation Coordination – General

Procedure for Insulation Coordination - General

The procedure for insulation coordination consists of the **selection of a set of standard withstand voltages** which characterize the insulation of the equipment.

Table 2 – Standard insulation levels for range I (1kV < U_m ≤ 245 kV)

Highest voltage for equipment (U_m) kV (r.m.s. value)	Standard rated short-duration power-frequency withstand voltage kV (r.m.s. value)	Standard rated lightning impulse withstand voltage kV (peak value)
3,6	10	20 40
7,2	20	40 60
12	28	60 75 95
17,5 [a]	38	

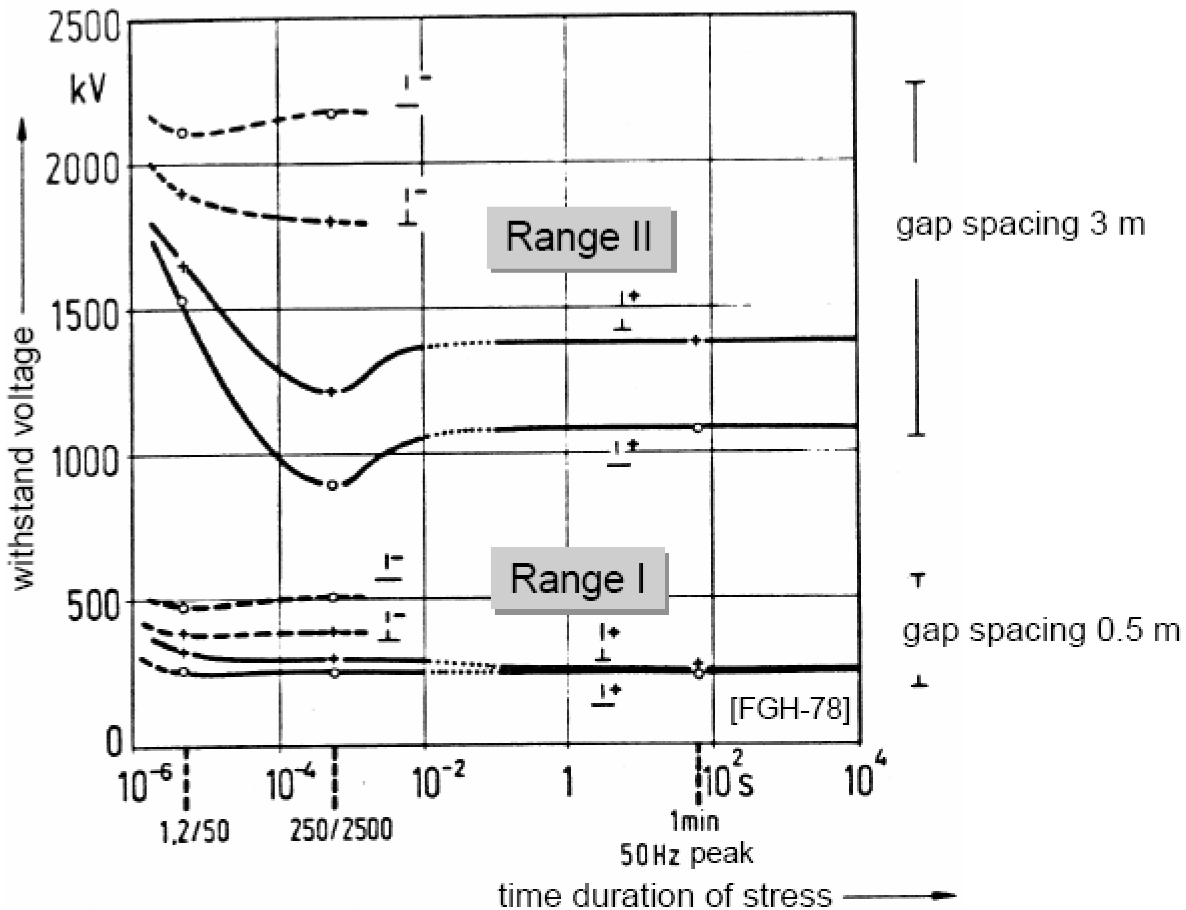
Range I

Table 3 – Standard insulation levels for range II (U_m > 245 kV)

Highest voltage for equipment (U_m) kV (r.m.s. value)	Standard rated switching impulse withstand voltage: Longitudinal insulation [a] kV (peak value)	Phase-to-earth kV (peak value)	Phase-to-phase (ratio to the phase-to-earth peak value)	Standard rated lightning impulse withstand voltage [b] kV (peak value)
300 [c]	750	750	1,50	850 950
	750	850	1,50	950 1050
362	850	850	1,50	950 1050

Range II

Basic difference between ranges I and II



Minimum of withstand voltage for switching overvoltage

Withstand voltage continuously decreasing with time duration of stress

Content

6. Procedure for Insulation Coordination – in 4 Steps

1

Determination of the representative overvoltages U_{rp}

- The representative overvoltages are derived from real service conditions, but have just standardized shapes.
- They are determined in amplitude, shape and duration by system analysis, taking into account overvoltage limiting devices.

3.19
representative overvoltages
U_{rp}
overvoltages assumed to produce the same dielectric effect on the insulation as overvoltages of a given class occurring in service due to various origins.

They consist of voltages with the standard shape of the class, and may be defined by one value or a set of values or a frequency distribution of values that characterize the service conditions

NOTE This definition also applies to the continuous power frequency voltage representing the effect of the service voltage on the insulation.

Procedure for Insulation Coordination in Four Steps

2

Determination of the coordination withstand voltages U_{cw}

- The coordination withstand voltages are the lowest values of withstand voltages of each overvoltage class, for which the expected low failure rate of the equipment is not exceeded over its full lifetime.
- Derived from the representative overvoltages U_{rp} by the coordination factor K_c.

> **3.24**
> **co-ordination withstand voltage**
> U_{cw}
> for each class of voltage, the value of the withstand voltage of the insulation configuration in actual service conditions, that meets the performance criterion

> **3.22**
> **performance criterion**
> basis on which the insulation is selected so as to reduce to an economically and operationally acceptable level the probability that the resulting voltage stresses imposed on the equipment will cause damage to equipment insulation or affect continuity of service. This criterion is usually expressed in terms of an acceptable failure rate (number of failures per year, years between failures, risk of failure, etc.) of the insulation configuration

Typical for Germany: 0.1% per year → 1 failure in 1000 years

> **3.25**
> **co-ordination factor**
> K_c
> factor by which the value of the representative overvoltage must be multiplied in order to obtain the value of the co-ordination withstand voltage

[IEC 60071-1]

2

Deterministic approach	Statistical approach
Assumed maximum of representative overvoltage	Statistical distribution of representative overvoltages
	Determination of failure probability of insulation
Multiplication by coordination factor based on operating experience	Calculation of failure risk depending on assumed coordination withstand voltage

Coordination withstand voltage

Assumed conventional U_{cw} (0% value) | Statistical U_{cw} (10% value)

ZAM Dec 2020

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 (PW = 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 Kc, 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 (PW = 90 %), Kc 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.

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.

Statistical method

- 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.

Examples

- pf: 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 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.
- TOV: With the deterministic method, the co-ordination short-duration withstand voltage is equal to the representative temporary overvoltage.
- TOV: When a statistical procedure is adopted and the representative temporary overvoltage is given by an amplitude/duration distribution frequency characteristic, 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.

Examples: Temporary overvoltages (TOV)

- 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.

Examples: Temporary overvoltages (TOV)

- 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

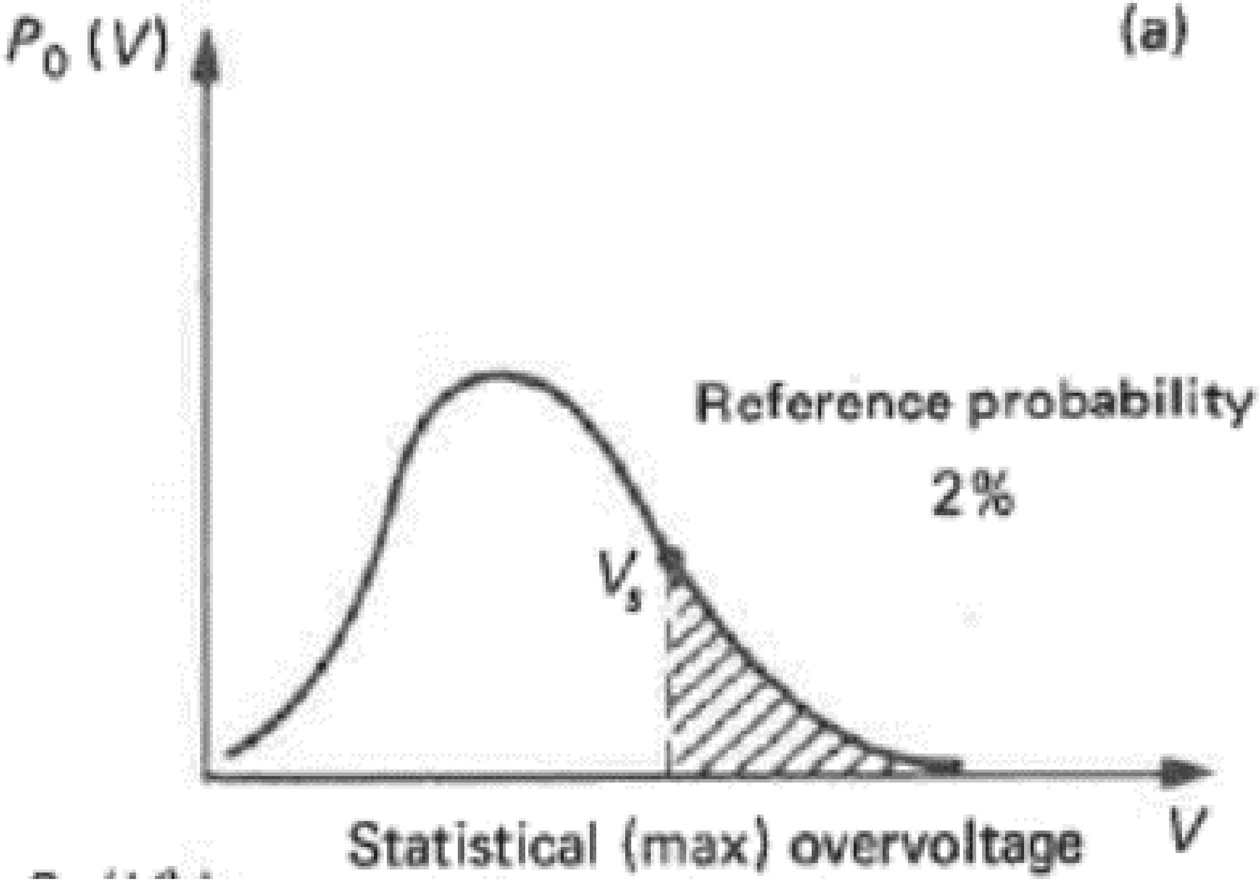
Statistical Technique

- Random nature of overvoltages (magnitude, form/shape, peak time) and certain (eg long insulators, air clearances) insulation withstand/breakdown behaviour (magnitude, time to breakdown=TBD) requires statistical treatment to determine Kcd

- i.e. TBD is also random

- Overvoltages/stresses can be represented by a probability density function
- f(Vm, t)
- Neglecting t variation, we get f(Vm) (or Po(V) in the next figure)
- Vs= SOV = switching (or lightning) overvoltage applied to the equipment as a result of an event of one specific type on the system, the peak value of which has a probability of being exceeded of 2%

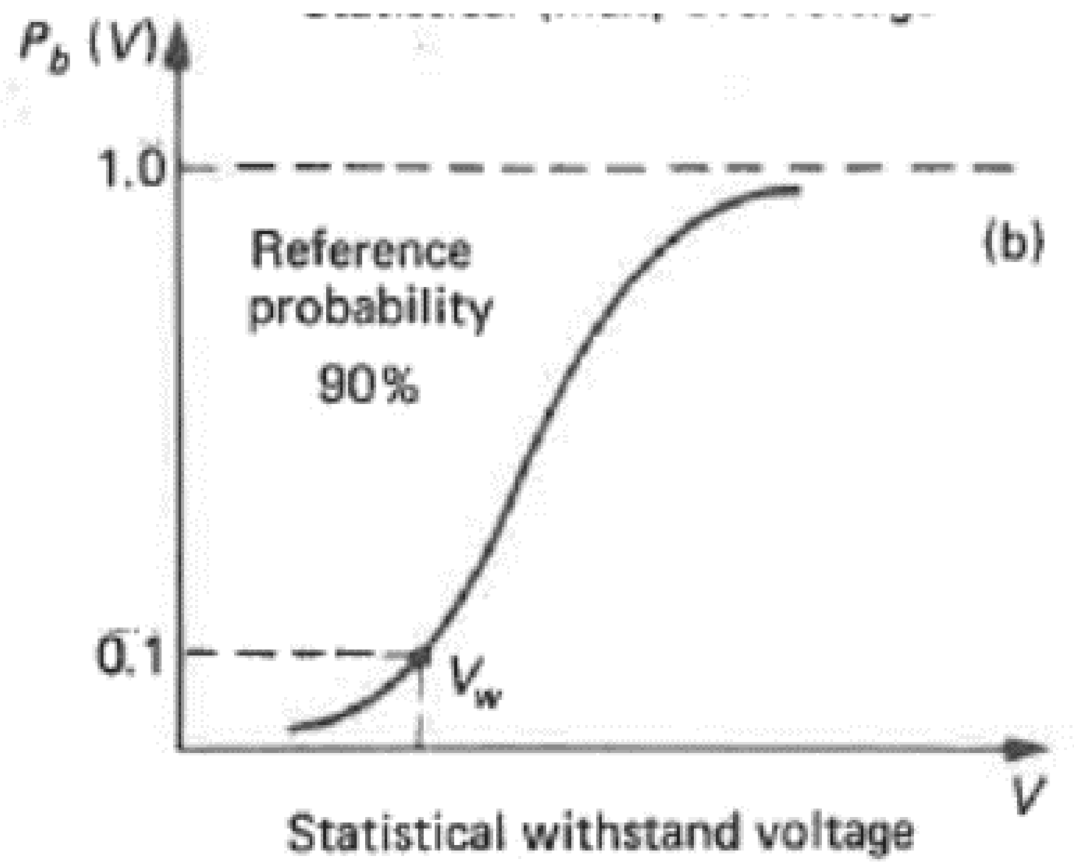
Statistical Technique



Statistical Technique

- The statistical variation of insulation withstand (breakdown) can be represented by P(Vm, t), where t considers variation in TBD
- Neglecting t, we have
- P(Vm, t)
- Insulation withstand can also be represented by a breakdown probability curve (S curve)
- Vw= SWV= peak value of a switching/lightning impulse test voltage at which the insulation exhibits under specified conditions a probability of withstand equal to 90%

Statistical Technique



Reference probabilities for overvoltage and for insulation withstand strength.

Statistical Technique

- Overvoltages whose magnitudes fall within an interval dVm, should produce an insulation risk of failure given by
- dR = P(Vm) f(Vm) dVm
- The overall risk of insulation failure can thus be written as
- R $= A = \int_0^{\infty} P(V_m)\, f(V_m)\, \mathrm{d}V_m$

- (R' sometimes is used for the above since R is for full treatment of Vm and t, ie when t and dt are considered in the equation!)
- Insulation can be theoretically be made sizable enough to eliminate any risk of insulation failure. However, this is economically unwise!
- It is therefore necessary to define a reasonable safety factor and design the insulation accordingly.

Statistical Technique

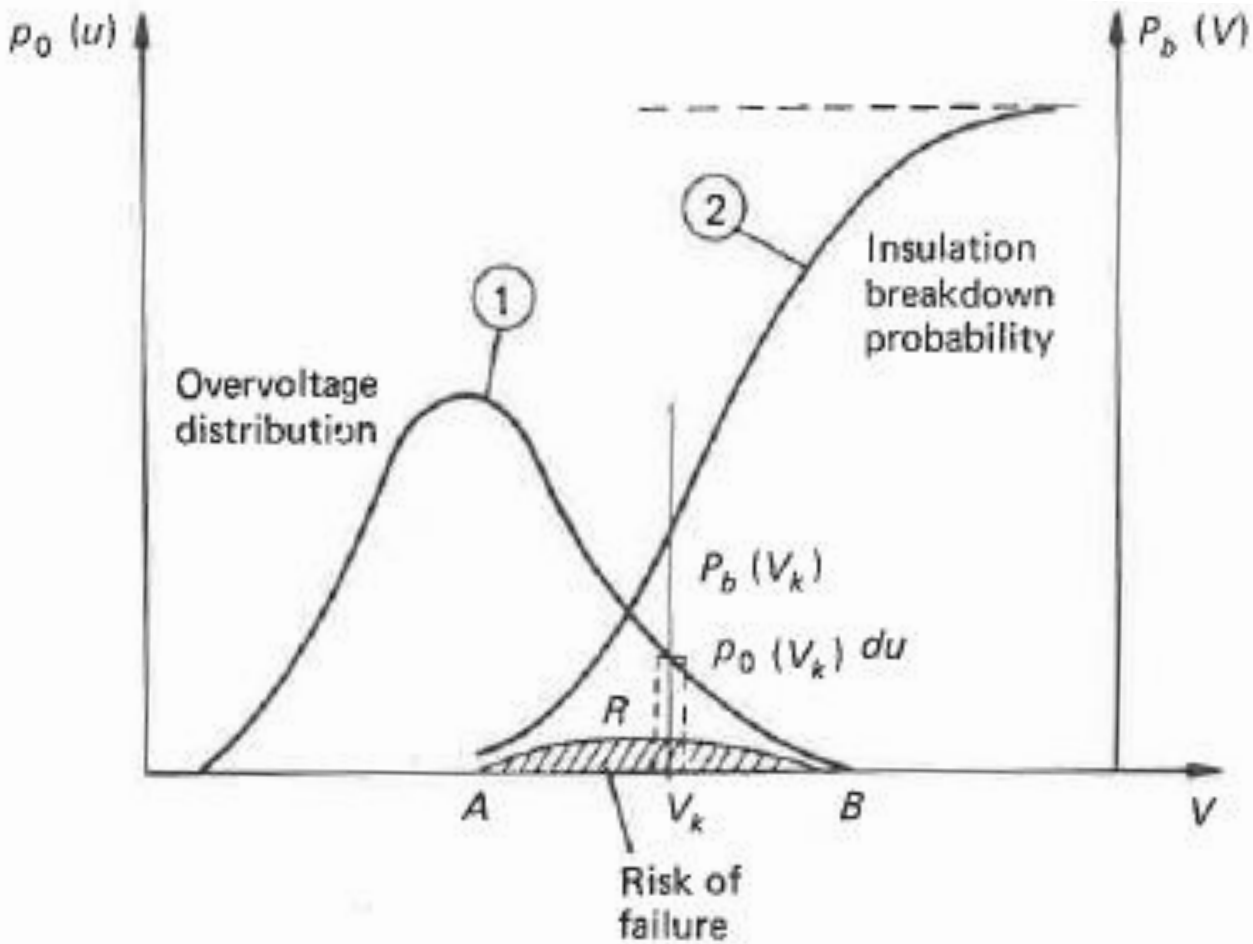
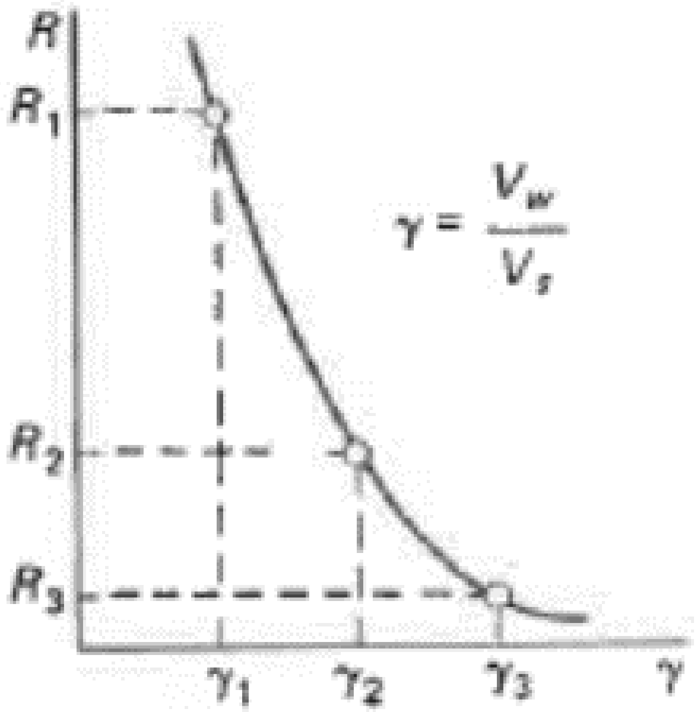


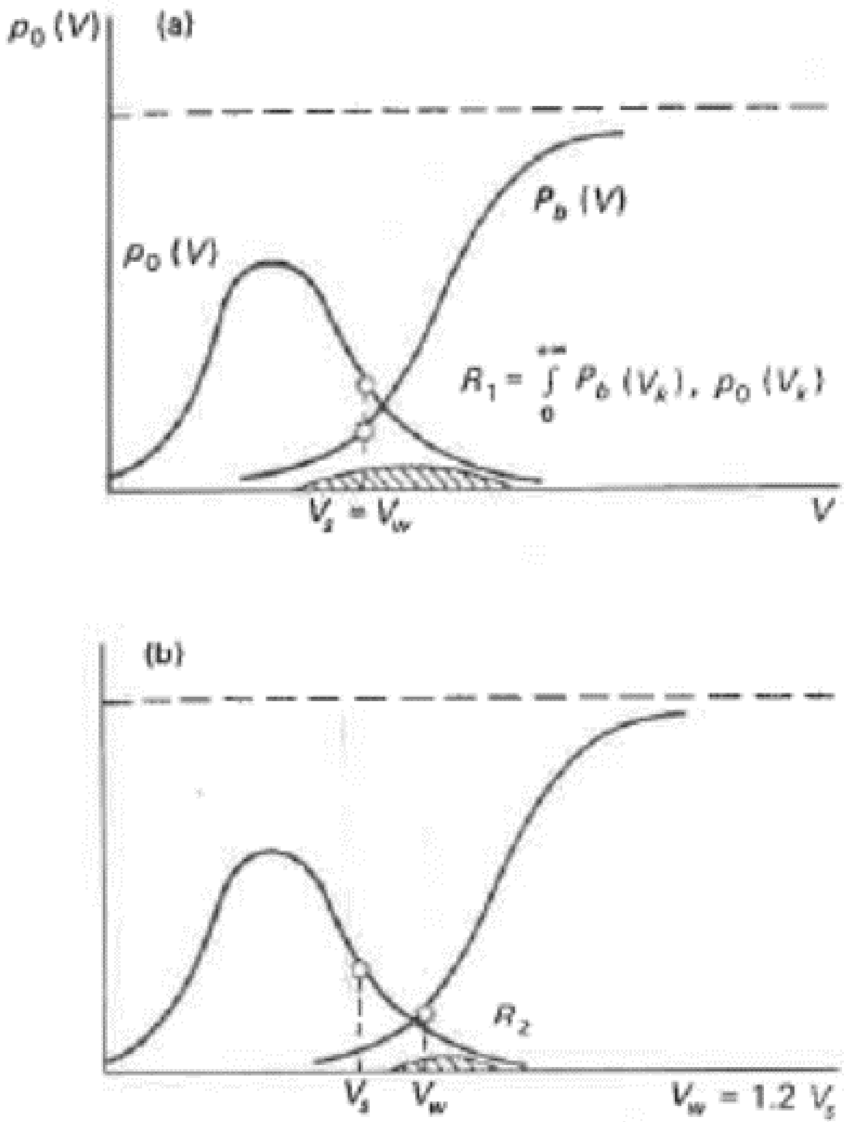
FIG. 7.11. Method of describing the risk of failure. 1. Probability density function

Statistical Technique

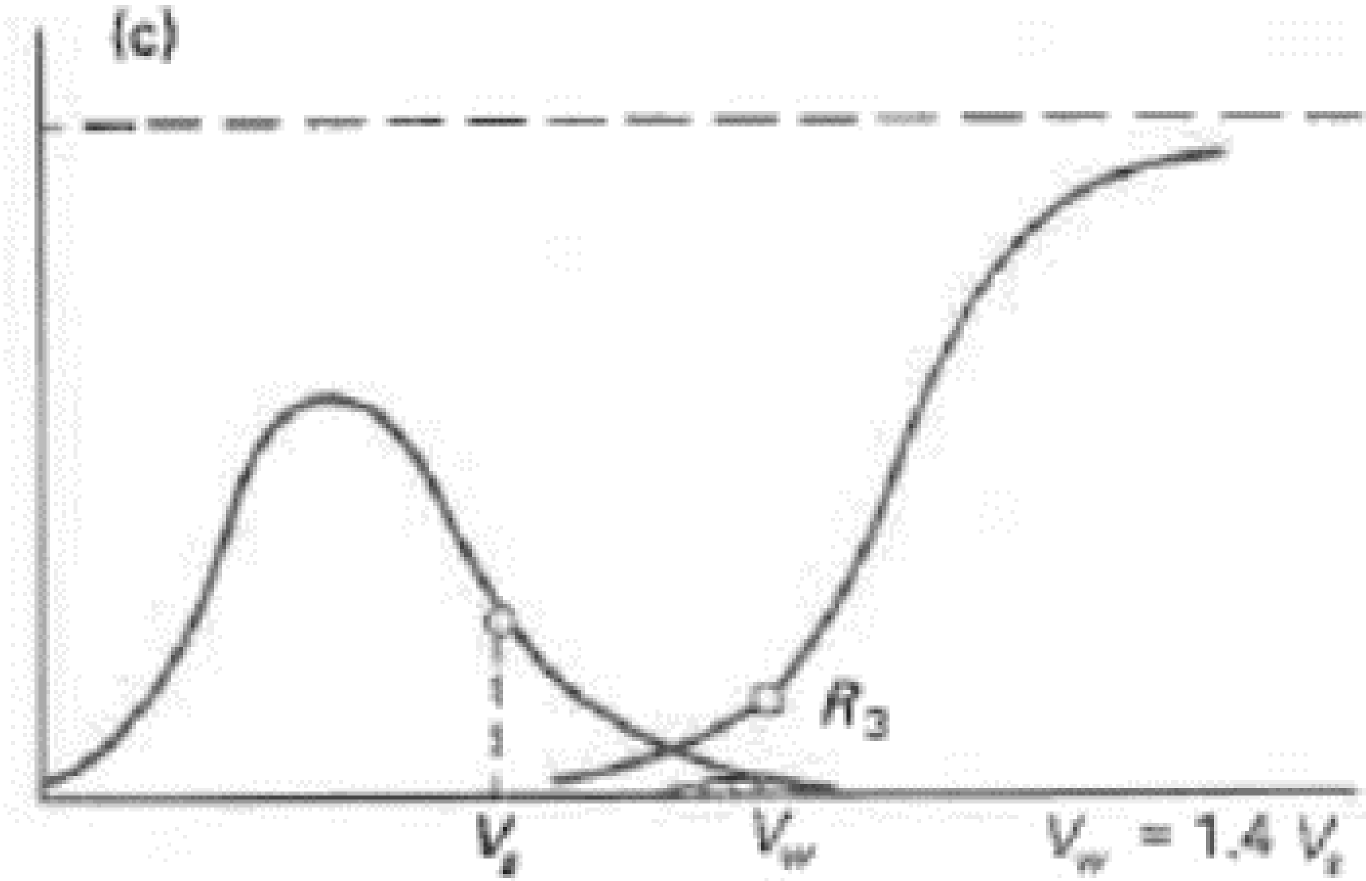


The statistical safety factor and its relation to the risk of failure (R).

Statistical Technique



Statistical Technique



Statistical Technique

- When protective devices are employed, the same procedure can be made.

- The area or ‘risk of failure’ of the protective device should be much larger than the that for the protected device.

Statistical Technique

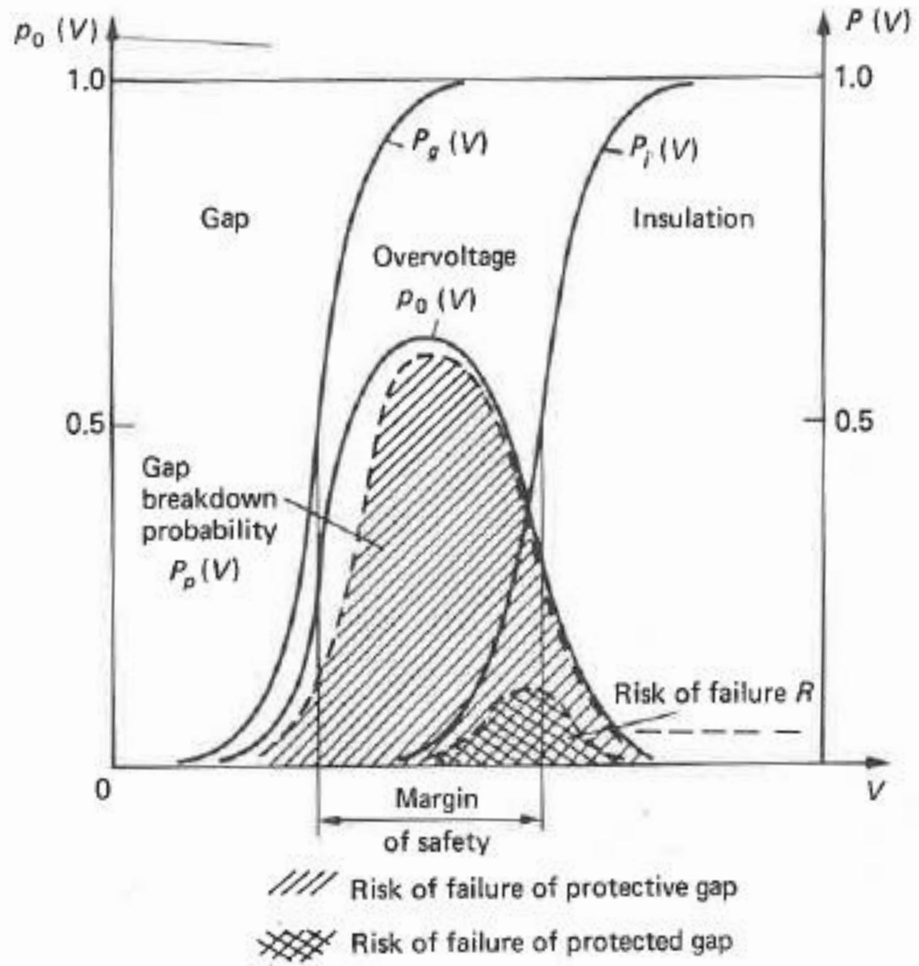


FIG. 7.14. Distribution functions of breakdown voltages for protective gap and protected insulation both subjected to an overvoltage $p_0(V)$.
P_p Risk of failure of protective gap.
R Risk of failure of protected gap.

Example

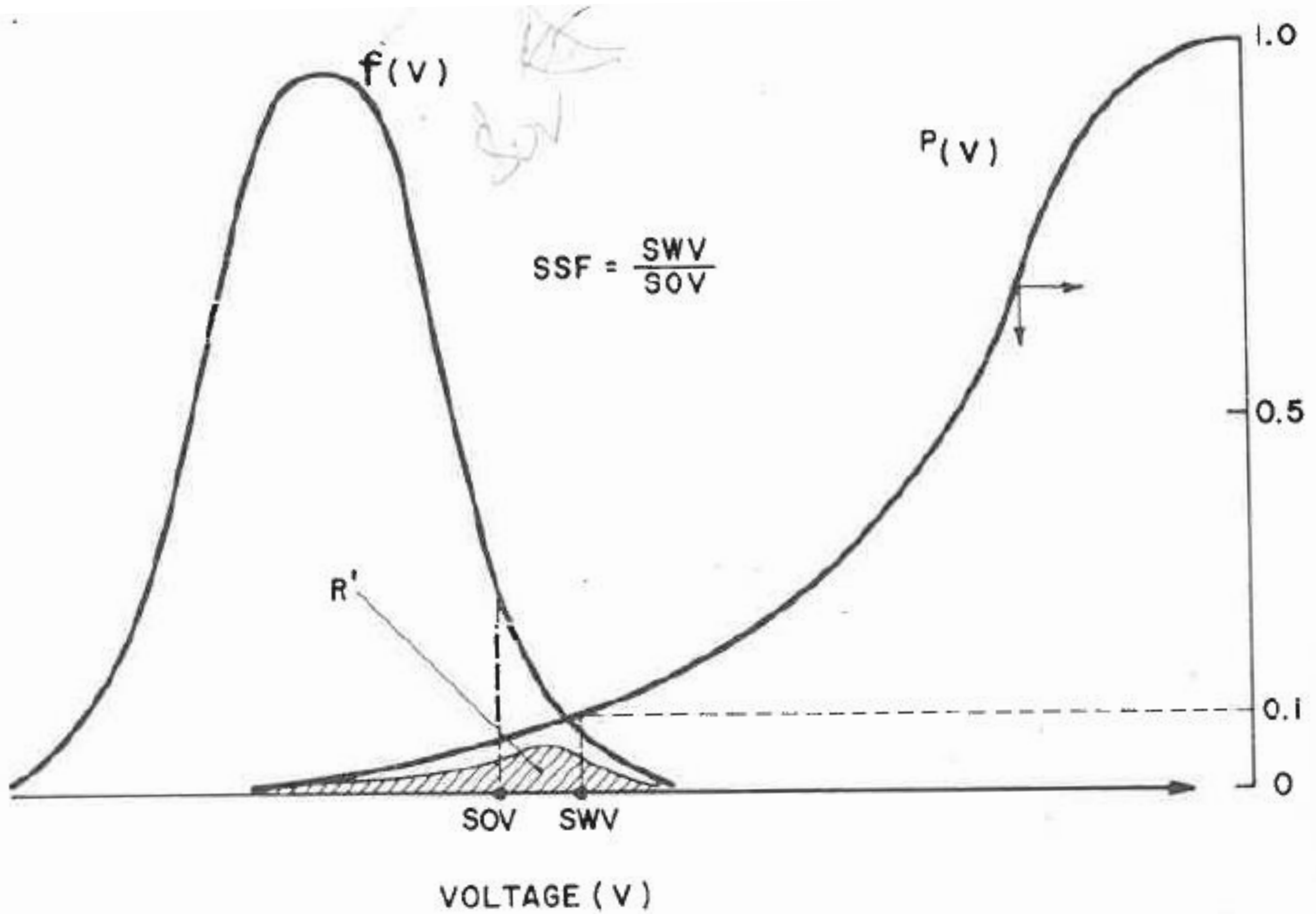


Fig. 15.4 Computation of the risk of insulation failure.

Example

$$SSF = \frac{SWV}{SOV} \tag{15.19}$$

In Figure 15.5 the effect of the statistical safety factor on the consequent risk of insulation failure is demonstrated (IEC, 1976). It appears that the relationship above is almost invariant for all EHV transmission networks — a fact that permits the use of SSF as a reliable design factor.

Example

The following procedural example for a disconnecting switch illustrates the application of statistical insulation coordination:

Highest voltage for equipment (line voltage) = 765 kV (rms)

Phase-to-earth voltage V_{ph} = 442 kV (rms)
= 625 kV (peak)
= 1.0 p.u.

SOV (from system studies) = 1255 kV (peak)
= 2.0 p.u.

Example

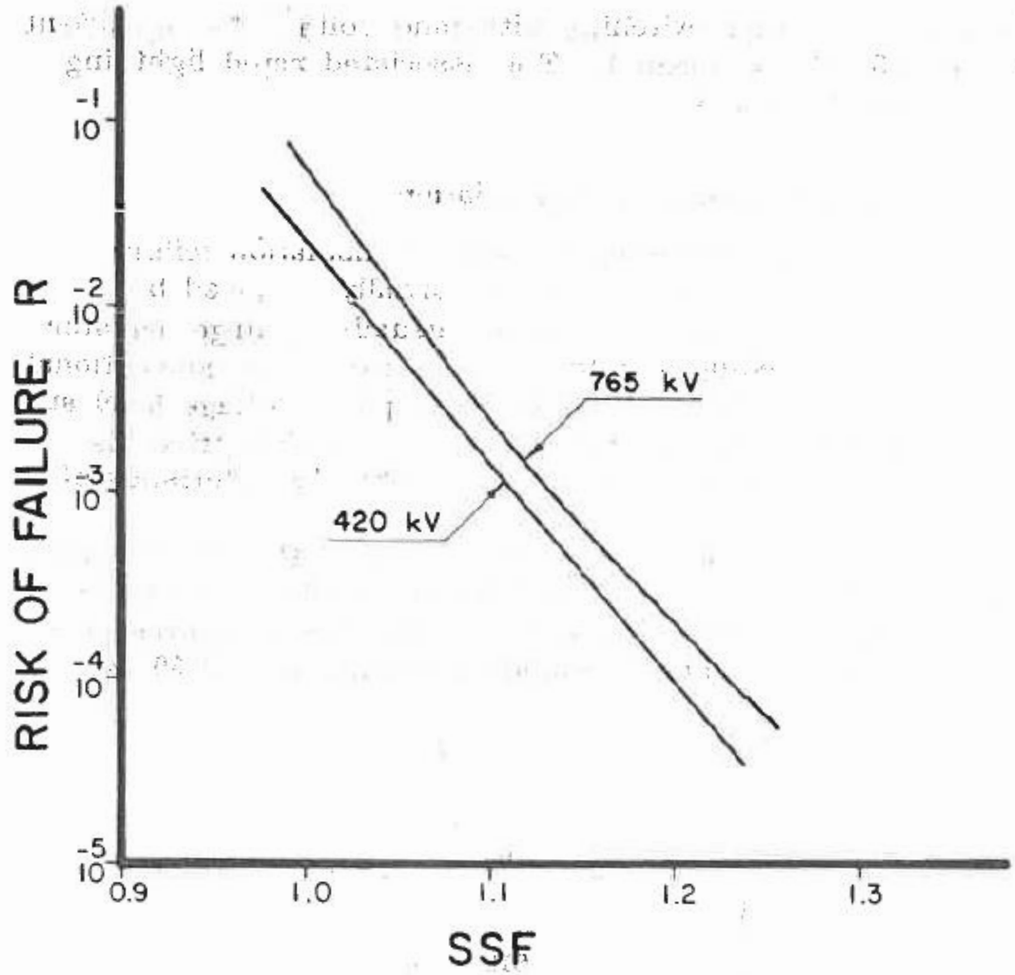


Fig. 15.5 Effect of the statistical safety factor on the risk of insulation failure.

Example

Maximum acceptable risk of insulation failure to ground $R = 10^{-4}$
Choice of insulation's SWV:

SWV			
kV	p.u.	SSF	R
1300	2.08	1.04	$1 \times 10^{-2} > 10^{-4}$
1425	2.28	1.14	$7 \times 10^{-4} > 10^{-4}$
1550	2.48	1.24	$7 \times 10^{-5} < 10^{-4}$

Procedure for Insulation Coordination in Four Steps

Determination of the required withstand voltages U_{rw}

3

- The required withstand voltages are determined by converting the coordination withstand voltages to appropriate standard test conditions.
- Usually different from the coordination withstand voltages.
- Derived from the coordination withstand voltages U_{cw} by the safety factor K_s and the atmospheric correction factor K_t or the altitude correction factor K_a.

> **3.27**
> **required withstand voltage**
> U_{rw}
> test voltage that the insulation must withstand in a standard withstand voltage test to ensure that the insulation will meet the performance criterion when subjected to a given class of overvoltages in actual service conditions and for the whole service duration. The required withstand voltage has the shape of the co-ordination withstand voltage, and is specified with reference to all the conditions of the standard withstand voltage test selected to verify it

> **3.30**
> **safety factor**
> K_s
> overall factor to be applied to the co-ordination withstand voltage, after the application of the atmospheric correction factor (if required), to obtain the required withstand voltage, accounting for all other differences in dielectric strength between the conditions in service during life time and those in the standard withstand voltage test

[IEC 60071-1]

Procedure for Insulation Coordination in Four Steps

3

Influences covered by the safety factor K_s

- Differences in equipment assembly
- Dispersion in product quality
- Quality of installation
- Aging of the installation during expected lifetime
- Other unknown influences

[IEC 60071-1]

Procedure for Insulation Coordination in Four Steps

Determination of the required withstand voltages U_{rw}

3

- The required withstand voltages are determined by converting the coordination withstand voltages to appropriate standard test conditions.
- Usually different from the coordination withstand voltages.
- Derived from the coordination withstand voltages U_{cw} by the safety factor K_s and/or the altitude correction factor K_a.

3.28
atmospheric correction factor
K_t
factor to be applied to the co-ordination withstand voltage to account for the difference in dielectric strength between the average atmospheric conditions in service and the standard reference atmospheric conditions

It applies to external insulation only, for all altitudes

NOTE 1 The factor K_t allows the correction of test voltages taking into account the difference between the actual atmospheric conditions during test and the standard reference atmospheric conditions. For the factor K_t, the atmospheric conditions taken into account are air pressure, temperature and humidity.

NOTE 2 For insulation co-ordination purposes usually only the air pressure correction needs to be taken into account.

3.29
altitude correction factor
K_a
factor to be applied to the co-ordination withstand voltage to account for the difference in dielectric strength between the average pressure corresponding to the altitude in service and the standard reference pressure

NOTE The altitude correction factor K_a is part of the atmospheric correction factor K_t.

[IEC 60071-1]

Procedure for Insulation Coordination in Four Steps

4

Selection of the rated and of the standard insulation level (set of standard rated withstand voltages U_w)

- Most economical set of standard withstand voltages U_w of the insulation to prove that all the required withstand voltages are met.
- For each range (I or II) a combination of only **two** withstand voltages defined:
  - Range I: standard lightning impulse withstand voltage
    standard short-duration power-frequency withstand voltage
  - Range II: standard switching impulse withstand voltage
    standard lightning impulse withstand voltage
- For range I, only phase-to-earth standard withstand voltages are defined, which have to cover phase-to-earth, phase-to-phase and longitudinal insulation.

Procedure for Insulation Coordination in Four Steps

Definitions

3.34
standard rated withstand voltage
U_w
standard value of the rated withstand voltage as specified in this standard (see 5.6 and 5.7)

3.35
rated insulation level
set of rated withstand voltages which characterize the dielectric strength of the insulation

3.36
standard insulation level
set of standard rated withstand voltages which are associated to U_m as specified in this standard (see Table 2 and Table 3)

3.23
withstand voltage
value of the test voltage to be applied under specified conditions in a withstand voltage test, during which a specified number of disruptive discharges is tolerated. The withstand voltage is designated as:

a) conventional assumed withstand voltage, when the number of disruptive discharges tolerated is zero. It is deemed to correspond to a withstand probability P_w = 100 %;

b) statistical withstand voltage, when the number of disruptive discharges tolerated is related to a specified withstand probability. In this standard, the specified probability is P_w = 90 %.

NOTE In this standard, for non-self-restoring insulation are specified conventional assumed withstand voltages, and for self-restoring insulation are specified statistical withstand voltages.

[IEC 60071-1]

Examples for…

... non-self-restoring insulation
(power transformers,
instrument transformers*))

*) mixed insulation

... self-restoring
insulation
(disconnectors,
insulators)

Procedure for Insulation Coordination in Four Steps

List of standard short-duration power-frequency withstand voltages (r.m.s. values in kV)

10	20	28	38	50
70	95	140	185	230
275	325	360	395	460
480	510	570	630	

List of standard impulse withstand voltages (peak values in kV)

20	40	60	75	95	125	145	170	250
325	450	550	650	750	850	950	1050	1175
1300	1425	1550	1675	1800	1950	2100	2250	2400

[IEC 60071-1]

Procedure for Insulation Coordination in Four Steps

Table 2 – Standard insulation levels for range I (1kV < U_m ≤ 245 kV)

Highest voltage for equipment (U_m) kV (r.m.s. value)	Standard rated short-duration power-frequency withstand voltage kV (r.m.s. value)	Standard rated lightning impulse withstand voltage kV (peak value)
3,6	10	20
		40
7,2	20	40
		60
12	28	60
		75
		95
17,5 [a]	38	75
		95
24	50	95
		125
		145
36	70	145
		170
52 [a]	95	250
72,5	140	325
100 [b]	(150)	(380)
	185	450
123	(185)	(450)
	230	550
145	(185)	(450)
	230	550
	275	650
170 [a]	(230)	(550)
	275	650
	325	750
245	(275)	(650)
	(325)	(750)
	360	850
	395	950
	460	1050

NOTE If values in brackets are considered insufficient to prove that the required phase-to-phase withstand voltages are met, additional phase-to-phase withstand voltage tests are needed.

[a] These U_m are non preferred values in IEC 60038 and thus no most frequently combinations standardized in apparatus standards are given.

[b] This U_m value is not mentioned in IEC 60038 but it has been introduced in range I in some apparatus standards.

Range I:

U_m = 1 kV up to and including U_m = 245 kV

The standard voltage values are **all the same** for

- phase-to-earth-,
- phase-to-phase-,
- longitudinal

insulation!

[IEC 60071-1]

Procedure for Insulation Coordination in Four Steps

Table 3 – Standard insulation levels for range II (U_m > 245 kV)

Highest voltage for equipment (U_m) kV (r.m.s. value)	Standard rated switching impulse withstand voltage: Longitudinal insulation [a] kV (peak value)	Standard rated switching impulse withstand voltage: Phase-to-earth kV (peak value)	Standard rated switching impulse withstand voltage: Phase-to-phase (ratio to the phase-to-earth peak value)	Standard rated lightning impulse withstand voltage [b] kV (peak value)
300 [c]	750	750	1,50	850
				950
	750	850	1,50	950
				1050
362	850	850	1,50	950
				1050
	850	950	1,50	1050
				1175
420	850	850	1,60	1050
				1175
	950	950	1,50	1175
				1300
	950	1050	1,50	1300
				1425
550	950	950	1,70	1175
				1300
	950	1050	1,60	1300
				1425
	950 1050	1175	1,50	1425
				1550
800	1175	1300	1,70	1675
				1800
	1175	1425	1,70	1800
				1950
	1175 1300	1550	1,60	1950
				2100

NOTE The introduction of U_m above 800 kV is under consideration, and 1050 kV, 1100 kV and 1200 kV are listed as U_m in IEC 60038 Amendment 2, 1997.

[a] Value of the impulse component of the relevant combined test while the peak value of the power-frequency component of opposite polarity is $U_m \times \sqrt{2} / \sqrt{3}$.

[b] These values apply as for phase-to-earth and phase-to-phase insulation as well; for longitudinal insulation they apply as the standard rated lightning impulse component of the combined standard rated withstand voltage, while the peak value of the power-frequency component of opposite polarity is $0{,}7 \times U_m \times \sqrt{2} / \sqrt{3}$.

[c] This U_m is a non preferred value in IEC 60038.

Range II:

U_m above 245 kV

Different standard voltage values for

- phase-to-earth-,
- phase-to-phase-,
- longitudinal

insulation!

[IEC 60071-1]

Procedure for Insulation Coordination in Four Steps

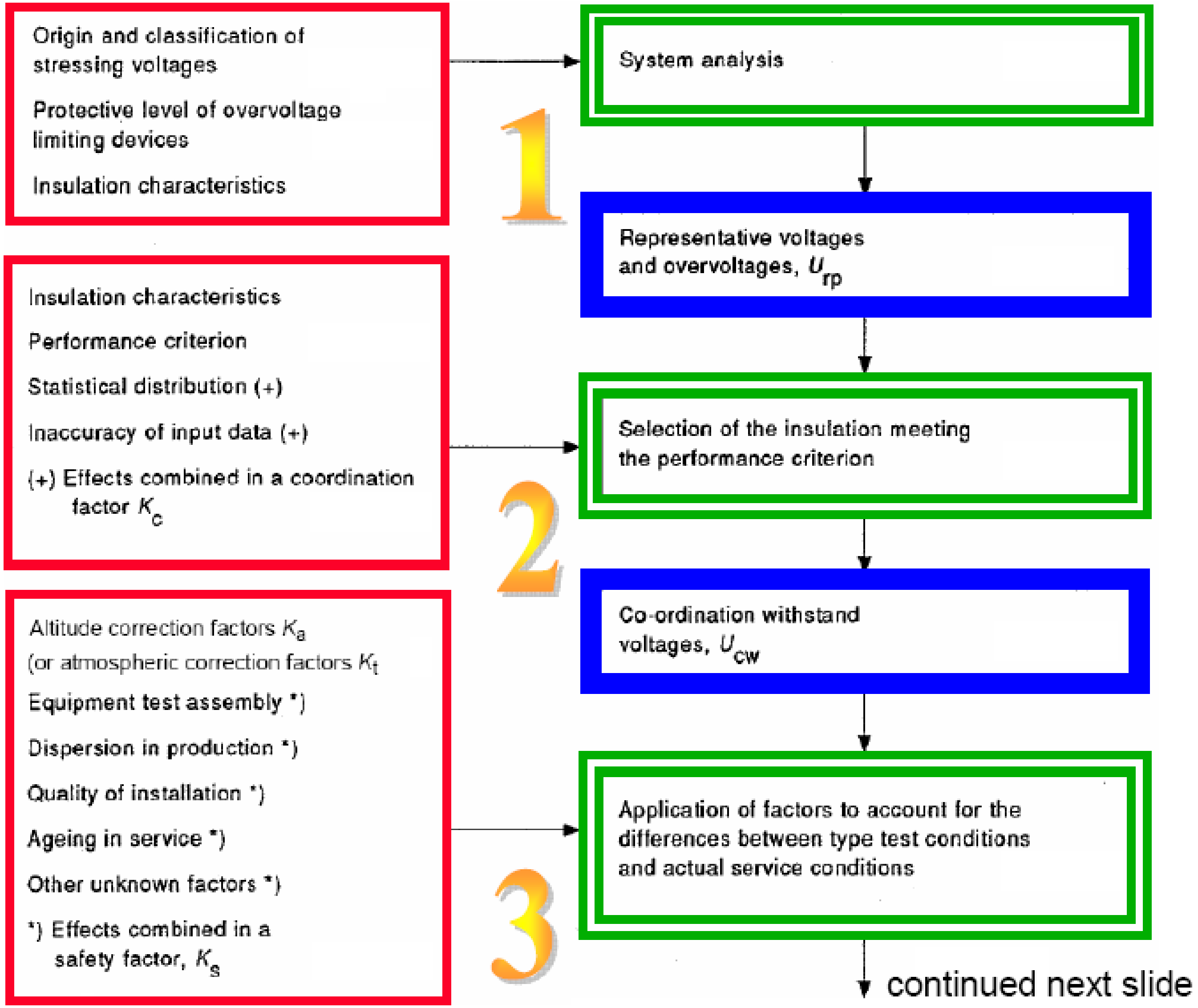
Outcome of insulation coordination

- For three types of insulation
  - » **phase to ground**
  - » **phase to phase**
  - » **longitudinal**
- and for 4 values each of required withstand voltages U_{rw}
  - » **required continuous operating voltage**
  - » **required short-duration power-frequency withstand voltage**
  - » **required switching impulse withstand voltage**
  - » **required lightning impulse withstand voltage**

twelve voltages

→ Standardization of tests for equipment

- Reduction of these 12 values to a necessary minimum number of withstand voltages U_w of the insulation
- Determination of necessary withstand voltages **from tables for two ranges of highest voltage for equipment**



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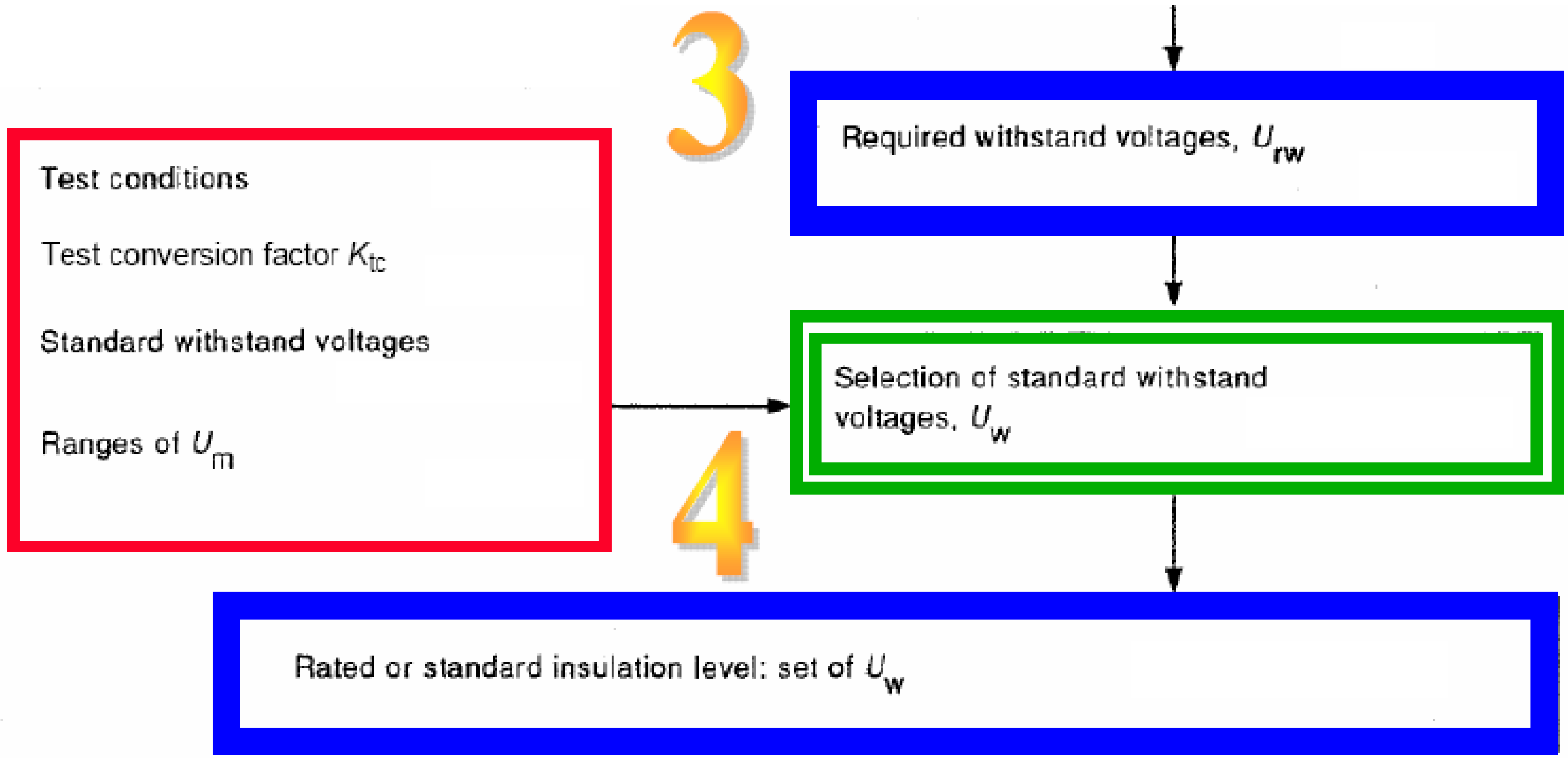

NOTE – In brackets the subclauses reporting the definition of the term or the description of the action.

sided boxes refer to required input.

sided boxes refer to performed actions.

sided boxes refer to obtained results.

ZAM Dec 2020

Examples

1. Example 1 (24 kV distribution level)
2. Example 2 (132 kV HV transmission level)

Example 1

- Show how the various insulation coordination values are calculated for **substations in distribution** systems with U_m = 24 kV.

  Assume the followings:

  – the **highest system** voltage is: U_s = 24kV

  – the **pollution level** is: light

  – the **altitude** is: H = 1000m (The altitude level here is assumed to cover all possible locations)

  – K_c = 1, K_{si} = 1.15, K_{se} = 1.05, K_a = 1.13,

For equipment in this voltage range, IEC71-1 specifies standard **rated short-duration power-frequency** and **lightning impulse** withstand voltages.

Example 1
Summary of answer

Table H.3 — Value related to the insulation co-ordination procedure for example H.3

Type of overvoltage		Temporary				Slow-front				Fast-front	
		Phase-to-earth		Phase-to-phase		Phase-to-earth		Phase-to-phase		Phase-to-earth and phase-to-phase	
Insulation		Internal	External	Internal	External	Internal	External	Internal	External	Internal	External
Step 1 Representative voltage stresses in service	Values of U_{rp}:	24 kV	24 kV	28 kV	28 kV	59 kV	59 kV	86 kV	86 kV	—	—
Step 2 Co-ordination withstand voltages	Values of K_c or K_{cd}: Values of U_{cw}:	1,0 24 kV	1,0 24 kV	1,0 28 kV	1,0 28 kV	1,0 59 kV	1,0 59 kV	1,0 86 kV	1,0 86 kV	— 95 kV	— 105 kV
Step 3 Required withstand voltages	Safety factor K_s: Altitude correction K_a: Values of U_{rw}:	1,15 — 28 kV	1,05 1,13 28 kV	1,15 — 32 kV	1,05 1,13 33 kV	1,15 — 68 kV	1,05 1,13 70 kV	1,15 — 99 kV	1,05 1,13 102 kV	1,15 — 109 kV	1,05 1,13 125 kV
Step 4	1) Test conversion factors	To short-duration power-frequency To lightning impulse				0,5 1,10	0,6 1,06	0,5 1,10	0,6 1,06		
Standard withstand voltages	2) Resulting required withstand voltages	Short duration power-frequency Lightning impulse				34 kV 75 kV	42 kV 74 kV	50 kV 109 kV	61 kV 108 kV		
Step 5	Selection of standard withstand voltages	Short-duration power-frequency 50 KV								Lightning impulse 125 kV	

Type of overvoltage		Temporary				Slow-front				Fast-front	
		Phase-to-earth (PE)		Phase-to-phase (PP)		PE		PP		PE and PP	
Insulation		Internal	External	Internal	External	Internal	External	Internal	External	Internal	External
Step 1	Urp	24	24	28	28	59	59	86	86	-	-
Step 2	Kc or Kcd	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	-	-
	Ucw	24	24	28	28	59	59	86	86	95	105
Step 3	Ks	1.15	1.05	1.15	1.05	1.15	1.05	1.15	1.05	1.15	1.05
	Ka	-	1.13	-	1.13	-	1.13	-	1.13	-	1.13
	Urw	28	28	32	33	68	70	99	102	109	125
Step 4	Conversion factors (for slow front)	To short-duration power-frequency				0.5	0.6	0.5	0.6		
		To lightning impulse				1.10	1.06	1.10	1.06		
	Urw	Short duration power-frequency				34	42	50	61		
		Lightning impulse				75	74	109	108		
Step 5	Standard withstand values	SDW : 50 kV								LIW: 125 kV	

Earth faults

Type of overvoltage		Temporary				*Slow-front*				Fast-front	
		PE		PP		*PE*		*PP*		PE and PP	
	Insulation	Int	Ext	Int	Ext	*Int*	*Ext*	*Int*	*Ext*	Int	Ext
Step 1	**Urp**	**24**	**24**	**28**	**28**	***59***	***59***	***86***	***86***	-	-
Step 2	Kc or Kcd	1.0	1.0	1.0	1.0	*1.0*	*1.0*	*1.0*	*1.0*	-	-
	Ucw	**24**	**24**	**28**	**28**	***59***	***59***	***86***	***86***	**95**	**105**
Step 3	Ks	1.15	1.05	1.15	1.05	*1.15*	*1.05*	*1.15*	*1.05*	1.15	1.05
	Ka	-	1.13	-	1.13	-	*1.13*	-	*1.13*	-	1.13
	Urw	**28**	**28**	**32**	**33**	***68***	***70***	***99***	***102***	**109**	**125**
Step 4	*Conversion factors (for **slow front**)*	*To short-duration power-frequency*				***0.5***	***0.6***	***0.6***	***0.6***		
		To lightning impulse				***1.10***	***1.06***	***1.10***	***1.06***		
	Urw	*Short duration power-frequency*				**34**	**42**	**50**	**61**		
		Lightning impulse				**75**	**74**	**109**	**108**		
Step 5	Standard withstand values	**SDW : 50**								**LIW: 125**	

Step 1: determination of the **representative overvoltages** – $\mathbf{U_{rp}}$

1. **Power-frequency** and **temporary overvoltages**

Possible overvoltages: **earth faults, load rejections**

- Owing to the isolated **neutral earthing practice (ie not solidly grounded)**, the highest **overvoltages phase-to-earth** originate from **earth faults**.

  Values up to the **highest system voltage** are frequent.

  In this example the representative temporary overvoltage is the assumed maximum value equal to the highest system voltage 24kV.

Load rejection (x1.15)

Type of overvoltage		Temporary				Slow-front				Fast-front	
		PE		PP		*PE*		*PP*		PE and PP	
	Insulation	Int	Ext	Int	Ext	*Int*	*Ext*	*Int*	*Ext*	Int	Ext
Step 1	Urp	24	24	28	28	*59*	*59*	*86*	*86*	-	-
Step 2	Kc or Kcd	1.0	1.0	1.0	1.0	*1.0*	*1.0*	*1.0*	*1.0*	-	-
	Ucw	24	24	28	28	*59*	*59*	*86*	*86*	95	105
Step 3	Ks	1.15	1.05	1.15	1.05	*1.15*	*1.05*	*1.15*	*1.05*	1.15	1.05
	Ka	-	1.13	-	1.13	-	*1.13*	-	*1.13*	-	1.13
	Urw	28	28	32	33	*68*	*70*	*99*	*102*	109	125
Step 4	*Conversion factors (for **slow front**)*	*To short-duration power-frequency*				*0.5*	*0.6*	*0.6*	*0.6*		
		To lightning impulse				*1.10*	*1.06*	*1.10*	*1.06*		
	Urw	*Short duration power-frequency*				34	42	50	61		
		Lightning impulse				75	74	109	108		
Step 5	Standard withstand values	SDW : 50								LIW: 125	

- Overvoltages phase-to-phase originate from **load rejections**.

  A full load rejection in the distribution system itself does not cause substantial high overvoltages.

  However, a load rejection in the transmission system, to which the distribution system is connected, may have to be considered.

  It is assumed that the **load rejection temporary overvoltage** reaches **1.15 times the highest system voltage**, which is

  $1.15 \times U_s = 27.6\text{kV}$ or approximately 28kV.

- Earth faults = 24kV, Load rejection = 28 kV

Thus the highest possible voltage stress and hence is the **representative temporary phase-to-phase** overvoltage:

$$\mathbf{U_{rp} = 28kV}$$

Switching 3pu

Switching 4.4pu

Type of overvoltage		Temporary				*Slow-front*				Fast-front	
		PE		PP		*PE*		*PP*		PE and PP	
	Insulation	Int	Ext	Int	Ext	*Int*	*Ext*	*Int*	*Ext*	Int	Ext
Step 1	**Urp**	**24**	**24**	**28**	**28**	***59***	***59***	***86***	***86***	-	-
Step 2	Kc or Kcd	1.0	1.0	1.0	1.0	*1.0*	*1.0*	*1.0*	*1.0*	-	-
	Ucw	**24**	**24**	**28**	**28**	***59***	***59***	***86***	***86***	**95**	**105**
Step 3	Ks	1.15	1.05	1.15	1.05	*1.25*	*1.05*	*1.15*	*1.05*	1.15	1.05
	Ka	-	1.13	-	1.13	-	*1.13*	-	*1.13*	-	1.13
	Urw	**28**	**28**	**32**	**33**	***68***	***70***	***99***	***102***	**109**	**125**
Step 4	*Conversion factors (for **slow front**)*	*To short-duration power-frequency*				***0.5***	***0.6***	***0.6***	***0.6***		
		To lightning impulse				***1.10***	***1.06***	***1.10***	***1.06***		
	Urw	*Short duration power-frequency*				**34**	**42**	**50**	**61**		
		Lightning impulse				**75**	**74**	**109**	**108**		
Step 5	Standard withstand values	**SDW : 50**								**LIW: 125**	

U_{rp} (according to type)

2. Slow-front overvoltages

- Overvoltages may originate from **earth faults** or **line energization** or **re-energization**.

  As distribution transformers usually remain connected, during a re-energization of lines, and as the reclosing is not fast, the presence of trapped charges is improbable.

- The re-energization overvoltages, therefore, have the same probability distribution as those due to energization.

- The **2% values in Table H.3** are selected according to **annex D** for the **phase-peak method** taking into account the **usual operation conditions**, **no closing resistors**, **complex feeding network** and **no parallel compensation** (60071-2)

The 2% values are assumed to be

$$\mathbf{U_{e2} = 2.6\ p.u.}\ \text{(phase-to-earth)}$$

and

$$\mathbf{U_{p2} = 3.86\ p.u}\ \text{(phase-to-phase)}$$

As the deterministic insulation co-ordination procedure is sufficient for distribution systems and as surge arresters do not usually limit slow-front overvoltages in this voltage range, the representative slow-front overvoltages U_{rp} are considered to correspond to the **truncation values** U_{et} and U_{pt} of the overvoltage probability distributions.

With the **formulae of annex D** the **truncation values** are obtained:

$$\mathbf{U_{et} = 3.0\ p.u.}$$

which leads to

$$U_{rp} = 59kV \text{ phase-to-earth}$$

and

$$\mathbf{U_{pt} = 4.4\ p.u.}$$

which leads to

$$U_{pt} = 86kV \text{ phase-to-phase.}$$

NA

Type of overvoltage		Temporary				*Slow-front*				Fast-front	
		PE		PP		*PE*		*PP*		PE and PP	
	Insulation	Int	Ext	Int	Ext	*Int*	*Ext*	*Int*	*Ext*	Int	Ext
Step 1	**Urp**	**24**	**24**	**28**	**28**	***59***	***59***	***86***	***86***	-	-
Step 2	Kc or Kcd	1.0	1.0	1.0	1.0	*1.0*	*1.0*	*1.0*	*1.0*	-	-
	Ucw	**24**	**24**	**28**	**28**	***59***	***59***	***86***	***86***	**95**	**105**
Step 3	Ks	1.15	1.05	1.15	1.05	*1.25*	*1.05*	*1.15*	*1.05*	1.15	1.05
	Ka	-	1.13	-	1.13	*-*	*1.13*	*-*	*1.13*	-	1.13
	Urw	**28**	**28**	**32**	**33**	***68***	***70***	***99***	***102***	**109**	**125**
Step 4	*Conversion factors (for **slow front**)*	*To short-duration power-frequency*				***0.5***	***0.6***	***0.6***	***0.6***		
		To lightning impulse				***1.10***	***1.06***	***1.10***	***1.06***		
	Urw	*Short duration power-frequency*				**34**	**42**	**50**	**61**		
		Lightning impulse				**75**	**74**	**109**	**108**		
Step 5	Standard withstand values	**SDW : 50**								**LIW: 125**	

3. Fast-front overvoltages

- With the exception of motor switching by some type of circuit-breakers, fast-front overvoltages due to switching operations can be **neglected**.

- Fast-front lightning overvoltages are transmitted on the lines connected to the substation.

  The **<u>simplified method</u>** **(**described in **F.4**) is applied to estimate the return periods of the representative lightning overvoltage amplitudes.

No reference value is specified and, therefore, no value can be given in Table H.3.

Kc, Kcd

	Type of overvoltage	Temporary				*Slow-front*				Fast-front	
		PE		PP		*PE*		*PP*		PE and PP	
	Insulation	Int	Ext	Int	Ext	*Int*	*Ext*	*Int*	*Ext*	Int	Ext
Step 1	Urp	24	24	28	28	*59*	*59*	*86*	*86*	-	-
Step 2	Kc or Kcd	1.0	1.0	1.0	1.0	*1.0*	*1.0*	*1.0*	*1.0*	-	-
	Ucw	24	24	28	28	*59*	*59*	*86*	*86*	95	105
Step 3	Ks	1.15	1.05	1.15	1.05	*1.25*	*1.05*	*1.15*	*1.05*	1.15	1.05
	Ka	-	1.13	-	1.13	-	*1.13*	-	*1.13*	-	1.13
	Urw	28	28	32	33	*68*	*70*	*99*	*102*	109	125
Step 4	*Conversion factors (for **slow front**)*	*To short-duration power-frequency*				*0.5*	*0.6*	*0.6*	*0.6*		
		To lightning impulse				*1.10*	*1.06*	*1.10*	*1.06*		
	Urw	*Short duration power-frequency*				34	42	50	61		
		Lightning impulse				75	74	109	108		
Step 5	Standard withstand values	SDW : 50								LIW: 125	

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Step 2

Determination of the **co-ordination withstand voltages U_{cw}**

1. Temporary overvoltages

- The deterministic insulation coordination procedure is applicable
- The deterministic coordination factor is Kc = 1

$$U_{cw} = K_c U_{rp} = U_{rp}$$

x Kcd

Type of overvoltage		Temporary				*Slow-front*				Fast-front	
		PE		[illegible]		*PE*		*PP*		PE and PP	
	Insulation	Int	Ext	Int	Ext	*Int*	*Ext*	*Int*	*Ext*	Int	Ext
Step 1	**Urp**	**24**	**24**	**28**	**28**	***59***	***59***	***86***	***86***	-	-
Step 2	Kc or Kcd	1.0	1.0	1.0	1.0	*1.0*	*1.0*	*1.0*	*1.0*	-	-
	Ucw	**24**	**24**	**28**	**28**	***59***	***59***	***86***	***86***	**95**	**105**
Step 3	Ks	1.15	1.05	1.15	1.05	*1.25*	*1.05*	*1.15*	*1.05*	1.15	1.05
	Ka	-	1.13	-	1.13	-	*1.13*	-	*1.13*	-	1.13
	Urw	**28**	**28**	**32**	**33**	***68***	***70***	***99***	***102***	**109**	**125**
Step 4	*Conversion factors (for **slow front**)*	*To short-duration power-frequency*				***0.5***	***0.6***	***0.6***	***0.6***		
		To lightning impulse				***1.10***	***1.06***	***1.10***	***1.06***		
	Urw	*Short duration power-frequency*				**34**	**42**	**50**	**61**		
		Lightning impulse				**75**	**74**	**109**	**108**		
Step 5	Standard withstand values	**SDW : 50**								**LIW: 125**	

ZAM Dec 2020

2. Slow-front overvoltages

The co-ordination withstand voltages Ucw are obtained as:
Ucw = Kcd Urp

The deterministic co-ordination factor is Kcd = 1 because the insulation co-ordination procedure is applied to the truncation values of the overvoltage distributions

Values of the co-ordination withstand voltages are the same as those for representative slow-front overvoltages:

Ucw = 59 kV phase-to-earth

and

Ucw = 86 kV phase-to-phase.

Use simplified method

Use simplified method

	Type of overvoltage	Temporary				Slow-front				Fast-front	
		PE		PP		PE		PP		PE and PP	
	Insulation	Int	Ext	Int	Ext	*Int*	*Ext*	*Int*	*Ext*	Int	Ext
Step 1	**Urp**	24	24	28	28	*59*	*59*	*86*	*86*	-	-
Step 2	Kc or Kcd	1.0	1.0	1.0	1.0	*1.0*	*1.0*	*1.0*	*1.0*	-	-
	Ucw	24	24	28	28	*59*	*59*	*86*	*86*	95	105
Step 3	Ks	1.15	1.05	1.15	1.05	*1.25*	*1.05*	*1.15*	*1.05*	1.15	1.05
	Ka	-	1.13	-	1.13	*-*	*1.13*	*-*	*1.13*	-	1.13
	Urw	28	28	32	33	*68*	*70*	*99*	*102*	109	125
Step 4	*Conversion factors (for **slow front**)*	*To short-duration power-frequency*				*0.5*	*0.6*	*0.6*	*0.6*		
		To lightning impulse				*1.10*	*1.06*	*1.10*	*1.06*		
	Urw	*Short duration power-frequency*				34	42	50	61		
		Lightning impulse				75	74	109	108		
Step 5	Standard withstand values	SDW : 50								LIW: 125	

Lightning overvoltages - Simplified method

Data needed:

Upl = protection level by arrester

A, n = from line number and configuration (use table F.2)

L = arrester separation distances ($L = a_1 + a_2 + a_3 + a_4$) (eg. Fig. 3)

Lsp = span length (m)

La = overhead line section with outage rate equal to acceptable failure rate

La = Ra/Rkm

Ra = acceptable failure rate is (eg Ra = 1/400 year)

Rkm = overhead line outage rate per year for a design corresponding to the first kilometre in front of the station

(eg. Rkm = 6×10^{-5}/(m.year))

Lightning overvoltages - Simplified method

Table F.2 — Factor *A* for various overhead lines
[applicable, in equations (F.17) and (F.19)]

Type of line	***A*** (kV)
Distribution lines (phase-phase flashovers):	
— with earthed crossarms (flashover to earth at low voltage)	900
— wood-pole lines (flashover to earth at high voltage)	2 700
Transmission lines (single-phase flashover to earth)	
— single conductor	4 500
— double conductor bundle	7 000
— four conductor bundle	11 000
— six and eight conductor bundle	17 000

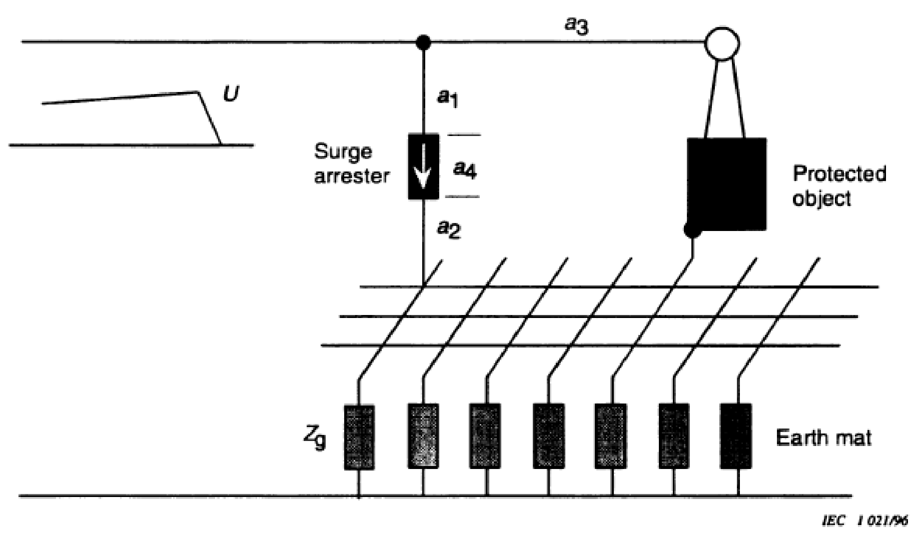
Lightning overvoltages - Simplified method

$T = L/c$ (3)

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

$L = a_1 + a_2 + a_3 + a_4$:

distances from Figure 3 (m).



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

Lightning overvoltages - Simplified method

Then, the co-ordination lightning impulse withstand voltage is equal to

$$U_{cw} = U_{pl} + \frac{A}{n}\frac{L}{L_{sp} + L_a}$$

Lightning overvoltages – Introductory Remarks

- For substations or parts of a substation to which no surge arrester is connected, the most important parameter is the amplitude of the impinging overvoltage

- For substations protected by surge arresters, it is its steepness and the separation distance between surge arrester and the equipment under consideration

- The steepness of an impinging overvoltage surge is reduced mainly by corona damping effects on the overhead line

Lightning overvoltages – Introductory Remarks

- The steepness of an impinging overvoltage surge is reduced mainly by corona damping effects on the overhead line

- The knowledge of this limit distance is of primary importance

Lightning overvoltages – Introductory Remarks

Determination of the limit distance (Xp)

<u>Protection with arresters in the substation</u>

- When more than one overhead line is connected to the substation, the original steepness (S) of the impinging surge can be divided by the number of lines (n).
- However, it is emphasized that the number of lines should correspond to the minimum number which reasonably remain in service taking into account possible outages during lightning storms.
- Allowing for the fact that the steepness of the impinging surge reduces inversely with the travel distance on the overhead line, the steepness S of the impinging surge to be used in equation (1) is approximately equal to:

Lightning overvoltages - Simplified method

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

where n is the number of overhead lines connected to the substation; if multi-circuit towers are involved and double-system back flashovers have to be taken into account, it is recommended to divide the number by two;

K_{co} is the corona damping constant according to Table F.1 [μs/(kV.m)];

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

Lightning overvoltages - Simplified method

Table F.1 — Corona damping constant K_{co}

Conductor configuration	K_{co} [µs/(kV.m)]
Single conductor	$1{,}5 \times 10^{-6}$
Double conductor bundle	$1{,}0 \times 10^{-6}$
Three or four conductor bundle	$0{,}6 \times 10^{-6}$
Six or eight conductor bundle	$0{,}4 \times 10^{-6}$

Lightning overvoltages - Simplified method

Hence

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

where

U is the lowest considered overvoltage amplitude;

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

Upl is the lightning impulse protective level of the arrester.

Lightning overvoltages – Introductory Remarks

Determination of the limit distance (Xp)

Protection with arresters in the substation

- When more than one overhead line is connected to the substation, the original steepness (S) of the impinging surge can be divided by the number of lines (n).
- However, it is emphasized that the number of lines should correspond to the minimum number which reasonably remain in service taking into account possible outages during lightning storms.
- Allowing for the fact that the steepness of the impinging surge reduces inversely with the travel distance on the overhead line, the steepness S of the impinging surge to be used in equation (1) is approximately equal to:

Lightning overvoltages – Introductory Remarks

Determination of the limit distance (Xp)

Self-protection of substation

- Not protected by arresters

Lightning overvoltages – Introductory Remarks

Estimation of the representative lightning overvoltage amplitude

- As the full travelling wave calculation including the simulation of the overhead line performance is extremely difficult, a simplified procedure has been proposed

- This procedure consists in calculating a lightning current with the desired return rate and calculating the overvoltage by travelling wave calculations in the substation including a short-line section equivalent circuit.

Lightning overvoltages – Introductory Remarks

Shielding penetration

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

Back flashovers

- The lightning current determining the design impinging surge is determined from the number of flashes to the overhead line tower and earth-wires within the limit distance and its probability to be exceeded is:

Lightning overvoltages - Simplified method

- A further simplification to the procedures described in **F.2 and F.3** is to apply the basic principles given there, but to adopt the following assumptions:-

  a. all lightning events within a certain distance from the substation cause higher overvoltages at the protected equipment than an assumed value, and all events outside this distance lower values;

  b. the overvoltage at the equipment can be calculated according to equation **(1) and equation (F.1).**

As mentioned already both assumptions are not strictly valid.

Lightning overvoltages - Simplified method

- Firstly, not all events within a certain distance are equally severe.

- They depend on the lightning current or on the amplitude of the impinging overvoltage surge.

- Secondly, the overvoltages may be higher than that calculated with equations (1) and (F.1).

- However, current practice of equipment protection by surge arresters has shown that both inaccuracies sufficiently cancel each other

Lightning overvoltages - Simplified method

As regards the distance X to be applied in equation (F.1), it has been shown that back flashovers do not occur at a tower close to the substation owing to the substation earth.

The minimum value of X is one overhead line span length.

The representative steepness S_{rp} to be applied in equation (1), therefore, is equal to:

$$S_{rp} = 1/[K_{co}(L_{sp} + L_t)]$$

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

Lightning overvoltages - Simplified method

Thus, introducing S_{rp} in equation (1) and putting $A = 2/(K_{co}\ c)$ for transmission lines, the dependence of the representative lightning overvoltage on the return rate is obtained by:

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

where

- U_{rp} is the representative lightning overvoltage amplitude (kV);
- A is a factor given in Table F.2 describing the lighting performance of the overhead line connected to the station;
- U_{pl} is the lightning impulse protection level of the surge arrester (kV);
- n is the minimum of lines connected to the substation (n=1 or n=2);
- L is the separation distance: $L = a_1 + a_2 + a_3 + a_4$ as shown on Figure 3 (m);
- L_{sp} is the span length (m);
- L_t is the overhead line length with outage rate equal to adopted return rate (m);
- R_t is the adopted overvoltage return rate (1/year);
- R_{km} is the overhead line outage rate per year for a design corresponding to the first kilometre in front of the station [see equation (F.16)] [usual unit: 1/(100 km.year); recommended unit: 1/(m.year)].

Lightning overvoltages - Simplified method

The co-ordination withstand voltage is obtained by replacing L_t by the line length L_a which yields an outage rate equal to the acceptable failure rate R_a:

$$L_a = R_a / R_{km} \tag{F.18}$$

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

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

where

U_{cw} is the co-ordination lightning impulse withstand voltage;

L_a is the overhead line section with outage rate equal to acceptable failure rate;

R_a is the acceptable failure rate for equipment.

Lightning overvoltages - Simplified method

For transmission lines, the factors A are obtained from Table F.2 and the corona damping constants K_{co} from Table F.1. For distribution systems, lightning overvoltages are usually multiphase and current sharing of the phase conductors has to be considered. For steel towers the flashovers of more than one tower during a lightning stroke lead to a further reduction of the lightning overvoltages. For these lines the factor A has been matched with the service practice.

GIS are, in general, better protected than open-air substations owing to a surge impedance much lower than that of the overhead lines. A generally valid recommendation for the estimation of the amelioration obtained for GIS as compared to open-air substations cannot be made. However, the use of the equation (F.19) for the open-air substation results in conservative estimates of the co-ordination lightning impulse withstand voltage or of the protective range and a reduction of the ratio A/n to half the value used for outdoor stations is still suitable.

Lightning overvoltages - Simplified method

The co-ordination lightning impulse withstand voltage is equal to

$$U_{cw} = U_{pl} + \frac{A}{n}\frac{L}{L_{sp} + L_a}$$

Table F.2 — Factor *A* for various overhead lines
[applicable, in equations (F.17) and (F.19)]

Type of line	*A* (kV)
Distribution lines (phase-phase flashovers):	
— with earthed crossarms (flashover to earth at low voltage)	900
— wood-pole lines (flashover to earth at high voltage)	2 700
Transmission lines (single-phase flashover to earth)	
— single conductor	4 500
— double conductor bundle	7 000
— four conductor bundle	11 000
— six and eight conductor bundle	17 000

Lightning overvoltages - Simplified method

- 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

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

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

where

Upl is the lightning impulse protective level of the arrester (kV);

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

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

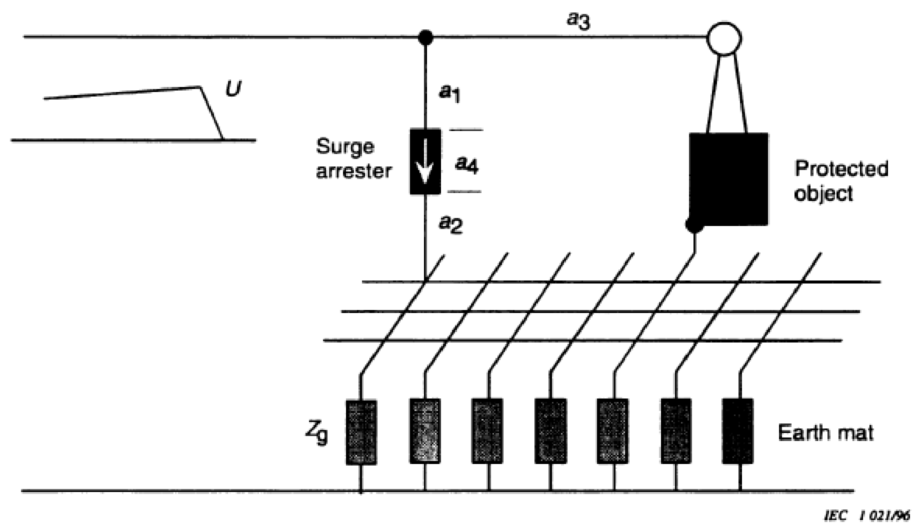
Lightning overvoltages - Simplified method

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

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

$$L = a_1 + a_2 + a_3 + a_4 :$$

distances from Figure 3 (m).



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

Step 2 (cont.)
2. Fast-front overvoltages

For the determination of the co-ordination lightning impulse withstand voltages, the following values are assumed:

— the arrester lightning impulse protection level is Upl = 80 kV;

— four wood-pole lines (n = 4) are connected to the station.

Referring to Table F.2, the corresponding value for the factor A is

2700

— the observed overhead line outage rate is Rkm = 6/(100 km.year) or in the recommended units

$$Rkm = 6 \times 10^{-5}/(\text{m.year});$$

— the span length is **Lsp = 100 m**;
— the acceptable failure rate is Ra = 1/400 year.

2. Fast-front overvoltages

- As it is common practice to install arresters close to the power transformers, the separation distance may be different for **internal** insulation (example: **3 m**) and **external** insulation (example: **5 m**).

- Therefore, the co-ordination withstand voltages values Ucw may be different for different equipment.

- With these values the overhead line section, in which the outage rate will be equal to the acceptable failure rate, will be in accordance with equation (F.18):

La = 42 m

2. Fast-front overvoltages

- This means that protection is required for lightning strokes to the first span of the overhead line.

- The co-ordination lightning impulse withstand voltages are obtained according to equation (F.19) as

Ucw = 95 kV

for internal insulation (power transformer, distance to the arrester = 3 m)

and

Ucw = 105 kV

for the more distant external insulation.

Lightning overvoltages - Simplified method

Data needed:

Upl = protection level by arrester

A, n = from line number and configuration (use table F.2)

L = arrester separation distances ($L = a_1 + a_2 + a_3 + a_4$) (eg. Fig. 3)

Lsp = span length (m)

La = overhead line section with outage rate equal to acceptable failure rate

La = Ra/Rkm

Ra = acceptable failure rate is (eg Ra = 1/400 year)

Rkm = overhead line outage rate per year for a design corresponding to the first kilometre in front of the station (eg. Rkm = 6×10^{-5}/(m.year))

Lightning overvoltages - Simplified method

Table F.2 — Factor *A* for various overhead lines
[applicable, in equations (F.17) and (F.19)]

Type of line	***A*** (kV)
Distribution lines (phase-phase flashovers):	
— with earthed crossarms (flashover to earth at low voltage)	900
— wood-pole lines (flashover to earth at high voltage)	2 700
Transmission lines (single-phase flashover to earth)	
— single conductor	4 500
— double conductor bundle	7 000
— four conductor bundle	11 000
— six and eight conductor bundle	17 000

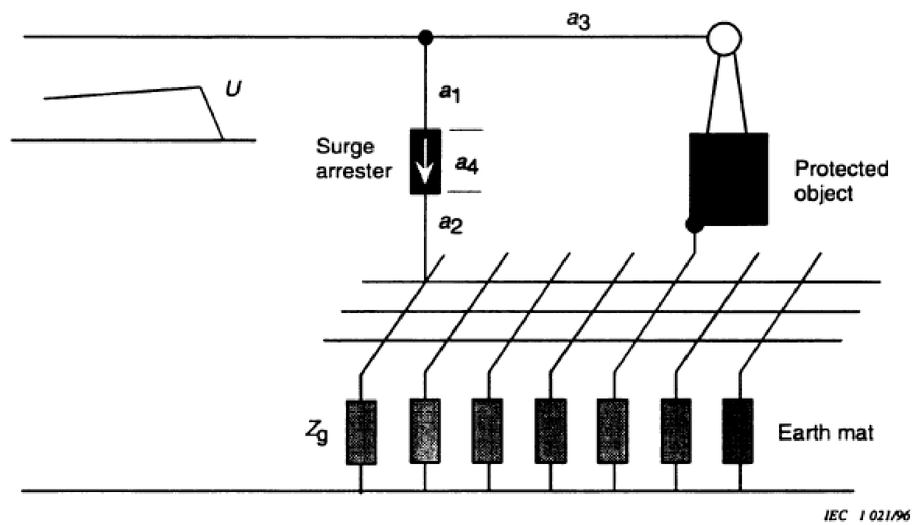
Lightning overvoltages - Simplified method

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

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

$$L = a_1 + a_2 + a_3 + a_4:$$

distances from Figure 3 (m).



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

Lightning overvoltages - Simplified method

Then, the co-ordination lightning impulse withstand voltage is equal to

$$U_{cw} = U_{pl} + \frac{A}{n}\frac{L}{L_{sp} + L_a}$$

Use formula

Use formula

Type of overvoltage		Temporary				Slow-front				Fast-front	
		PE		PP		PE		PP		PE and PP	
	Insulation	Int	Ext	Int	Ext	*Int*	*Ext*	*Int*	*Ext*	Int	Ext
Step 1	**Urp**	**24**	**24**	**28**	**28**	***59***	***59***	***86***	***86***	-	-
Step 2	Kc or Kcd	1.0	1.0	1.0	1.0	*1.0*	*1.0*	*1.0*	*1.0*	-	-
	Ucw	**24**	**24**	**28**	**28**	***59***	***59***	***86***	***86***	**95**	**105**
Step 3	Ks	1.15	1.05	1.15	1.05	*1.25*	*1.05*	*1.15*	*1.05*	1.15	1.05
	Ka	-	1.13	-	1.13	-	*1.13*	-	*1.13*	-	1.13
	Urw	**28**	**28**	**32**	**33**	***68***	***70***	***99***	***102***	**109**	**125**
Step 4	*Conversion factors (for **slow front**)*	*To short-duration power-frequency*				***0.5***	***0.6***	***0.6***	***0.6***		
		To lightning impulse				***1.10***	***1.06***	***1.10***	***1.06***		
	Urw	*Short duration power-frequency*				**34**	**42**	**50**	**61**		
		Lightning impulse				**75**	**74**	**109**	**108**		
Step 5	Standard withstand values	**SDW : 50**								**LIW: 125**	

Ks

Type of overvoltage		Temporary				*Slow-front*				Fast-front	
		PE		PP		*PE*		*PP*		PE and PP	
	Insulation	Int	Ext	Int	Ext	*Int*	*Ext*	*Int*	*Ext*	Int	Ext
Step 1	**Urp**	**24**	**24**	**28**	**28**	***59***	***59***	***86***	***86***	-	-
Step 2	Kc or Kcd	1.0	1.0	1.0	1.0	*1.0*	*1.0*	*1.0*	*1.0*	-	-
	Ucw	**24**	**24**	**28**	**28**	***59***	***59***	***86***	***86***	**95**	**105**
Step 3	Ks	1.15	1.05	1.15	1.05	*1.15*	*1.05*	*1.15*	*1.05*	1.15	1.05
	Ka	-	1.13	-	1.13	*-*	*1.13*	*-*	*1.13*	-	1.13
	Urw	**28**	**28**	**32**	**33**	***68***	***70***	***99***	***102***	**109**	**125**
Step 4	*Conversion factors (for **slow front**)*	*To short-duration power-frequency*				***0.5***	***0.6***	***0.6***	***0.6***		
		To lightning impulse				***1.10***	***1.06***	***1.10***	***1.06***		
	Urw	*Short duration power-frequency*				**34**	**42**	**50**	**61**		
		Lightning impulse				**75**	**74**	**109**	**108**		
Step 5	Standard withstand values	**SDW : 50**								**LIW: 125**	

Step 3 Withstand voltages

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

The required withstand voltages are obtained by applying the recommended safety factors (see **4.3.4**) an
the altitude correction (see **4.2.2**). For the example given, it is assumed that substations of the same desig
shall be used up to altitudes of 1 000 m.

H.3.3.1 *Safety factors*

The recommended safety factors from **4.3.4** are:

— for internal insulation: $K_s = 1{,}15$;

— for external insulation: $K_s = 1{,}05$.

H.3.3.2 *Altitude correction factor*

The altitude correction factor is defined in **4.2.2**. It is applicable to the external insulation only and its valu
depends on the overvoltage shape [parameter m in equation (11)].

— For power-frequency (clean insulators), $m = 1{,}0$.

— For slow-front overvoltages, the value of m depends on the value of U_{cw}. For values of U_{cw} less than 300 kV phase-to-earth or 1 200 kV phase-to-phase, $m = 1{,}0$.

— For lightning impulse withstand, $m = 1{,}0$ and $K_a = 1{,}13$.

H.3.3.3 *Temporary overvoltage*

— Phase-to-earth:

- internal insulation $\Rightarrow$ $U_{rw} = U_{cw} \times 1{,}15 = 24 \times 1{,}15 = 28$ kV;
- external insulation $\Rightarrow$ $U_{rw} = U_{cw} \times 1{,}05 \times 1{,}13 = 24 \times 1{,}05 \times 1{,}13 = 28$ kV.

— Phase-to-phase:

- internal insulation $\Rightarrow$ $U_{rw} = U_{cw} \times 1{,}15 = 28 \times 1{,}15 = 32$ kV;
- external insulation $\Rightarrow$ $U_{rw} = U_{cw} \times 1{,}05 \times 1{,}13 = 28 \times 1{,}05 \times 1{,}13 = 33$ kV.

Step 3 Withstand voltages

Slow-front

H.3.3.4 *Slow-front overvoltage*

— Phase-to-earth:

- internal insulation $\Rightarrow$ $U_{rw} = U_{cw} \times 1,15 = 59 \times 1,15 = 68$ kV;
- external insulation $\Rightarrow$ $U_{rw} = U_{cw} \times 1,05 \times 1,13 = 59 \times 1,05 \times 1,13 = 70$ kV.

— Phase-to-phase:

- internal insulation $\Rightarrow$ $U_{rw} = U_{cw} \times 1,15 = 86 \times 1,15 = 99$ kV;
- external insulation $\Rightarrow$ $U_{rw} = U_{cw} \times 1,05 \times 1,13 = 86 \times 1,05 \times 1,13 = 102$ kV.

H.3.3.5 *Fast-front overvoltage*

— internal insulation: $\Rightarrow$ $U_{rw} = U_{cw} \times 1,15 = 95 \times 1,15 = 109$ kV;

— external insulation: $\Rightarrow$ $U_{rw} = U_{cw} \times 1,05 \times 1,13 = 95 \times 1,05 \times 1,13 = 125$ kV.

Step 3 Withstand voltages

Fast-front

Step 4 Conversion to SDW

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

For the selection of the standard withstand voltages in Table 2 of IEC 71-1, the required switching impulse withstand voltages are converted into short-duration power-frequency withstand voltages and into lightning impulse withstand voltages by applying the test conversion factors of Table 2 (for internal insulation, factors corresponding to liquid-immersed insulation are selected).

H.3.4.1 *Conversion to short-duration power-frequency withstand voltage (SDW)*

— Phase-to-earth:

- internal insulation $\Rightarrow$ $\mathrm{SDW} = U_{\mathrm{rw}} \times 0{,}5 = 68 \times 0{,}5 = 34$ kV;
- external insulation $\Rightarrow$ $\mathrm{SDW} = U_{\mathrm{rw}} \times 0{,}6 = 70 \times 0{,}6 = 42$ kV.

— Phase-to-phase:

- internal insulation $\Rightarrow$ $\mathrm{SDW} = U_{\mathrm{rw}} \times 0{,}5 = 99 \times 0{,}5 = 50$ kV;
- external insulation $\Rightarrow$ $\mathrm{SDW} = U_{\mathrm{rw}} \times 0{,}6 = 102 \times 0{,}6 = 61$ kV.

Ka

Type of overvoltage		Temporary				Slow-front				Fast-front	
		PE		PP		*PE*		*PP*		PE and PP	
	Insulation	Int	Ext	Int	Ext	*Int*	*Ext*	*Int*	*Ext*	Int	Ext
Step 1	**Urp**	**24**	**24**	**28**	[illegible]	***59***	***59***	***86***	***86***	-	-
Step 2	Kc or Kcd	1.0	1.0	1.0	1.0	*1.0*	*1.0*	*1.0*	*1.0*	-	-
	Ucw	**24**	**24**	[illegible]	**28**	***59***	***59***	***86***	***86***	**95**	**105**
Step 3	Ks	1.15	1.05	1.15	1.05	*1.25*	*1.05*	*1.15*	*1.05*	1.15	1.05
	Ka	-	1.13	-	1.13	-	*1.13*	-	*1.13*	-	1.13
	Urw	**28**	**28**	**32**	**33**	***68***	***70***	***99***	***102***	**109**	**125**
Step 4	*Conversion factors (for* ***slow front****)*	*To short-duration power-frequency*				***0.5***	***0.6***	***0.6***	***0.6***		
		To lightning impulse				***1.10***	***1.06***	***1.10***	***1.06***		
	Urw	*Short duration power-frequency*				**34**	**42**	**50**	**61**		
		Lightning impulse				**75**	**74**	**109**	**108**		
Step 5	Standard withstand values	**SDW : 50**								**LIW: 125**	

x Ks.Ka

Type of overvoltage		Temporary				*Slow-front*				Fast-front	
		PE		PP		*PE*		*PP*		PE and PP	
	Insulation	Int	Ext	Int	Ext	*Int*	*Ext*	*Int*	*Ext*	Int	Ext
Step 1	**Urp**	**24**	**24**	**2**[illegible]	**28**	***59***	***59***	***86***	***86***	-	-
Step 2	Kc or Kcd	1.0	1.0	[illegible].0	1.0	*1.0*	*1.0*	*1.0*	*1.0*	-	-
	Ucw	**24**	**24**	**28**	**28**	***59***	***59***	***86***	***86***	**95**	**105**
Step 3	Ks	1.15	1.[illegible]	1.15	1.05	*1.25*	*1.05*	*1.15*	*1.05*	1.15	1.05
	Ka	-	1.13	-	1.13	*-*	*1.13*	*-*	*1.13*	-	1.13
	Urw	**28**	**28**	**32**	**33**	***68***	***70***	***99***	***102***	**109**	**125**
Step 4	*Conversion factors (for **slow front**)*	*To short-duration power-frequency*				***0.5***	***0.6***	***0.6***	***0.6***		
		To lightning impulse				***1.10***	***1.06***	***1.10***	***1.06***		
	Urw	*Short duration power-frequency*				**34**	**42**	**50**	**61**		
		Lightning impulse				**75**	**74**	**109**	**108**		
Step 5	Standard withstand values	**SDW : 50**								**LIW: 125**	

To SDW

Type of overvoltage		Tempora[illegible]				*Slow-front*				Fast-front	
		PE		[illegible]		*PE*		*PP*		PE and PP	
	Insulation	Int	Ext	Int	Ext	*Int*	*Ext*	*Int*	*Ext*	Int	Ext
Step 1	**Urp**	**24**	**24**	**28**	**[illegible]8**	***59***	***59***	***86***	***86***	-	-
Step 2	Kc or Kcd	1.0	1.0	1.0	[illegible]	*1.0*	*1.0*	*1.0*	*1.0*	-	-
	Ucw	**24**	**24**	**28**	[illegible]	***59***	***59***	***86***	***86***	**95**	**105**
Step 3	Ks	1.15	1.05	1.15	1.0[illegible]	*1.25*	*1.05*	*1.15*	*1.05*	1.15	1.05
	Ka	-	1.13	-	1.13	*-*	*1.13*	*-*	*1.13*	-	1.13
	Urw	**28**	**28**	**32**	**33**	***68***	***70***	***99***	***102***	**109**	**125**
Step 4	*Conversion factors (for* ***slow front****)*	*To short-duration power-frequency*				***0.5***	***0.6***	***0.6***	***0.6***		
		To lightning impulse				***1.10***	***1.06***	***1.10***	***1.06***		
	Urw	*Short duration power-frequency*				**34**	**42**	**50**	**61**		
		Lightning impulse				**75**	**74**	**109**	**108**		
Step 5	Standard withstand values	**SDW : 50**								**LIW: 125**	

Step 4 Conversion to LIW

H.3.4.2 *Conversion to lightning impulse withstand voltage (LIW)*

— Phase-to-earth:

- internal insulation $\Rightarrow$ $\text{LIW} = U_{\text{rw}} \times 1{,}10 = 68 \times 1{,}1 = 75$ kV;
- external insulation $\Rightarrow$ $\text{LIW} = U_{\text{rw}} \times 1{,}06 = 70 \times 1{,}06 = 74$ kV.

— Phase-to-phase:

- internal insulation $\Rightarrow$ $\text{LIW} = U_{\text{rw}} \times 1{,}10 = 99 \times 1{,}1 = 109$ kV;
- external insulation $\Rightarrow$ $\text{LIW} = U_{\text{rw}} \times 1{,}06 = 102 \times 1{,}06 = 108$ kV.

To LIW

Type of overvoltage		Tempor[illegible]				*Slow-front*				Fast-front	
		PE		[illegible]		*PE*		*PP*		PE and PP	
	Insulation	Int	Ext	Int	Ext	*Int*	*Ext*	*Int*	*Ext*	Int	Ext
Step 1	**Urp**	**24**	**24**	**28**	**28**	***59***	***59***	***86***	***86***	-	-
Step 2	Kc or Kcd	1.0	1.0	1.0	[illegible]	*1.0*	*1.0*	*1.0*	*1.0*	-	-
	Ucw	**24**	**24**	**28**	[illegible]	***59***	***59***	***86***	***86***	**95**	**105**
Step 3	Ks	1.15	1.05	1.15	[illegible]	*1.25*	*1.05*	*1.15*	*1.05*	1.15	1.05
	Ka	-	1.13	-	1.13	-	*1.13*	-	*1.13*	-	1.13
	Urw	**28**	**28**	**32**	**33**	***68***	***70***	***99***	***102***	**109**	**125**
Step 4	*Conversion factors (for **slow front**)*	*To short-duration power-frequency*				***0.5***	***0.6***	***0.6***	***0.6***		
		To lightning impulse				***1.10***	***1.06***	***1.10***	***1.06***		
	Urw	*Short duration power-frequency*				**34**	**42**	**50**	**61**		
		Lightning impulse				**75**	**74**	**109**	**108**		
Step 5	Standard withstand values	**SDW : 50**								**LIW: 125**	

SDW = factor x Usf

Type of overvoltage		Tempor				*Slow-front*				Fast-front	
		PE				*PE*		*PP*		PE and PP	
	Insulation	Int	Ext	Int	Ext	*Int*	*Ext*	*Int*	*Ext*	Int	Ext
Step 1	**Urp**	**24**	**24**	**28**	**28**	***59***	***59***	***86***	***86***	-	-
Step 2	Kc or Kcd	1.0	1.0	1.0	0	*1.0*	*1.0*	*1.0*	*1.0*	-	-
	Ucw	**24**	**24**	**28**	3	***59***	***59***	***86***	***86***	**95**	**105**
Step 3	Ks	1.15	1.05	1.15	1	*1.25*	*1.05*	*1.15*	*1.05*	1.15	1.05
	Ka	-	1.13	-	1.1	*-*	*1.13*	*-*	*1.13*	-	1.13
	Urw	**28**	**28**	**32**	**33**	***68***	***70***	***99***	***102***	**109**	**125**
Step 4	*Conversion factors (for **slow front**)*	*To short-duration power-frequency*				***0.5***	***0.6***	***0.6***	***0.6***		
		To lightning impulse				***1.10***	***1.06***	***1.10***	***1.06***		
	Urw	*Short duration power-frequency*				**34**	**42**	**50**	**61**		
		Lightning impulse				**75**	**74**	**109**	**108**		
Step 5	Standard withstand values	**SDW : 50**								**LIW: 125**	

LIW = factor x Usf

Type of overvoltage		Tempor				*Slow-front*				Fast-front	
		PE				*PE*		*PP*		PE and PP	
	Insulation	Int	Ext	Int	Ext	*Int*	*Ext*	*Int*	*Ext*	Int	Ext
Step 1	**Urp**	**24**	**24**	**28**	**28**	***59***	***59***	***86***	***86***	-	-
Step 2	Kc or Kcd	1.0	1.0	1.0	.0	*1.0*	*1.0*	*1.0*	*1.0*	-	-
	Ucw	**24**	**24**	**28**	**8**	***59***	***59***	***86***	***86***	**95**	**105**
Step 3	Ks	1.15	1.05	1.15	5	*1.25*	*1.05*	*1.15*	*1.05*	1.15	1.05
	Ka	-	1.13	-	1	*-*	*1.13*	*-*	*1.13*	-	1.13
	Urw	**28**	**28**	**32**	**3**	*68*	*70*	*99*	*102*	**109**	**125**
Step 4	*Conversion factors (for **slow front**)*	*To short-duration power-frequency*				***0.5***	***0.6***	***0.6***	***0.6***		
		To lightning impulse				***1.10***	***1.06***	***1.10***	***1.06***		
	Urw	*Short duration power-frequency*				**34**	**42**	**50**	**61**		
		Lightning impulse				**75**	**74**	**109**	**108**		
Step 5	Standard withstand values	**SDW : 50**								**LIW: 125**	

Analyse PF

Analyse LIW

Type of overv		Temporary				Slow				Fast-front	
		PE		PP		*PE*		*PP*		PE and PP	
Insul			Ext	Int	Ext	*Int*	*Ext*	*Int*	*Ext*	Int	Ext
Step 1	**Urp**	**24**	**24**	**28**	**28**	***59***	***59***	***86***	***8[illegible]***	-	-
Step 2	Kc or Kcd	1.0	[illegible]	1.0	1.0	*1.0*	*1.0*	*1.0*	*1.0*	-	-
	Ucw	**24**	**24**	**28**	**28**	***59***	***59***	***86***	***86***	**95**	**105**
Step 3	Ks	1.15	1.05	1.15	1.05	*1.25*	*1.05*	*1.15*	*1.05*	1.15	1.05
	Ka	-	1.13		1.13	-	*1.13*	-	*1.13*	-	1.13
	Urw	**28**	**28**	**32**	**33**	***68***	***70***	***99***	***102***	**109**	**125**
Step 4	*Conversion factors (for **slow front ONLY**)*	*To short-duration power-frequency*				***0.5***	***0.6***	***0.6***	***0.6***		
		To lightning impulse				***1.10***	***1.06***	***1.10***	***1.06***		
	Urw	*Short duration power-frequency*				**34**	**42**	**50**	**61**		
		Lightning impulse				**75**	**74**	**109**	**108**		
Step 5	Standard withstand values	**SDW : 50**								**LIW: 125**	

Step 5 Selection of standard withstand voltages

H.3.5 ***Step 5: selection of standard withstand voltages***

Table 2 of IEC 71-1 gives for $U_m = 24$ kV a standard short-duration power-frequency withstand voltage of 50 kV. This is adequate to cover the requirements for temporary overvoltage and all slow-front overvoltages except the phase-to-phase requirement for external insulation which can be accommodated by adequate air clearances. Table 2 of IEC 71-1 provides three possible values for the standard lightning impulse withstand voltage for $U_m = 24$ kV. Selection of a value of 125 kV covers the lightning impulse requirement as well as the switching impulse withstand voltage for external phase-to-phase insulation.

H.3.6 ***Summary of insulation co-ordination procedure for example H.3***

Table H.3 summarizes values obtained while completing the insulation co-ordination procedure for this example, for a considered maximum operating voltage $U_s = 24$ kV.

Choose SDW

Type of overvoltage		Temporary				*Slow-front*				Fast-front	
		PE		PP		*PE*		*PP*		PE and PP	
	Insulation	Int	Ext	Int	Ex	*Int*	*Ext*	*Int*	*Ext*	Int	Ext
Step 1	**Urp**	**24**	**24**	**28**	**28**	***59***	***59***	***86***	***86***	-	-
Step 2	Kc or Kcd	1.0	1.0	1.0	1.0	*1.0*	*1.0*	*1.0*	*1.0*	-	-
	Ucw	**24**	**24**	**28**	**28**	***59***	***59***	***86***	***86***	**95**	**105**
Step 3	Ks	1.15	1.05	1.15	1.05	*1.25*	*1.05*	*1.15*	*1.05*	1.15	1.05
	Ka	-	1.13	-	1.13	-	*1.13*	-	*1.13*	-	1.13
	Urw	**28**	**28**	**32**	**33**	***68***	***70***	***99***	***102***	**109**	**125**
Step 4	*Conversion factors (for **slow front**)*	*To short-duration power-frequency*				***0.5***	***0.6***	***0.6***	***0.6***		
		To lightning impulse				***1.10***	***1.06***	***1.10***	***1.06***		
	Urw	*Short duration power-frequency*				**34**	**42**	**50**	**61**		
		Lightning impulse				**75**	**74**	**109**	**108**		
Step 5	Standard withstand values	**SDW : 50**								**LIW: 125**	

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Choose LIW

Type of overvoltage		Temporary				*Slow-front*				Fast-front	
		PE		PP		*PE*		*PP*		PE and PP	
	Insulation	Int	Ext	Int	Ext	*Int*	*Ext*	*Int*	*Ext*	Int	Ext
Step 1	**Urp**	**24**	**24**	**28**	**28**	***59***	***59***	***86***	***86***	-	-
Step 2	Kc or Kcd	1.0	1.0	1.0	1.0	*1.0*	*1.0*	*1.0*	*1.0*	-	-
	Ucw	**24**	**24**	**28**	**28**	***59***	***59***	***86***	***86***	**95**	**105**
Step 3	Ks	1.15	1.05	1.15	1.05	*1.25*	*1.05*	*1.15*	*1.05*	1.15	1.05
	Ka	-	1.13	-	1.13	-	*1.13*	-	*1.13*	-	1.13
	Urw	**28**	**28**	**32**	**33**	***68***	***70***	***99***	***102***	**109**	**125**
Step 4	*Conversion factors (for **slow front**)*	*To short-duration power-frequency*				***0.5***	***0.6***	***0.6***	***0.6***		
		To lightning impulse				***1.10***	***1.06***	***1.10***	***1.06***		
	Urw	*Short duration power-frequency*				**34**	**42**	**50**	**61**		
		Lightning impulse				**75**	**74**	**109**	**108**		
Step 5	Standard withstand values	**SDW : 50**								**LIW: 125**	

Example 2

(a) Briefly describe the importance of insulation coordination in a high voltage system.

(5 marks)

(b) A 132 kV substation is to be designed. Determine the insulation withstand voltages (for external insulation and phase-earth voltages only) for the substation. The following information is available:

Type of neutral earthing:	solidly grounded
Altitude, H:	1000 m
Maximum TOV level =	1.5 p.u. rms
U_{et} =	3.0 p.u. peak
K_c =	1.0
U_{pl} =	290 kV peak
n =	4

A =	2700
L_{sp} =	100m
L_a =	42 m
L =	5 m

U_{cw} FFO = $U_{pl} + (A.L)/(n.(L_{sp}+L_a))$

K_s internal =	1.15
K_s external =	1.05
K_a phase-earth =	1.13
SDW =	U_{rw} x 0.6
LIW =	U_{rw} x 1.3

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IEC 60071-1 Data:

U_m (kV)	Standard rated SDW (kV rms)	Standard LIW (kV peak)
145	(185)	(450)
	230	550
	275	650

Annex K
(informative)

Examples of insulation co-ordination procedure in Malaysia

The insulation co-ordination procedure includes determining the voltage stresses from all origins on equipment and the corresponding electric strength required based on acceptable margins of protection or acceptable levels of performance. These margins (or levels) are mostly empirical.

As described in Figure 1 of MS IEC 60071-1, there are in fact four main steps in this insulation co-ordination procedure, which can be identified as follows:

– step 1: determination of the representative overvoltages (U_{rp});
– step 2: determination of the co-ordination withstand voltages (U_{cw});
– step 3: determination of the required withstand voltages (U_{rw});
– step 4: determination of the standard withstand voltages (U_{w}).

These main steps, with associated links connecting them, will be illustrated in some examples contained in this annex. Not only will the required standard withstand voltages be determined but also the calculation related to phase-to-ground and phase-to-phase clearances will be illustrated, as applicable.

K1 **Numerical example for a system in range I (with nominal voltage of 132 kV)**

K2 **Numerical example for a system in range II (with nominal voltage of 500 kV)**

K3 **Numerical example for substations in distribution systems with Um up to 36 kV in range I**

Table K3. Values related to the insulation co-ordination procedure for example K3

<table>
<tr><th colspan="2" rowspan="2">Type of overvoltage</th><th colspan="4">Temporary</th><th colspan="4">Slow-front</th><th colspan="2">Fast-front</th></tr>
<tr><th colspan="2">Phase-to-earth</th><th colspan="2">Phase-to-phase</th><th colspan="2">Phase-to-earth</th><th colspan="2">Phase-to-phase</th><th colspan="2">Phase-to-earth & Phase-to-phase</th></tr>
<tr><th colspan="2">Insulation</th><th>Internal</th><th>External</th><th>Internal</th><th>External</th><th>Internal</th><th>External</th><th>Internal</th><th>External</th><th>Internal</th><th>External</th></tr>
<tr><td>Step1
Representative voltage stresses in service</td><td>Values of U_{rp}:</td><td>33 kV</td><td>33 kV</td><td>38 kV</td><td>38 kV</td><td>81 kV</td><td>81 kV</td><td>119 kV</td><td>119 kV</td><td>-</td><td>-</td></tr>
<tr><td>Step2
Coordination withstand voltages</td><td>Values of K_c or K_{cd}:
Values of U_{cw}:</td><td>1.0
33 kV</td><td>1.0
33 kV</td><td>1.0
38 kV</td><td>1.0
38 kV</td><td>1.0
81 kV</td><td>1.0
81 kV</td><td>1.0
119 kV</td><td>1.0
119 kV</td><td>-
93 kV</td><td>-
93 kV</td></tr>
<tr><td>Step3
Required withstand voltages</td><td>Safety factor K_s:
Altitude correction factor K_a:
Values of U_{rw}:</td><td>1.15
-
38 kV</td><td>1.05
1.13
39 kV</td><td>1.15
-
44 kV</td><td>1.05
1.13
45 kV</td><td>1.15
-
93 kV</td><td>1.05
1.13
96 kV</td><td>1.15
-
137 kV</td><td>1.05
1.13
141 kV</td><td>1.15
-
107 kV</td><td>1.05
1.13
110 kV</td></tr>
<tr><td rowspan="2">Step4
Standard withstand voltage</td><td>1) Test conversion factor</td><td colspan="4">To short-duration power-frequency
To lightning impulse</td><td rowspan="3">0.5
1.10

47 kV
102 kV</td><td rowspan="3">0.6
1.06

58 kV
102 kV</td><td rowspan="3">0.5
1.10

68 kV
150 kV</td><td rowspan="3">0.6
1.06

85 kV
149 kV</td><td rowspan="2"></td><td rowspan="2"></td></tr>
<tr><td>2) Resulting required withstand voltages</td><td colspan="4">Short-duration power-frequency
Lightning impulse</td></tr>
<tr><td>Step5</td><td>Selection of standard withstand voltages</td><td colspan="4">Short-duration power-frequency 70 kV</td><td colspan="2">Lightning impulse
170 kV</td></tr>
</table>

Table K2. Summary of required withstand voltages obtained for example K1.2

(part 2, with capacitor switching at remote station (station 2))

Values of U_{rw} : - in kV r.m.s. for short duration power frequency -in kV peak for switching or lightning impulse		External insulation				Internal insulation	
		Line entrance equipment		Other equipment			
		$U_{rw(s)}$	$U_{rw(c)}$	$U_{rw(s)}$	$U_{rw(c)}$	$U_{rw(s)}$	$U_{rw(c)}$
Short duration power frequency	phase-to-earth	**141**	197	**141**	197	**145**	151
	phase-to-phase	**227**	366	**227**	366	**233**	275
Switching Impulse	phase-to-earth	310	-	310	-	302	
	phase-to-phase	567	-	567	-	550	
Lightning Impulse	phase-to-earth	**629**	403	**629**	403	468	332
	phase-to-phase	629	**631**	629	**631**	468	**605**

Table K1. Summary of minimum required withstand voltages obtained from example K1.1

(part 1, without capacitor switching at remote station (station 2))

Values of U_{rw} : - in kV r.m.s. for short duration power frequency -in kV peak for switching or lightning impulse		External insulation				Internal insulation	
		Line entrance equipment		Other equipment			
		$U_{rw(s)}$	$U_{rw(c)}$	$U_{rw(s)}$)	$U_{rw(c)}$	$U_{rw(s)}$	$U_{rw(c)}$)
Short duration power frequency	phase-to-earth	141	199	145	185	145	142
	phase-to-phase	227	366	233	285	233	217
Switching Impulse	phase-to-earth	312	-	292	-	283	
	phase-to-phase	568	-	449	-	435	
Lightning Impulse	phase-to-earth	629	406	629	380	468	311
	phase-to-phase	629	632	629	494	468	476

Table K2. Summary of required withstand voltages obtained for example K1.2

(part 2, with capacitor switching at remote station (station 2))

Values of U_{rw} : **- in kV r.m.s. for short duration power frequency** **-in kV peak for switching or lightning impulse**		**External insulation**				**Internal insulation**	
		Line entrance equipment		**Other equipment**			
		$U_{rw(s)}$	$U_{rw(c)}$	$U_{rw(s)}$	$U_{rw(c)}$	$U_{rw(s)}$	$U_{rw(c)}$
Short duration power frequency	phase-to-earth	**141**	197	**141**	197	**145**	151
	phase-to-phase	**227**	366	**227**	366	**233**	275
Switching Impulse	phase-to-earth	310	-	310	-	302	
	phase-to-phase	567	-	567	-	550	
Lightning Impulse	phase-to-earth	**629**	403	**629**	403	468	332
	phase-to-phase	629	**631**	629	**631**	468	**605**

Tutorials

(1) A 22 kV substation is to be designed. Determine the insulation withstand voltages for the substation. The following information is available:

Neutral earthing:		isolated
Altitude, H:	1000 m	
Maximum TOV level (p-p) =	1.15 p.u. rms	
U_{et} =		3.0 p.u. peak
U_{pt} =		4.4 p.u. peak
K_c =		1.0
U_{pl} =		80 kV peak
n =		4
A =		2700
L_{sp} =		100m
L_a =		42 m
L =		5 m for external and 3 m for internal
$U_{cw\ FFO}$ =		$U_{pl} + (A.L)/(n.(L_{sp}+L_a))$
$K_{s\ internal}$ =	1.15	
$K_{s\ external}$ =	1.05	
$K_{a\ phase\text{-}earth}$ =	1.13	
$SDW_{internal}$ =	U_{rw} x 0.5	
$SDW_{external}$ =	U_{rw} x 0.6	
$LIW_{internal}$ =	U_{rw} x 1.1	
$LIW_{external}$ =	U_{rw} x 1.06	

Tutorials

(2) Briefly describe the differences between internal and external insulation, slow and fast front impulses, temporary overvoltage and power frequency voltage.

(3) The following voltages were determined in an insulation coordination design. **Briefly** explain the reasoning behind each of these voltages, and where applicable, including examples:

Representative voltages U_{rp}
Coordination voltage U_{cw}
Required withstand voltage U_{rw}
Standard withstand voltage U_{w}

(4) Briefly explain the reasoning why the specification of standard withstand voltages is different between range I (U_m<245kV) and range II (U_m >245kV).