TECHNICAL REPORT

IEC TR 62066

First edition
2002-06

Surge overvoltages and surge protection in low-voltage a.c. power systems – General basic information

Surtensions de choc et protection contre la foudre dans les réseaux à basse tension – Informations générales fondamentales

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

SURGE OVERVOLTAGES AND SURGE PROTECTION IN LOW-VOLTAGE AC POWER SYSTEMS – GENERAL BASIC INFORMATION

FOREWORD

1) The IEC (International Electrotechnical Commission) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of the IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, the IEC publishes International Standards. Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. The IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.
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The main task of IEC technical committees is to prepare International Standards. However, a technical committee may propose the publication of a technical report when it has collected data of a different kind from that which is normally published as an International Standard, for example “state of the art”.

IEC 62066, which is a technical report, has been prepared by Technical Committee 64: Electrical installations and protection against electric shock.

The text of this technical report is based on the following documents:

Enquiry draft	Report on voting
64/1125/CDV	64/1163/RVC

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

This publication has been drafted in accordance with the ISO/IEC Directives, Part 3.

The committee has decided that the contents of this publication will remain unchanged until 2006. At this date, the publication will be

- reconfirmed;
- withdrawn;
- replaced by a revised edition, or
- amended.

This document, which is purely informative, is not to be regarded as an International Standard.

A bilingual version of this document may be issued at a later date.

SURGE OVERVOLTAGES AND SURGE PROTECTION IN LOW-VOLTAGE AC POWER SYSTEMS – GENERAL BASIC INFORMATION

1 Scope

IEC 62066 is a technical report that presents a general overview on the different kinds of surge overvoltages that can occur on low-voltage installations. Typical surge magnitude and duration as well as frequency of occurrence are described. Information on overvoltages resulting from interactions between power system and communications system is also provided.

Additionally, general guidelines are given concerning surge protection means and systems on the basis of availability and risk considerations, including interactions and the need for coordination and consideration of temporary overvoltages in the selection of surge-protective devices.

2 Reference documents

IEC 60364-4-44:2001, *Electrical installations of buildings – Part 4-44: Protection for safety – Protection against voltage disturbances and electromagnetic disturbances*

IEC 60364-5-53:2001, *Electrical installations of buildings – Part 5-53: Selection and erection of electrical equipment – Isolation, switching and control*

IEC 60664-1:1992, *Insulation coordination for equipment within low-voltage systems – Part 1: Principles, requirements and tests*
Amendment 1 (2000)

IEC/TR 61000-2-5:1995, *Electromagnetic compatibility (EMC) – Part 2: Environment – Section 5: Classification of electromagnetic environments.* Basic EMC publication

IEC 61000-4-1:2000, *Electromagnetic compatibility (EMC) – Part 4: Testing and measurement techniques – Overview of IEC 61000-4 series*

IEC 61000-4-4:1995, *Electromagnetic compatibility (EMC) – Part 4: Testing and measurement techniques – Section 4: Electrical fast transient/burst immunity test.* Basic EMC publication

IEC 61000-4-5:1995, *Electromagnetic compatibility (EMC) – Part 4: Testing and measurement techniques – Section 5: Surge immunity test*
Amendment 1 (2000)

IEC/TR 61000-5-2:1997, *Electromagnetic compatibility (EMC) – Part 5: Installation and mitigation guidelines – Section 2: Earthing and cabling*

IEC 61024-1:1990, *Protection of structures against lightning – Part 1: General principles*

IEC 61024-1-1:1993, *Protection of structures against lightning – Part 1: General principles – Section 1: Guide A – Selection of protection levels for lightning protection systems*

IEC 61312-1:1995, *Protection against lightning electromagnetic impulse – Part 1: General principles*

IEC/TS 61312-3:2000, *Protection against lightning electromagnetic impulse – Part 3: Requirements of surge protective devices (SPDs)*

IEC 61643-1:1998, *Surge protective devices connected to low-voltage power distribution systems – Part 1: Performance requirements and testing methods*

IEC 61643-12:2002, *Low-voltage surge protective devices – Part 12: Surge protective devices connected to low-voltage power distribution systems – Selection and application principles*

IEC 61662:1995, *Assessment of the risk of damage due to lightning*
Amendment 1 (1996)

IEC 61663-2:2001, *Lightning protection – Telecommunications lines – Part 2: Lines using metallic conductors*

ITU-T K.20, *Resistibility of telecommunication equipment installed in a telecommunications centre to overvoltages and overcurrents*

ITU-T K.21, *Resistibility of telecommunication equipment installed in customers' premises to overvoltages and overcurrents*

IEEE 1036:1992, *Guide for application of shunt power capacitors*

NOTE Other documents are listed in the bibliography, which includes documents that were used in developing the present report, documents cited in support of a recommendation, and documents suggested as further reading for information.

3 Definitions

For the purposes of this technical report, the terms and definitions given in other relevant IEC publications (see clause 2) apply, as well as the definitions listed below.

3.1
combination wave
waveform delivered by a generator that applies a 1,2/50 voltage impulse across an open circuit and an 8/20 current impulse into a short circuit. The voltage, current amplitude and waveforms that are delivered to the SPD are determined by the generator and the impedance of the SPD to which the surge is applied. The ratio of peak open-circuit voltage to peak short-circuit current is 2 Ω; this is defined as the fictive impedance Z_f. The short-circuit current is symbolized by I_{sc}. The open-circuit voltage is symbolized by U_{oc}

NOTE For the purposes of this technical report, the combination wave delivered by a surge generator in accordance with definition 3.24 of IEC 61643-1 may be applied to equipment other than an SPD.

3.2
combined multi-port SPD
surge-protective device integrating in a single package the means for providing surge protection at two or more ports of an equipment connected to different systems, such as a power system and a communications system

NOTE In addition to providing surge protection for each port, the device may also provide means to avoid shifting of the reference potentials between the equipment ports.

3.3
coordination of SPDs (cascade)
selection of characteristics for two or more SPDs to be connected across the same conductors of a system but separated by some decoupling impedance such that, given the parameters of the impedance and of the impinging surge, this selection will ensure that the energy deposited in each of the SPDs is commensurate with its rating

3.4
direct stroke
stroke impacting the structure of interest

3.5
equipotential bonding
provision of electric connections between conductive parts, intended to achieve equipotentiality

NOTE In typical installations, the equipotential bonding is provided for safety at the power frequency. At surge current frequencies, the length of the bonding conductors inescapably introduces some difference in potentials.

3.6
facility
physical entity (for example, a hospital, factory, machinery, etc.) that is built, constructed, installed or established to perform some particular function or to serve or facilitate some particular end

3.7
lightning flash to earth
electrical discharge of atmospheric origin between cloud and earth consisting of one or more strokes

NOTE For the purpose of this technical report, flash to earth can be understood not only as the earth (soil) but also as a flash to a structure, a power system, etc., as opposed to a cloud-to-cloud event.

3.8
lightning protection system (LPS)
complete system used to protect a space against the effects of lightning. It consists of both external and internal lightning protection systems

NOTE In particular cases, an LPS may consist of an external LPS or an internal LPS only.

3.9
near flash
flash striking in the vicinity of the structure of interest

3.10
point of strike
point where a lightning stroke contacts the earth, a structure, or an LPS

3.11
prospective overvoltage
theoretical overvoltage that would appear on the conductors of a power supply system or user installation before flashover of basic insulation or operation of voltage-limiting devices

3.12
SPD disconnector
internal or external device required for disconnecting an SPD from the system in the event of SPD failure. It is intended to prevent a persistent fault on the system and may give visible indication of the SPD failure

3.13
steepness factor
ratio for a current impulse, of the front-of wave slope defined for the interval between 10 % and 90 % of the crest value, to the slope defined for the interval between 10 % and 30 % of the crest value

3.14
stroke (lightning)
single electrical discharge in a lightning flash to earth

3.15
surge overvoltage
temporary or transient voltage occurring in the system, resulting from a surge current due to an atmospheric discharge, an induction phenomenon, switching, or a fault in the system itself

3.16
surge protective device (SPD)
device that is intended to limit transient overvoltages and divert surge currents. It contains at least one non-linear component

3.17
surge reference equalizer
device used for connecting equipment to external systems whereby all conductors connected to the protected load are routed, physically and electrically, through a single enclosure with a shared reference point between the input and output ports of each system

NOTE Sharing the reference point may be accomplished within the device either by a direct bond or through a suitable device, such as an SPD which maintains isolation during normal conditions but provides an effective bond during the occurrence of a surge in one or both systems.

3.18
temporary overvoltage (TOV)
oscillatory overvoltage at power frequency at a given location, of relatively long duration and which is undamped or weakly damped

NOTE Temporary overvoltages usually originate from switching operations or faults (for example, sudden load rejection, single-phase faults) and/or from non-linearities (ferro-resonance effects, harmonics).

3.19
thermal runaway
operational condition when the sustained power loss of an SPD exceeds the thermal dissipation of the housing and connections, leading to a cumulative increase in the temperature of the internal elements culminating in failure

4 Overvoltages in low-voltage systems

Overvoltages in low-voltage systems result from several types of events or mechanisms and may be classified in four categories. The scope of this technical report is limited to low-voltage a.c. power systems, focussing on the first two categories but also giving guidelines for the third category shown below. A significant fourth category of overvoltages can occur from interactions of the a.c. power system with other systems, such as communications system, so that this fourth category is also relevant to the subject of this technical report.

a) Lightning overvoltages

   Lightning overvoltages are the result of a direct flash to or near the power system, structures (with or without lightning protection system) or to the soil. Distant lightning flashes can also induce overvoltages in the circuits of an installation. These overvoltages are the subject of clause 5, where the various coupling mechanisms are described.

b) Switching overvoltages

Switching overvoltages are the result of intentional actions on the power system, such as load, inductor or capacitor switching in the transmission or distribution systems by the utility, or in the low-voltage system by end-user operations. They can also be the result of unintentional events such as power system faults and their elimination. Both are the subject of clause 6.

c) Temporary overvoltages

Temporary overvoltages occur in power systems, as the result of a wide range of system conditions, both normal operation and abnormal conditions. Both are the subject of clause 7. Their occurrence is relevant to the selection of suitable surge-protective devices.

d) System interaction overvoltages

Overvoltages can occur between different systems, such as power and communications, during the flow of surge currents in one of the systems. These are briefly described in clause 8.

Clauses 5, 6, 7, and 8 referenced above present an overview of these overvoltages and causes, without discussion of consequences, need for mitigation, or risk analysis. These related topics are discussed in subsequent clauses.

5 Lightning overvoltages

5.1 General

Lightning is a natural and unavoidable event which affects low-voltage systems (power systems as well as signal/communication systems) through several mechanisms. The obvious interaction is a flash to the power system, but other coupling mechanisms can also produce overvoltages (see figure 1). To better understand the diversity of mechanisms, this subclause first presents a summary of the basic parameters of a lightning stroke between a cloud and any object at the ground level. Figure 2 gives examples of lightning flashes to a typical complex electrical system.

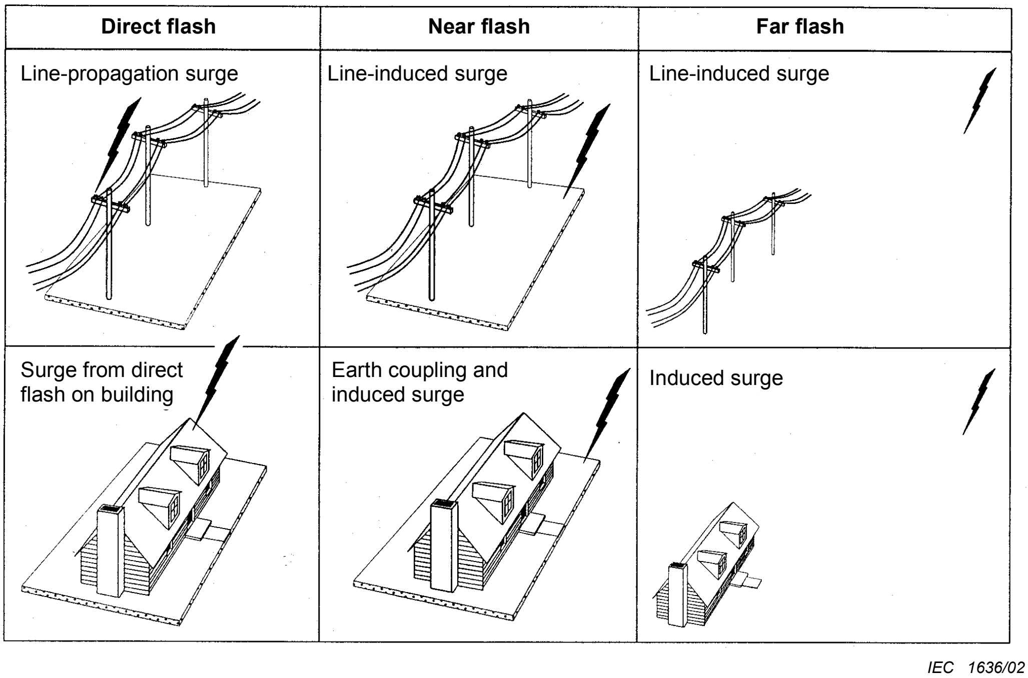


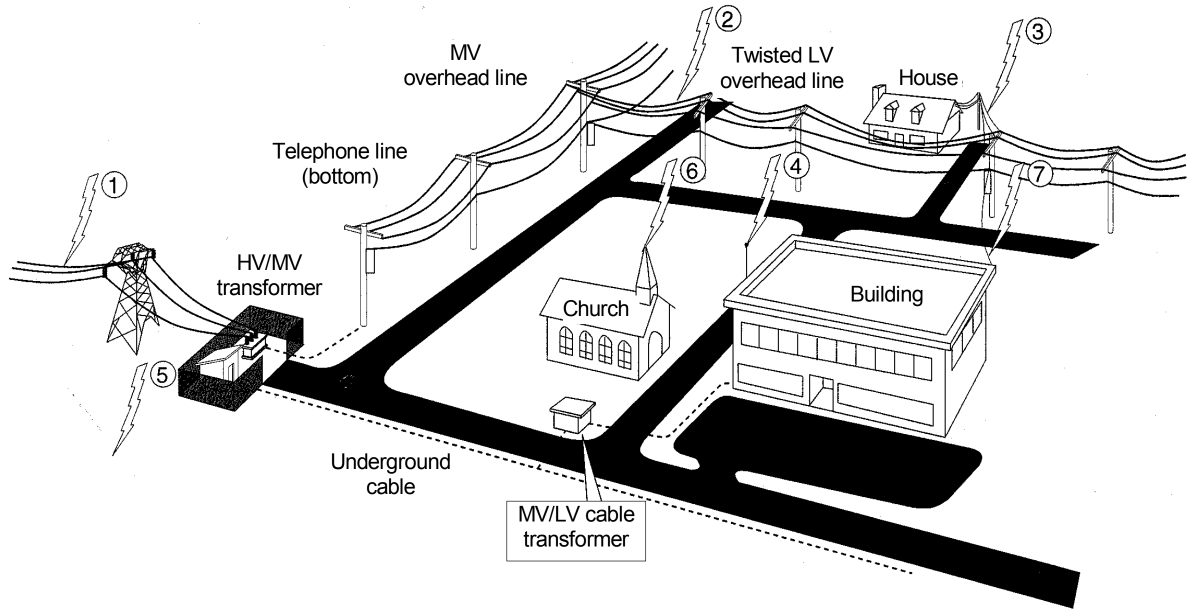
Figure 1 – Examples of lightning flash coupling mechanisms

The significant lightning parameters include waveforms, amplitudes, and frequency of occurrence. The concepts of near flash and far flash involve several attributes and associated effects as shown in table 1. The literature contains data obtained by measurements as well as data produced by computations. Three types of coupling mechanisms are reviewed that can produce overvoltages in low-voltage systems. While this discussion makes reference to overvoltages, consideration of the current associated with the overvoltage, or the current initially causing the overvoltage is an important aspect of the subject. In the case of a direct flash to the electrical system, the immediate effect is the flow of lightning current through the earthing impedances, resulting in overvoltages. The effective impedance of the lightning channel is high (a few thousand ohms). Accordingly, the lightning current can practically be considered as an ideal current source. In the case of a near flash, the immediate effect is the voltage induced in circuit loops, or resistive coupling, which in turn can produce surge currents. In the case of a far flash, the surges are limited to induced voltages. Therefore, the response of an electrical system to the lightning event is an important consideration in assessing the possible surge currents and overvoltages.

For a given flash, the severity of the overvoltage appearing at the end-user facility reflects the characteristics of the coupling path such as distance and nature of the system between the point of flash and the end-user facility, earthing practices and earth connection impedance, presence of surge-protective devices (SPDs) along the path, and branching out of the distribution system. All of these factors vary over a wide range according to the general practice of the utility as well as local configurations.

Table 1 – Attributes and effects of lightning flashes

Attributes	Direct stroke	Near stroke	Far stroke
Impact – Mechanical	Structure		
Impact – Thermal	Structure and circuits		
Energy	Service entrance SPDs (high stress)	Service entrance SPDs (low stress)	Installation SPDs (low stress)
Rate of current change	Adjacent circuits	Nearby circuits	Large-loop circuits
Earth potential rise	Adjacent circuits	Nearby circuits	
Inductive coupling	Adjacent circuits	Nearby circuits	Large-loop circuits
Capacitive coupling	Adjacent circuits	Nearby circuits	
Resistive coupling	Connected circuits	Nearby circuits	
Conducted by line propagation	Service entrance SPDs (high stress)	Service entrance SPDs (medium stress)	Service entrance SPDs (low stress)



Key

1 Direct stroke on HV line
2 Direct stroke on MV line
3 Direct stroke on LV line
4 Direct stroke on lightning protection system
5 Stroke on the soil
6 Stroke on nearby structures
7 Stroke on telephone line

Figure 2 – Examples of lightning flashes to a complex electrical system

Consequently, it is difficult, if not impossible, to present a discussion of the subject that can be universally applicable. However, it is useful to consider the first stage of the lightning event in the absence of mitigation means (deliberate or inherent). This first-stage assessment of the event leads to the concept of a prospective overvoltage, which is more generally applicable. Then, in a subsequent subclause, inherent mitigating effects are discussed to present information on how the prospective overvoltage is propagated toward the end-user facility. This propagation involves various mitigation mechanisms, including inherent mitigation resulting from the system configuration and deliberate mitigation through the provision of various SPDs by the utility or end-user.

In the following paragraphs, the basic lightning parameters are briefly described, then the coupling mechanisms corresponding to the three types defined above are discussed, and finally a probability is derived from consideration of the various mechanisms. Cloud-to-earth lightning flashes occur in two modes, depending on the respective polarity of the cloud and earth.

A positive ground flash consists of the following components:

– the positive impulse current and, possibly,
– the positive continuing current.

A negative ground flash consists of the following components:

– the negative impulse current of the initial stroke, and, possibly,
– the negative impulse currents of the subsequent strokes, and, possibly,
– the negative continuing current.

Objects of limited height are exposed to positive and negative ground flashes. Figure 3 shows the related possible lightning current waveforms.

Objects of significant height, such as towers higher than 100 m, are also exposed to positive and negative ground flashes. In this case, discharge can also be initiated by a continuing current. Occurrence of a single continuing current is also possible.

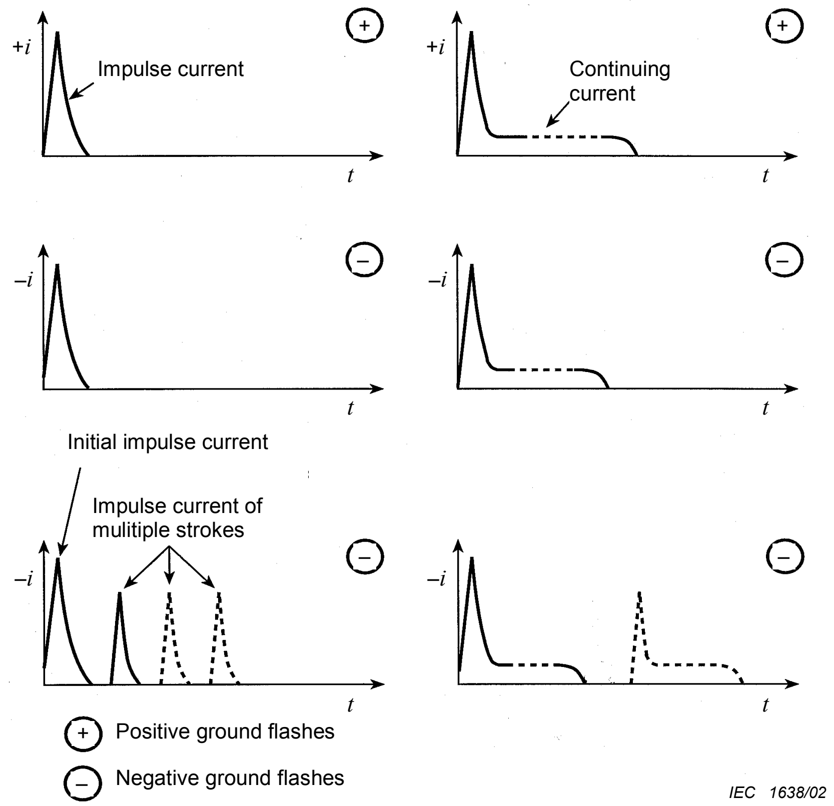
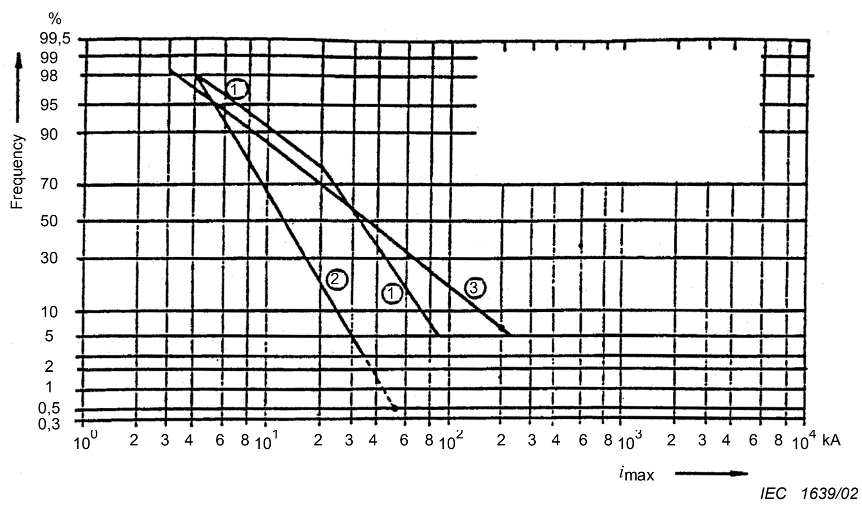


Figure 3 – Possible waveforms of lightning current striking ground-based objects

Figure 4 shows the frequency distribution of peak current for three types of strokes, and table 2 shows the 50 % and 5 % levels of other parameters. In general, 90 % of the lightning flashes are of negative polarity. The percentage of negative/positive flashes varies with climatic regions, however. A more comprehensive description of these parameters is given in annex A.



Key

1 Negative first strokes

2 Negative subsequent strokes

3 Positive ground flashes

Figure 4 – Frequency distribution of peak currents for three types of lightning events

Table 2 – Statistics of the significant parameters of lightning events

Lightning flash parameter	Percentile	
	50 %	**5 %**
Peak current (kA)		
Negative first strokes	20	90
Negative subsequent strokes	12	29
Positive ground flashes	35	250
Total charge (C)		
Negative ground flash	8	40
Positive ground flash	80	350
Transient charge (C)		
Negative first strokes	5	20
Negative subsequent strokes	1	4
Positive ground flashes	16	150
Specific energy (kJ/Ω)		
Negative first strokes	55	550
Negative subsequent strokes	6	52
Positive ground flashes	650	15 000
Maximum slope of transient current (kA/µs)		
Negative first strokes	24	65
Negative subsequent strokes	40	162
Positive ground flashes	2	32
NOTE These values give the characteristics of the return-stroke current at the channel base (lower base where the measurements were made).		

The peak value of a lightning impulse current is the significant parameter for the voltage drop across the impedance of the earthing electrode or object and thus for the potential difference between the object and its environment. The charges transported by the impulse current and the continuing current are the significant parameters for burning damage to metals caused by lightning current arcs. The specific energy is the significant parameter for heating of lightning current-carrying conductors as well as for mechanical effects from electromagnetic forces. The rate of rise is the significant parameter for the voltages induced in conductor loops in the vicinity of the stroke and for the resulting currents. The multiple-stroke discharge is the main cause for upsets of digital systems, due to the recurrence of spurious signals for one flash event and the steeper rise of current in the subsequent strokes.

The worldwide annual frequency of thunderstorm days is shown in figure 5. This information is now being superseded by maps of flash density for regions where a lightning detection system is in operation. Flash density maps provide more accurate information than the traditional thunderstorm day and it is expected that they will supersede the thunderstorm maps as they become available.

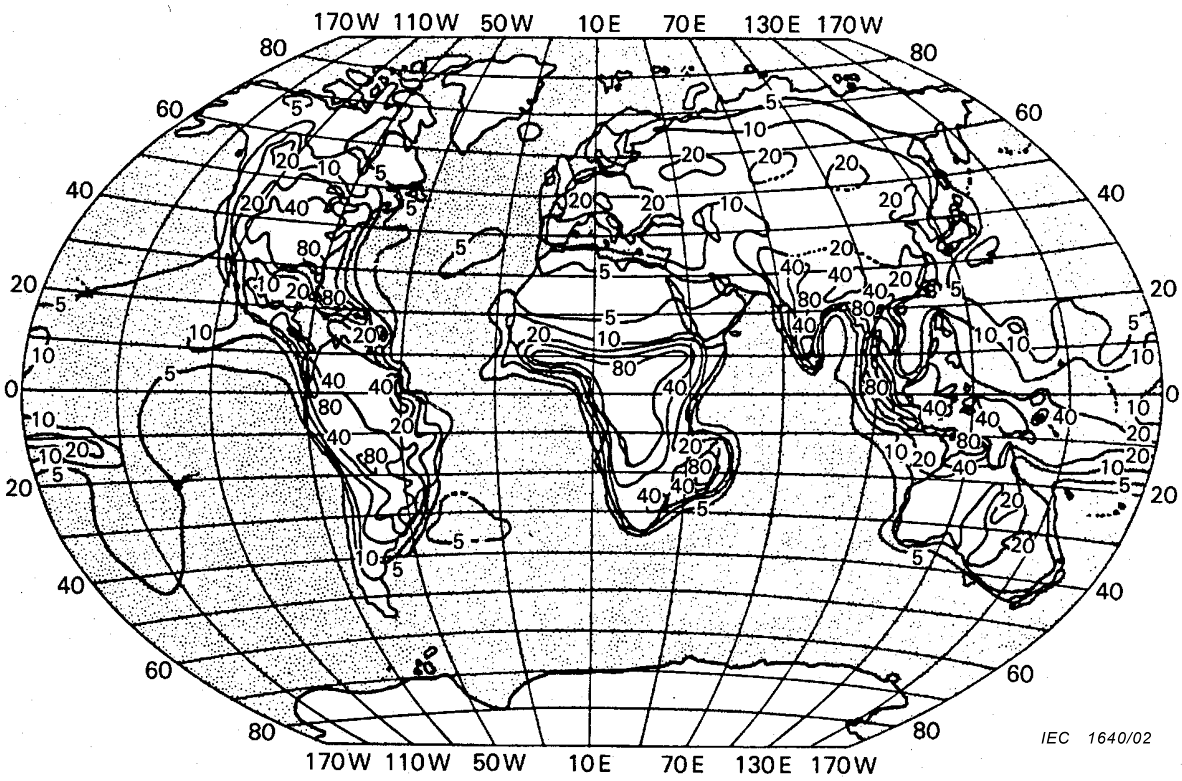


Figure 5 – Map of annual thunderstorm days [7] [1)]

5.2 Origin of lightning surge overvoltages

Lightning surge overvoltages in electrical systems may be classified according to their origin as follows:

– overvoltages due to direct flashes to overhead lines;

– overvoltages induced on overhead lines due to flashes at some distance;

– overvoltages caused by resistive, inductive and capacitive coupling from systems carrying lightning currents.

5.2.1 Direct flashes to overhead lines

As mentioned earlier, the effective impedance of the lightning channel is high and the lightning current can practically be considered as an ideal current source. The resulting overvoltages are therefore determined by the effective impedance that is seen by the lightning current. For a flash to an overhead line conductor, the impedance is in the first moments determined by the characteristic impedance (surge impedance) of the line. This impedance (Z_0) is normally in the range 400 Ω to 500 Ω for one conductor. As shown in figure 6, the current (I) is initially divided in two parts, one in each direction.

1) Figures in square brackets refer to the bibliography.

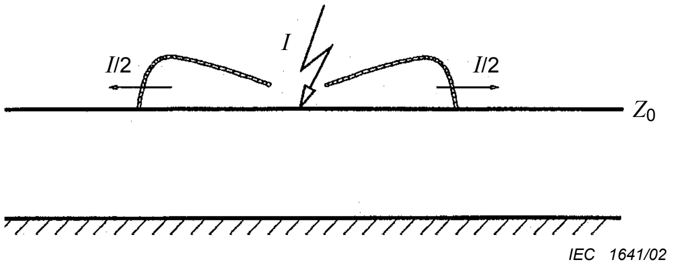


Figure 6 – Direct flash to an overhead line

The voltage surges (U) generated by the current at the point of attachment are defined by (1):

$$U = Z_0 \times I/2 \qquad (1)$$

where

U is the voltage surge (kV);

Z_0 is the surge impedance (Ω);

I is the lightning current (kA).

For a moderate current of 20 kA and a surge impedance of 400 Ω, the prospective voltage surge at the point of attachment of the stroke is 4 000 kV. On medium-voltage (MV)[1)] and low-voltage (LV) lines, therefore, flashovers will usually occur between all line conductors and, in most cases, also to earth somewhere along the line. After flashover, the effective impedance is reduced, particularly depending on the value of earthing resistances involved. However, even for a rather low effective impedance, as for instance 10 Ω, the voltage will still be 200 kV on the line for the 20 kA lightning current assumed in this example and further flashovers can occur.

The frequency of lightning flashes to an overhead line depends on local flash density, line type (especially the height) and possible shielding effects of the surroundings. For lines in an open area, an estimate of the number of flashes to the line can be found by assuming that flashes within a distance of three times the line height (H) will strike the line. An effective area (A) can then be defined by:

$$A = 6 \times H \times L \qquad (2)$$

where

A is the effective area;

H is the height;

L is the line length

[1)] For the purposes of this technical report, the distribution transformer will be used as the boundary between the low-voltage system – less than 1 000 V r.m.s. according to the IEC definition – and the primary voltage. The latter, regardless of its value, will be referred to as “medium voltage”, notwithstanding the practice of differentiating between “medium voltage” and “high voltage” when referring to the system architecture.

The number of flashes (N) per year is then found by multiplying A by the local flash density (N_g) as follows:

$$N = A \times N_g \times 10^{-6} \quad (3)$$

where

N is the number of flashes per year;

A is the effective area (m^2);

N_g is the local flash density per km^2 and per year.

For a line of 5 m in height and assuming N_g to be equal to 1, N is found to be 0,03 per km of line and per year, that is, three flashes per 100 km and per year.

5.2.2 Induced overvoltages on overhead lines

Due to the electromagnetic field changes caused by a lightning flash, overvoltages are induced in overhead lines of all kinds, including at a considerable distance from the flash. As a crude approximation, the prospective overvoltages U (in kilovolts) between the line conductors and earth (closest to the strike) can be estimated from (4) as indicated in [53] and [16]:

$$U = 30 \times (H/d) \times I \quad (4)$$

where

I is the lightning current (kA);

H is the height of the conductors above earth (m);

d is the distance to the flash (m).

The voltages have essentially the same value for all conductors since the phase separation is small compared to the distance to the flash.

As an example, consider a high-voltage line with a conductor height of 10 m: for a lightning current of 30 kA, the induced voltage is in the order of 100 kV for a flash at 100 m distance. For a LV line with height of only 5 m, a current of 100 kA will produce a prospective voltage of 1,8 kV even at a distance of 10 km.

5.2.3 Overvoltages caused by coupling from other systems

A lightning flash to earth can result in an earth potential of high value at the point of strike (and in the vicinity). This phenomenon will cause overvoltages in electrical systems using this point of earth as reference for their earthing system.

In figure 7, an example of such a case is shown. The potential rise of the earthing system is determined by the lightning current and the effective earthing impedance. At first, the earth electrode potential is determined by the local impedance, that could be 10 Ω for instance. This means that a high voltage is produced between the earthing system and electrical installations inside the building, with a high probability of causing either insulation breakdown or operation of SPDs. Following such events, current impulses can flow into the various systems, mainly determined by their impedance to earth. In this way overvoltages are produced in the power supply system as well as in other services (telecommunication, data and signalling systems, etc.). Furthermore, overvoltages are transferred to other buildings, structures and installations. For instance, all power installations supplied from the same distribution transformer as the one struck by lightning can be affected.

Due to the high electromagnetic fields caused by the lightning current, inductive and capacitive coupling to electrical systems close to a lightning path can also cause overvoltages of concern, especially on electronic and data systems, causing failures and/or malfunctions.

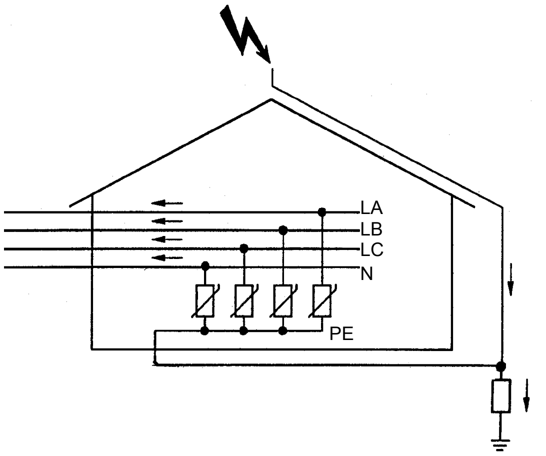


Figure 7 – Example of resistive coupling from lightning protection system

5.3 Lightning surges transferred from MV systems

Because their structures are longer and higher than other structures located in their vicinity (houses, trees), MV overhead lines are in general more exposed to lightning than LV lines. The number of lightning flashes affecting a line depends on the keraunic level of the local area. The propagation of the surge through the MV system and the transfer rate to the LV system depend on the physical construction of the system. Some important differences can exist between the designs used in different countries.

The lightning surges in MV systems are caused by direct flashes or are induced by near flashes as described in 5.2. In addition, back-flashovers can occur from flashes striking earth wires or extraneous metal parts of structures or equipment, or striking the earth close to a line structure.

5.3.1 Surge overvoltage magnitude and propagation in MV systems

The surge propagation depends on the MV system structure, and in particular on the overvoltage protection devices installed. High-level lightning surges are in general attenuated quickly during their propagation on the line by losses and flashover across the line insulators. In practice, after a few line spans, the overvoltage magnitude is reduced to the insulation levels of the line isolators. With the exception of direct flashes to the MV/LV transformer or its vicinity, it can be assumed that overvoltages in an MV system are limited by the insulation level of the line isolators. In a 20 kV system, this is about 150 kV to 180 kV. For wood-pole lines without earthed cross-arms, however, much higher surges can occur.

A second limitation of the surge level is provided by the overvoltage protection devices located usually at the primary side of the MV/LV transformer, or at the entrance of underground networks. These protection devices may be ZnO or SiC surge arresters or air gaps. The residual overvoltage (in the range of 70 kV for a 20 kV system for instance) depends on the rated value and earthing impedance of the protection devices. When air gaps are used, one can expect that the lightning surge might be followed by a power frequency follow current that can generate a temporary overvoltage.

Annex A includes an example of measurements of lightning-related overvoltages on a typical 20 kV power distribution system.

5.3.2 Surge transfer to the LV system

The overvoltage surges generated in the MV system by lightning are transferred to the LV distribution system in two different manners:

– by capacitive and inductive coupling through the MV/LV transformer;

– by earth coupling.

The transferred surge magnitude depends on many parameters such as:

– LV earthing system (TT, TN, IT);

– characteristics of the LV line and LV load;

– LV overvoltage protection equipment;

– coupling conditions between MV and LV earthing;

– transformer design.

The analysis of lightning surge propagation and transfer to LV systems can be carried out by using a high-frequency model. Such a model represents the transformer principally by its capacitive coupling which is considered to be its most important characteristic when considering frequencies in the range of the MHz (see annex A).

In case of direct lightning to the MV line, the surge arrester operation or an insulator spark-over diverts the surge current through the earthing system and can produce a resistive earth coupling between the MV and LV systems. An overvoltage is transferred to the LV system as shown in the typical case of figure 8a. Depending on the earthing impedance values, this earth coupling overvoltage can be much higher than the capacitive coupling through the transformer. On the other hand, separating the earthing electrodes as in figure 8b decreases this problem. However, this configuration will cause voltage stress between the transformer case and the secondary winding.

In a TN system, if the neutral is also earthed at the customer installation, smaller overvoltages will occur. It should also be noted that this kind of resistive coupling may be avoided by using a separate earthing system for the LV part of the transformer.

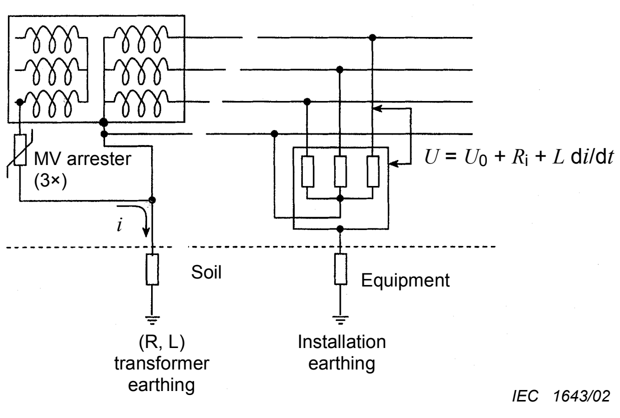


Figure 8a

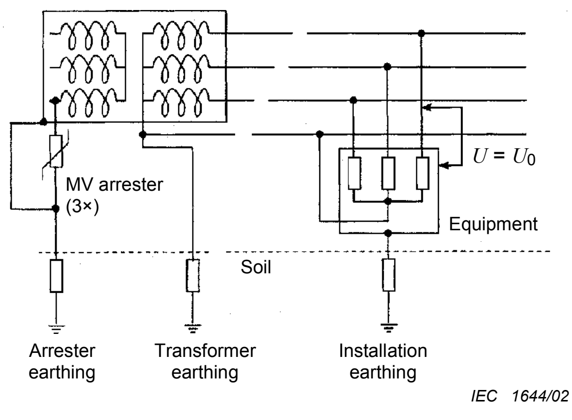


Figure 8b

Figure 8 – Typical earth coupling mechanisms

A typical value of the overvoltage transmitted by capacitive and inductive coupling to the secondary of the MV/LV transformer side is 2 % of the MV phase-to-earth voltage between phase and neutral conductors and 8 % between phase conductor and earth. These values are typical for a loaded LV circuit. When the LV side of the transformer is open, or very lightly loaded, the values can be significantly higher, depending on the LV system.

Induced lightning surges on the MV system produce much less surge current (usually less than 1 kA) than direct flashes, and the overvoltages are in practice transferred to the LV system only by capacitive coupling and do not exceed a few kilovolts. In such cases, the overvoltage induced directly in the LV system (at least in the part which is not far from the lightning impact point) is in general higher than the one transferred from the MV side. If an SPD operates or a sparkover occurs, the current will be small and accordingly the resistive coupling is negligible.

5.4 Surges caused by direct flash to LV lines

5.4.1 Prospective overvoltages

As shown in 5.2, and in the illustrative examples of annex A, extremely high prospective overvoltages are produced when direct lightning flashes occur on overhead lines. Flashover will result between all line conductors, and in most cases to earth somewhere in the vicinity of the flash (primarily at the poles). Flashover can also occur in non-protected installations supplied by that line.

In a combined overhead line/cable system, the overvoltages will be somewhat reduced due to the lower surge impedance of cables compared to overhead lines. The amount of reduction depends on the current duration and on the total capacitance to earth of the system. However, usually this reduction is not sufficient to avoid overvoltages exceeding normal insulation levels in LV installations. Therefore, direct flashes to LV lines should generally be expected to cause damages.

5.4.2 Practical limitations

In a practical case, the overvoltages will be limited by SPDs that might be installed at the distribution transformer and at the consumer’s premises. However, such devices will be very much stressed and a high risk of damage to SPD elements might be expected in the case of direct flashes, unless the SPDs are specifically designed for that purpose.

5.5 Lightning surges induced into LV systems

5.5.1 Prospective overvoltages

Estimates of prospective induced overvoltages in LV systems, due to lightning at some distance from an overhead line, can be derived from the simple formula (4) given in 5.2.2. According to this formula, induced overvoltages in excess of normal LV insulation withstand can occur even for lightning flashes at 10 km distance from the line.

This kind of surge is therefore of primary concern for LV distribution systems using overhead lines. Lightning induced overvoltages occur mainly between conductors and earth. The voltage difference between the conductors is initially small, especially when twisted conductors are used. However, due to different loads on phase conductors (depending on the LV system), interactions of surge protective devices, possible flashovers, etc., considerable line-to-line stresses can also occur.

An example illustrating induced overvoltages in LV systems is shown in figure 9. Twisted conductors (including the neutral) are assumed. Furthermore, the neutral is earthed at both ends of the line. It is seen that the voltages are showing damped oscillations with a frequency equal to the characteristic frequency of the line.

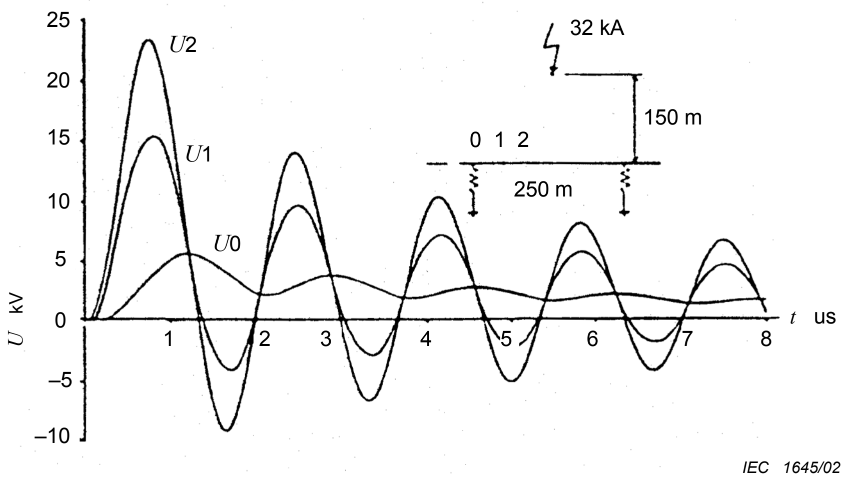


Figure 9 – Typical overvoltages induced on an LV line by a near lightning flash

5.5.2 Assessment of the probability of occurrence

The assessment of the number of induced overvoltages on an LV line in function of the amplitudes can be made on the basis of the simple Rusck formula (4) cited above. Such a simulation has been performed for a line of 5 m in height and 1 km in length [29], assuming a normalized flash density (N_g) of 1 flash per km^2 and per year, and the lightning current distribution proposed by CIGRE [10]. Similar results based on the same model, and supported by experimental data on LV lines for eight years, have also been obtained by Popolansky [51].

Another approach has been followed by CIGRE-CIRED JWG 05 (CC05), starting from the experimental measurements made by Eriksson in South Africa [18] and developing a principal formula giving the same results:

$$N_i = 1{,}9 \times 10^{-6} \times N_g; H \times L\left[3{,}5 + 2{,}5 \log \frac{30(1-c)}{U}\right]^{3{,}75} \tag{5}$$

In this formula N_i is the number of induced overvoltages, N_g, H, L, and U are as defined in equations (2), (3) and (4), and c is a factor taking into account the reduction effect due to a grounded neutral or an earth conductor (the factor c can range from zero in absence of such a conductor to 0,7 or even 0,9 in case of a multiple-grounded neutral conductor in a preassembled bundle). Although established for MV lines, the above formula has been validated by simulations based on the model established by CIGRE TF 33.01.01 [46].

Simulations performed in Italy [45] have confirmed the important part played by a multi-grounded neutral conductor, as was already suggested by equation (5). It is shown in particular that N_i is also proportional to the square of the span length between two groundings of the neutral, and that the closer to this grounding the measurements are made, the smaller the expected overvoltages are.

Figure 10 shows a comparison of the curves obtained from Johannesen's simulations and from CC05 simulations (assuming c = 0). Other results of simulations performed by Electricité de France with the ANASTASIA code [52] and presented in figure A.4 are also shown on the same figure. In order to make the comparison valid, all the data have been normalized for a line of 1 km in length, and 10 m in height, with N_g = 1 (assuming that N_i is proportional to N_g, H and L). It should be noted, however, that somewhat different assumptions are made for the simulations. For instance, for the ANASTASIA simulations, the line was terminated by a LV/MV transformer at one end and left open at the other end. For Johannesen [29], the line was terminated in matched impedances (no reflections) and only the flashes along the sides of the line were taken into consideration. Therefore, a direct comparison of the curves is difficult but the results may be considered as general indication of the range of lightning-induced overvoltages that can be expected.

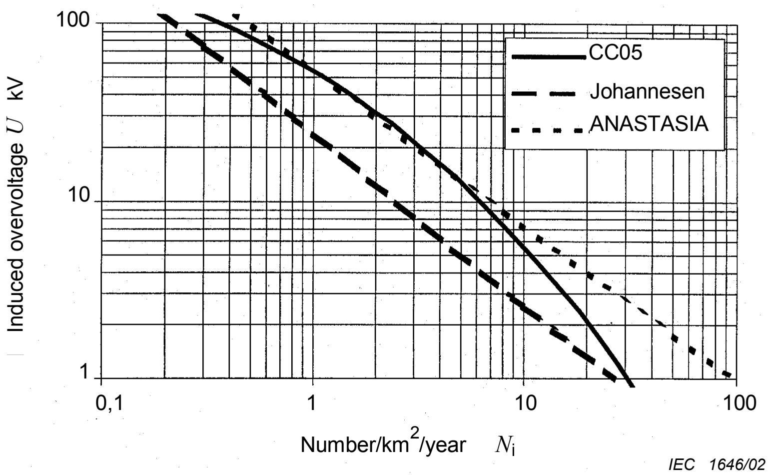


Figure 10 – Example of estimated frequency of occurrence of prospective induced lightning overvoltages on LV overhead lines

These distributions represent the prospective overvoltages (not influenced by any reaction of the system, such as a flashover). In practical cases, distortion and limitations are present due to multiple branches, cable sections, loads, flashovers, overvoltage protection devices, etc. The statistical distributions on this figure should therefore be expected to be somewhat modified in real cases. In particular, the frequency of overvoltages with magnitudes exceeding the normal line insulation level will be reduced.

5.6 Examples of induced overvoltages

From the preceding data on the occurrence of overvoltages, one might expect more surge-related failures of equipment than those actually being observed. This discrepancy can be explained by several factors: actual probability of the event at a given location, mitigating effect of multiple paths offered to the surges, actual behaviour of transmission lines, loading effect by linear as well as non-linear loads, presence of SPDs, unrecognized flashover in the face of extreme overvoltages, etc.

5.6.1 Simulations

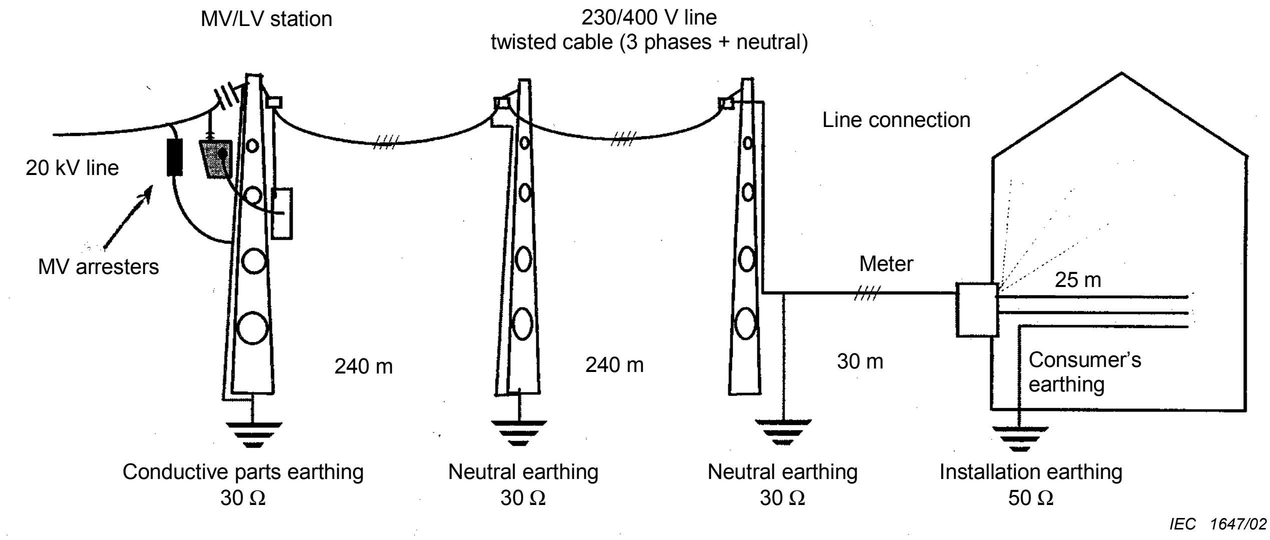
As an example of prospective overvoltages that might be expected, a simulation with Monte-Carlo statistics was performed on a model of a LV distribution system shown in figure 11. The ground flash density was assumed to be 2,2 flashes per km^2 per year, and all loads were simply modelled by resistors, independent from frequency. Table 3 shows the results of this analysis. The last column shows high levels of overvoltages, but these occur only in case of a direct lightning stroke on the LV system. The probability of occurrence of such surges in this example is once in 22 years.

Table 3 – Line-to-earth prospective overvoltage levels in the LV installation, occurrences per year

	>1,5 kV	>2,5 kV	>4 kV	>6 kV	>20 kV
Unloaded TT system	6	3	1,8	1	0,045
Loaded TT system	4	1,7	1	0,5	0,045
Loaded TN system	1	0,6	0,35	0,25	0,045

NOTE 1 The numbers shown in the table were obtained for an overhead twisted cable distribution system. For a distribution system with overhead open conductors in air, the voltage levels can be expected to be twice as high for the same probabilities.

NOTE 2 In this example, when performing a variation of the model to represent a TN system, it was found that the value of the earthing impedance had no significant influence because the LV neutral is connected direct to earth.



Dimensions in millimetres

Figure 11 – Model of distribution system used in the simulation

This analysis demonstrates that for the typical LV line of figure 11, and for a flash density of 2,2 flashes per year per km^2, the prospective number of overvoltages exceeding the insulation level defined by IEC 60664-1, such as 4 kV for a 230 V TN system, is in the order of one occurrence every other year.

In 5.5.2, reference is made to measurements [50] made in regions with similar ground flash density (2 to 3 flashes per km^2/year). These measurements were made on LV lines between live conductors and a local earth electrode at the measuring sites. Therefore, these data (showing voltages in excess of 4 kV about 10 times per year) are not directly comparable to the simulation results presented in table 3. However, taking into account the specific parameters used for the simulation circuit, and the fact that here the line-to-earth voltages within the installation are studied, it seems that the measurements and the simulation results are in reasonable agreement.

NOTE This analysis has been complemented by further computations with the ANASTASIA programme, assuming that an SPD with a protection level of 2,5 kV is installed at the service entrance of the installation. The current flowing through the SPD was also computed. These simulation results confirm that the surge currents produced by induced overvoltages are in general less than 1 kA. For instance, the maximum SPD current was only 60 A for a 100 kA flash to the soil at a distance of 200 m from the LV line. The current in the SPD has also been computed in the case of a direct 100 kA flash to the MV line at 250 m from the MV/LV transformer; the resulting current in the SPD was about 200 A. These two results were obtained for an assumed earthing resistance of 50 Ω at the service entrance. Lower earthing resistances will tend to increase the SPD currents.

5.6.2 Measurements

Measurements made in France, and still being continued, have shown that the prospective values of table 3 are not reached very often, because in practice the LV line is generally connected to a number of installations and because operation of an arrester or a flashover, which can occur in any part of the LV system, will reduce the overvoltage applied to the rest of the system.

Measurements on lightning-induced overvoltages in LV lines are reported in [50] for an area of similar flash density, but for phase or neutral with respect to local earth electrode. The line lengths were in the order of 1 km. Depending on the shielding of the line by surrounding objects, overvoltages in excess of 4 kV occurred about 8 to 12 times per year. Note that these overvoltages occurred between lines and local earth, not across the customer loads.

Systematic monitoring of overvoltages at several sites recently made in Germany produced the statistics detailed in table B.3. The cause of the overvoltage, whether switching or lightning, is not identified in this survey. It is possible that the few recordings at the high end (four events above 2 kV and two events above 6 kV) in a total of 151 events above 1 kV (among 3 000 events above 500 V) were associated with lightning surges.

5.7 Overvoltages caused by flashes to the structures or in close vicinity

5.7.1 Lightning current dispersion among parallel installations

When lightning strikes a structure which is one of several supplied in parallel by a LV power system, the flow of lightning current into the earth[1)] divides among the various paths available. These include local earth (building earthing), as well as distant earth points through any and all metallic paths, primarily the power supply cable.

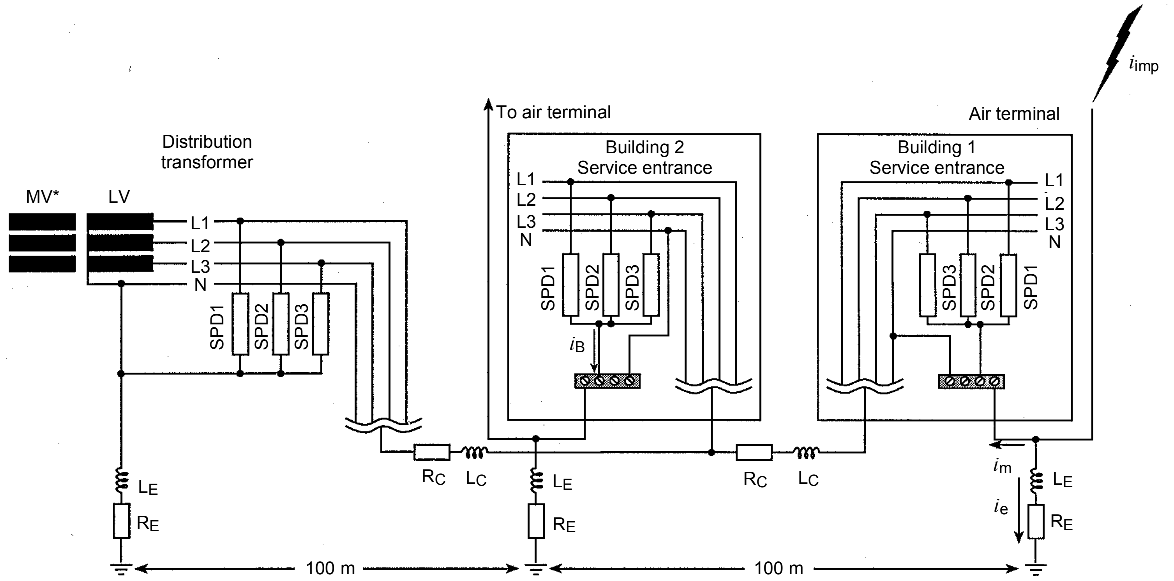
To quantify this dispersion, two examples have been simulated, using the PSPICE programme, as detailed in annex A, and summarized here. Figure 12 shows two buildings supplied from a substation where building 1 is struck by lightning as defined in IEC 61312-1.

At building 1 of figure 12, the injected current i_{imp} flows from the air-termination system of the lightning protection system through the down-conductor to the earth-termination system. At that point, the lightning current divides into two components, i_{e} flowing into the local earth of the building, and i_{m} flowing through the power supply cable toward the distant earth. These two currents divide according to the inverse ratio of the impedances. In the initial phase of the impulse current, the current division is determined by the ratio of the inductances. Experimental data have confirmed this behaviour [14]. In the tail, where the rate of change is low, the division is determined by the ratio of the resistances as in (6):

$$i_{\mathrm{m}}/i_{\mathrm{e}} = R_{\mathrm{e}}/R_{\mathrm{m}} \qquad (6)$$

With several buildings electrically connected, the effective resistance R_{m} decreases, which means, according to (6), that the portion of the lightning current that flows out of the struck building into the LV system will increase when more buildings are connected into the string. For the example of figure 12, table 4 shows the current amplitudes among the available paths to earth (after the initial inductance-dominated stage) as computed by the numerical simulation detailed in annex A. For these computations, no evidence was found of any oscillations caused by reflections, because of the low 10 Ω earthing impedances and no capacitances having been postulated in the model [5]. Other examples of current dispersion are given in annex A. For cases where the waveform is shorter, the current dispersion cannot be simply assessed by considering only the resistances [31].

1) The path of the lightning current as it divides among available paths is often presented as originating from the cloud and flowing into the earth. It should be noted, however, that for a negative cloud-to-earth ground stroke (figure 3), the lightning is a ‘return stroke’ from the earth – ‘into the earth’ – with positive charges neutralizing the negative charges in the lightning channel (inclusive branches) and the cloud.



* The coupling of the MV side not specified.

Dimensions in millimetres

Figure 12 – Model for computing dispersion of lightning current among parallel buildings in an example of TN-C system

Different practices on earthing the neutral are found in different countries, so that some differences can be expected in the way the lightning current will disperse among the available paths [31], but the general principle illustrated by the example remains applicable. When the neutral is earthed at every building, as in a TN-C-S system, no SPD is involved in the neutral conductor paths, providing some relief for the other SPDs associated with the line conductors. System designers should take these differences into consideration.

As a general conclusion, the higher the density of buildings in an area, the greater the portion of the lightning current flowing to earth through the incoming LV power system cable. This conclusion has implications for the building being struck as well as for adjacent buildings.

Table 4 – Current dispersion in available paths in the example of figure 12 (10/350 µs, 100 kA)

Available path to earth	Approximate current amplitude, (beyond initial stage) kA	Approximate charge C
Earthing electrode(s) of building 1 ($i_{Earthing}$)	33	16,5
Outgoing from building 1 towards building 2		
Total (I_m) via power supply cable	66	33
Direct via neutral	17	9
Through SPD1	16	8
Through SPD2	16	8
Through SPD3	16	8
Into earthing electrode of building 2		
Total	34	16,5
Direct via neutral	9	4,7
Through SPD1	8	4
Through SPD2	8	4
Through SPD3	8	4
Outgoing from building 2 towards transformer station via power supply cable		
Total	33	16
Direct via neutral	9	4,5
Direct via line 1	8	4
Direct via line 2	8	4
Direct via line 3	8	4

5.7.2 Overvoltages resulting from current dispersion

The current dispersion among the available paths will produce overvoltages primarily between the conductors and local earth. Depending on the configuration of the LV installation and the presence or absence of SPDs, these overvoltages can be large or can be moderate. Some examples derived from the simulation described above are provided in greater detail in clause A.5, where two examples are described of overvoltages resulting from a surge current postulated to appear at the service entrance of an installation. In those examples, an impulse current was injected at the entrance of actual buildings and measurements were made of the overvoltages appearing at selected points inside the building.

Recent experiments have been conducted on a replica of a multi-earthed low-voltage installation, with injection of triggered lightning at various points of the installation [14]. Results basically agree with the preceding statements and show the beneficial effect of improved neutral earthing at the service entrance and the significance of taking into consideration resistive, inductive, and mutual coupling effects.

It should be noted that the earth potential rise resulting from a direct flash to a building or structure normally exceeds the insulation level of the low-voltage installation and consequently produces flashovers and overvoltages that propagate to adjacent buildings (installations) connected to the same low-voltage distribution network.

Consequently, even for an underground network, a building not struck by a lightning flash can be exposed to overvoltages. The number of buildings (installations) involved in this propagation process increases with the soil resistivity. Moreover, for a given flash density in the area, the presence of a tall building, although reducing the probability of direct flashes to smaller buildings in its vicinity, enhances the probability of conducted overvoltages.

Overvoltages between conductors and local earth stress the insulation of connected equipment which usually has sufficient withstand levels according to IEC 60664-1 recommendations, while the working components of power equipment are stressed by overvoltages appearing between conductors. At first glance, it might be rationalized that the most threatening situation would be the overvoltages applied to the working components of the power equipment. However, overvoltages to earth can become a problem, not so much for the power equipment insulation, but as a result of shifts in reference potentials between the power system and the communications system that might be connected to the equipment. This potential problem is discussed in greater detail in clause 8 and in annex D.

As discussed above, the differences existing in neutral earthing practices and provision of SPDs, if any, make it difficult to give broadly applicable numerical results, and caution must be exercised against unwarranted generalization from illustrative examples.

5.7.3 Frequency of occurrence

The annual frequency N_d of direct flashes to a structure can be assessed by the product of the annual ground flash density N_g (flashes per km^2 per year) by the effective collection area of the structure A_e (km^2) as follows:

$$N_d = N_g \times A_e \tag{7}$$

The effective collection area of the structure is defined as the measure of the ground surface which has the same annual frequency of direct lightning flashes as the structure. It is a function of the structure dimensions and depends on ground topology and surrounding objects (see IEC 61024-1).

For a rectangular structure on a flat site, A_e is given by the following:

$$A_e = 10^{-6} (A + 3\ h \times p + 9\pi h^2) \tag{8}$$

where

A is the horizontal area of the structure in m^2;

h is the height of the structure, in m;

p is the perimeter of the roof, in m.

Depending on N_g, the order of magnitude of N_d for a small building is about 10^{-2} to 10^{-3} per year. However, as stated in previous sections, the probability of occurrence of overvoltages in the low-voltage network due to flashes to other buildings will be much higher, but at lower stress levels. For instance, simulations made for a typical overhead network [45] have concluded that the rate of occurrence of the latter overvoltage (by propagation) is in the order of 0,1 to 0,3 events per year.

The level of stress depends, of course, on the nature of the soil, on the type of network (overhead, underground), and on the number and quality of neutral earthing. There are no firm data on the relationship between specific stress levels and their frequency of occurrence, but IEC 61662 provides some guidance on the subject.

5.8 Recapitulation on lightning overvoltages

Lightning overvoltages originate from a source beyond human control and their severity at the point of utilization of electric power depends on many parameters determined by the point of impact of the lightning stroke and by the structure of the power system. While the structure of the power system is under human control, its parameters are generally determined by considerations other than lightning protection.

These overvoltages may be classified according to their point of impact: direct flashes, near flashes, far flashes. For direct flashes, the overvoltages result from the flow of lightning current in the structure of interest and the associated earthing system. For near flashes, the overvoltages result from induction of voltages in the conductor loops and to some extent earth potential rise associated with the lightning current. For far flashes, the overvoltages are limited to those induced into circuit loops.

Increasing stresses occur as the point of impact of the stroke is closer to the structure of interest, but the likelihood of such high stress is lower than that of a stress of lower magnitude associated with more remote flashes. In any case, statistical considerations, which will be discussed in clauses dealing with risk analysis, are an essential part of the decisions to be made concerning protection against these lightning overvoltages.

Lightning occurrences and lightning characteristics are of statistical nature, and there are still uncertainties involved. For instance, most direct current measurements have been made for high towers, and the results might not in general be representative. Geographical area including climatic conditions can also be decisive.

Measurements as well as theoretical studies are still going on in several parts of the world, and more reliable data on lightning and lightning effects are expected in the future.

Note that any proposal for applying theoretical considerations or results of limited measurements to define a relationship between frequency of occurrence and magnitude of lightning overvoltages should always be reconciled with reality checks, as discussed in clause 9.

6 Switching overvoltages

6.1 General

Generally, any switching operation, fault initiation, interruption, etc. in an electrical installation is followed by a transient phenomenon in which overvoltages can occur. The sudden change in the system can initiate damped oscillations with high frequencies (determined by the resonant frequencies of the network), until the system is again stabilized to its new steady state. The magnitude of the switching overvoltages depends on many parameters, such as the type of circuit, the kind of switching operation (closing, opening, restriking), the loads, and the circuit-breaker or fuse. In this clause, the phenomenon is described in principle, utilizing simple examples in order to present a general basic description.

Figure 13 shows an elementary circuit where an RLC load is being switched on by a circuit breaker and figure 14 shows typical transients associated with this switching. The voltage is superimposed on the power frequency voltage of the power system and is in this example stabilized within about one cycle. The maximum voltage is mainly determined by the closing instant of the breaker in relation to the voltage of the supply system. The highest high-frequency overvoltage usually occurs when the breaker is closed at the maximum of the voltage (not to be confused with the offset current, which is highest for closing at 0 V.)

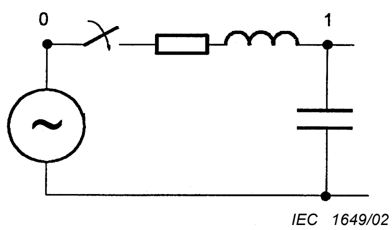


Figure 13 – Generation of overvoltage by switching an RLC circuit

In most cases, the maximum overvoltage is in the order of twice the amplitude of the system voltage, but higher values can occur, especially when switching inductive loads (motors, transformers) or capacitive loads. Also, interruption of short-circuit currents can cause high overvoltages. If current chopping occurs, relatively high energy can be stored in inductive loads, and oscillations can occur on the load side of the opening switch or fuse.

The frequency of the oscillations during switching operations is determined by the system characteristics, and sometimes resonance phenomena can occur. In such cases, very high overvoltages can be produced. The probability of resonance with harmonics of the power frequency of the system is usually low. However, if the characteristic frequency of a switched part of a system is close to one or more resonant frequencies of the rest of the system, a state of transient resonance can occur.

Lightning overvoltages described in clause 5 are mainly based on theoretical calculations, and the concept of prospective overvoltages (no inherent voltage limitation) was introduced in that context. In contrast, for switching overvoltages, extensive theoretical studies in the different existing and complex low-voltage systems have not been found in the literature[1)], and are also difficult to perform. Instead, data are obtained from staged measurements and recordings of transients as they occur in existing systems or in laboratory experiments.

The following considerations regarding switching overvoltages are to a large extent based on measurements in real low-voltage systems. Therefore, the reported voltages are limited by the withstand of the system and connected apparatus. In addition, surge protective devices (SPDs) in the system (and built-in SPDs) will limit the measured voltages. This fact should be noted when considering the numerical values shown in this clause and in annex B.

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1) Except for capacitor switching transients in MV systems, which are passed on to LV systems, see clause B.2. These have been the subject of several studies as well as field measurements [23], [13].

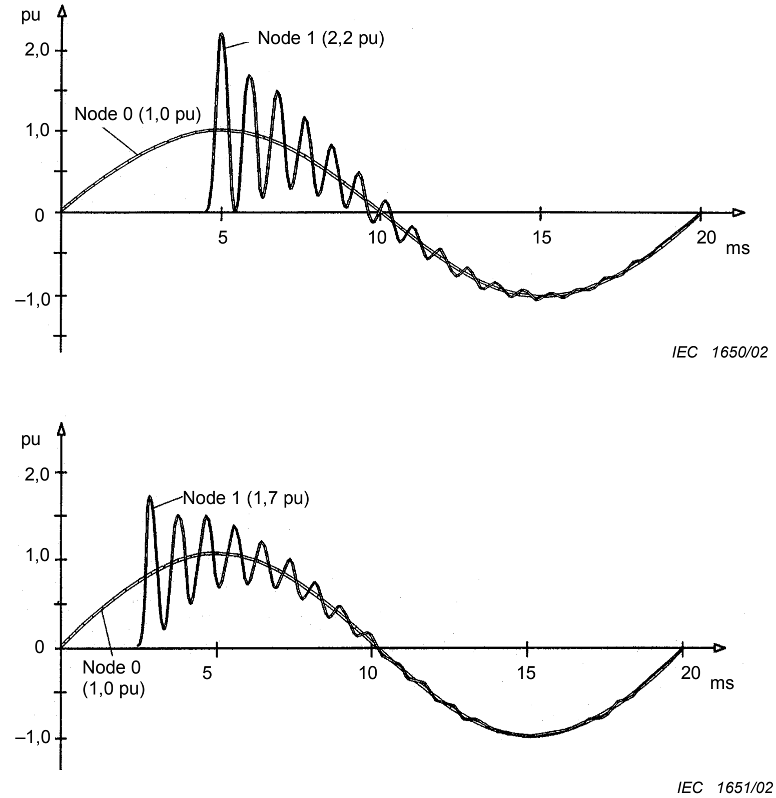


Figure 14 – Typical switching overvoltages

The typical shape of switching surges is determined by the response of the low-voltage installation. This situation results in most cases in a ringing wave as shown in principle in figure 14. Figure 15 is an example of a measured switching overvoltage recorded in a real system, showing similar characteristics, but at higher frequency than those shown in figure 14.

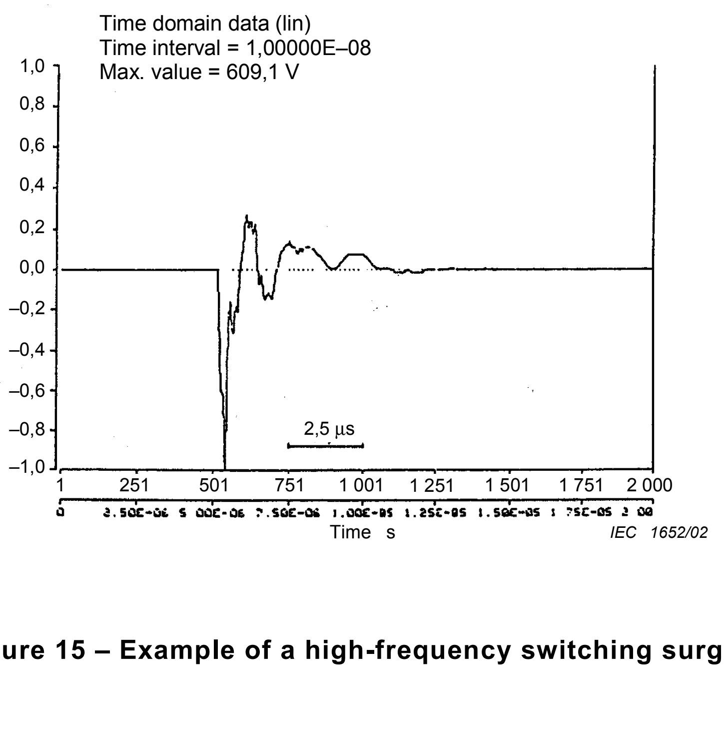


Figure 15 – Example of a high-frequency switching surge

The oscillation frequency is typically in the order of several hundred kilohertz. The rise times are usually in the range of 0,1 µs to 0,5 µs and the maximum rate of rise usually is in the order of some kV/µs. A typical distribution of the rates of rise (which does not include very short spikes) is shown in figure 16.

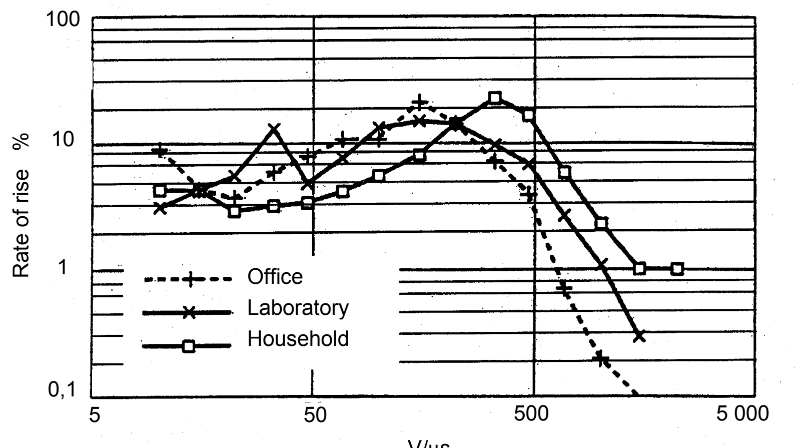


Figure 16 – Distribution of the rate of rise of switching surges at different locations

As the maximum amplitudes of switching surges are not higher than a few kV, the rise times will be in the range of 0,5 µs to 2 µs. The distribution of the rise times is shown in figure 17. Therefore, the maximum rate of rise of typical switching surges more or less corresponds with the rise time of the standard waveshapes of the 1,2/50 µs impulse or the 0,5 µs - 100 kHz ring wave. The correspondence with the 1,2/50 µs impulse is shown in figure 18 for rather low amplitudes.

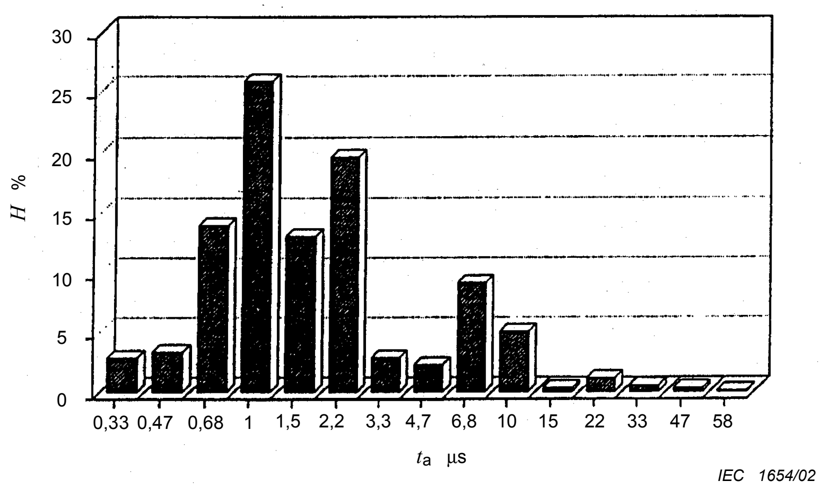


Figure 17 – Distribution of the rise time of switching surges

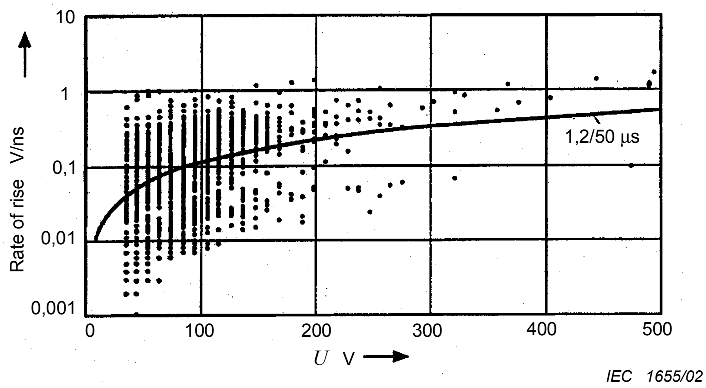


Figure 18 – Rate of rise of the switching surges and their crest values

The duration of the surges is distributed over a much wider time range. If switching overvoltages caused by operation of fuses with high rated current in case of short-circuit interruption are excluded, the typical duration (time to half-value) is from 1 µs to 50 µs, which is shown in figure 19.

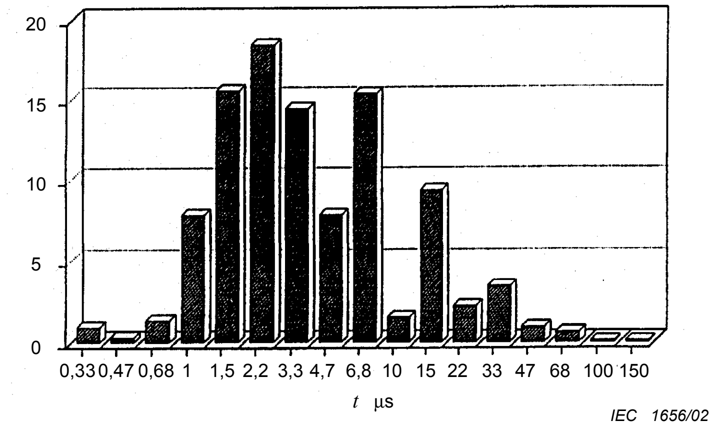


Figure 19 – Distribution of the duration of the switching surges

6.2 Operation of circuit-breakers and switches

Circuit-breakers and switches are widely used in every installation for either protecting electrical equipment by switching off in case of overload or short circuit, or for controlling the operation of equipment by switching on and off. The frequency of switching depends on the field of application with higher rates in the industrial and relatively lower rates in the domestic range.

The switched currents in case of most resistive loads are in the range of the rated current of the equipment. However, filament lamps draw an inrush current approximately 10 times their rated current, as the filament has a low resistance when cold, giving rise to higher switched currents. For non-resistive loads such as switched-mode power supplies, the switched currents are much higher than the rated current.

One reason is inrush current when capacitors are charging up. For instance, in the case of a 100 W television set, the rated current is 0,4 A but the inrush current is approximately 20 A, which is 50 times higher. Another reason is crest factor of the non-sinusoidal current, with peak currents higher than that expected from the rated r.m.s. value.

Opening of mechanical switchgear, either manually or by an electromechanical operation, produces an electric arc during each switching process. A high-frequency oscillation is generated by the sudden voltage change together with the inductances and capacitances in the environment of the switch. This oscillation is superimposed on the voltage between the line conductors and between a line conductor and earth, and the total voltage is stressing the insulation of electrical equipment with respect to exposed conductive parts and other circuits. In contrast to transient overvoltages transmitted via the public distribution network into the customer's installation, switching transients generated within the customer's installation by circuit-breakers and switches affect the electrical equipment without significant attenuation, so that the amplitude of those transients is relatively high.

The magnitude of switching overvoltages can be assessed by detailed measurements in electrical installations and their statistical evaluation. By such measurements, it is possible to characterize the frequency of the occurrence of transient overvoltages depending either on certain time periods during a year or on certain weekdays or a certain time of the day. If such a time-dependent characteristic exists, the occurrence of transients can be inferred from events within the electrical installation, for instance by switching or by operating appliances which can create interference because of their design.

Measurements in industrial and other installations have shown that the frequency of the occurrence of overvoltages decreases with their magnitude. In low-voltage systems, switching overvoltages are expected to be not much higher than 4 kV because at that level clearances of electrical equipment are likely to be insufficient to prevent flashover, and thus limit the peak values. As an example, the statistical distribution of switching overvoltages obtained from measurements in industrial systems is shown in figure 20.

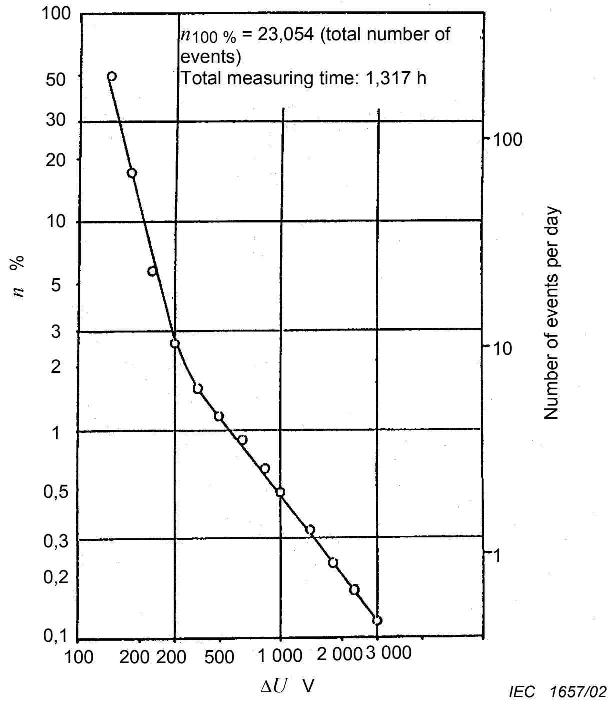


Figure 20 – Example of distribution of switching surge amplitudes measured in industrial distribution systems rated 230/400 V

Statistical evaluation of extended measurements led to the conclusion that only 1 to 2 out of 1 000 recorded switching overvoltages have amplitudes in excess of 2,5 kV. Other long-term measurements, which were performed in installations of different kind and in different locations (see annex B), show similar results. Most of the recorded transient overvoltages were even below 1 kV and only one value was around 6 kV.

It should not be concluded that circuit-breaker and switch operations in general cause minor problems with regard to the generation of switching transients. The data presented in measurement results are not all-inclusive and switching surges can exist more frequently than these data indicate. Therefore, when assessing the need for SPDs, consideration should be given to this fact. It should be noted that, especially in industrial installations, the energy stress on SPDs can be relatively high.

NOTE The above-mentioned measurements have been performed in real installations with equipment connected. Therefore, even if SPDs external to equipment in the installation concerned had been disconnected, the results obtained are always influenced by the construction of the equipment connected (for example, clearances, creepage distances, impulse voltage withstand, filter- and/or SPD-components inside the equipment) and will not represent the prospective overvoltages occurring in the installation in question. The only way to take into account these influencing factors would be to perform combined measurements of impulse voltages and corresponding surge currents occurring at an installation, thus giving an indication about the energy stress to be expected for equipment, if no external SPDs are installed. Due to the complexity of such measurements, no such data are available for the time being. See [34], [9] and [37] for more information on this possible problem.

6.3 Operation of fuses

Compared to other surges caused by operational switching, the occurrence of surges due to fuse operation is less frequent. However, in case of interruption of a short circuit, very severe switching surges can be generated. This condition is mainly influenced by the rate of rise of the short-circuit current, the characteristic of the fuse and its current rating, and the inductance of the circuit.

In electrical equipment, miniature fuses with current ratings between 0,0032 A and 10 A are frequently used.

The switching surge in case of short-circuit interruption by a miniature fuse with a rated current of 1 A is shown in figure 21. In that case, the amplitude of the switching surge is rather high but the duration is fairly short. In a series of tests performed in the range of current ratings between 1 A and 10 A, the amplitudes of the switching surges were found to be rather constant, as high as 2,6 kV.

However, due to the increased time duration (table 5) of the surges, the energy-delivery capability is substantially increasing with the rated current of the fuse. The rate of rise of the surges can reach 2,6 kV/µs. For some current ratings of the fuse, the switching surge is also influenced by the fuse characteristic. A fast-blow fuse will cause surges of shorter duration than a slow-blow fuse.

Table 5 – Time to half-value of the switching surges versus rated current of miniature fuses

Fuse rating A	**Time to half value** µs
1	8
1	24
1,6	36
10	64

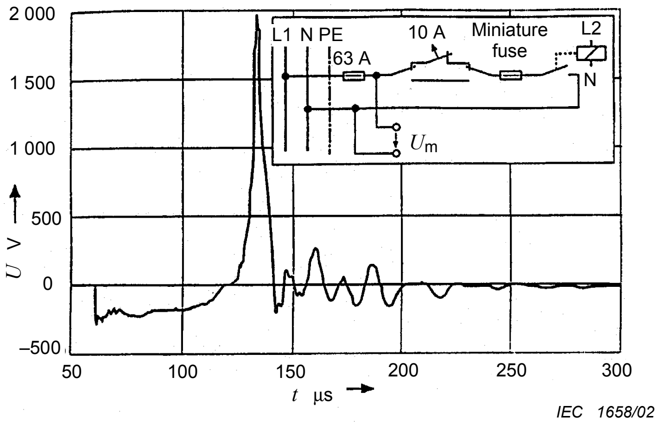


Figure 21 – Switching surge during interruption by a miniature fuse [48]

Clearing of a short circuit in a feeder of a distribution system by a fuse installed near the busbar is a relevant matter because the overvoltage generated by the switching of the fuse is effective on all other current-using equipment connected to the same busbar. Experience based on statistics has shown that such a fault occurs very rarely in the public low-voltage supply. However, this type of fault is relevant for industrial distribution systems, where a short-circuit is not a very rare event. Annex B provides two examples of measurements, one made for a short circuit occurring near a feeder fuse, the other for a short circuit occurring at the end of the cable.

6.4 Frequency of occurrence

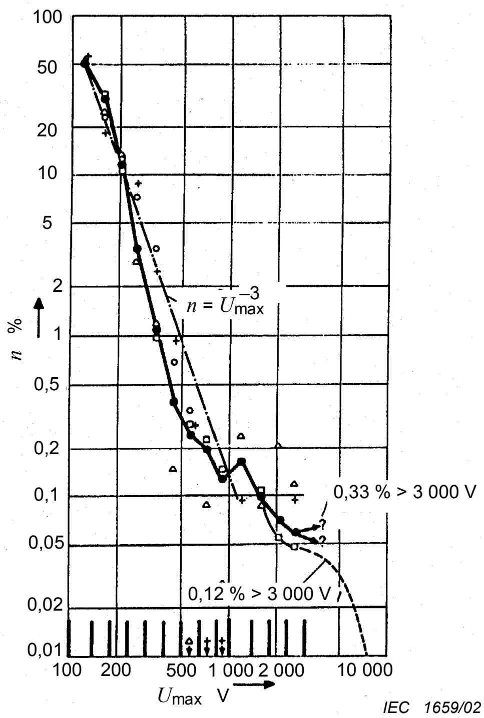
Both the relative values of the probability of occurrence of switching surges and the absolute values may be evaluated. The first method, relative values, is more appropriate if different measurements and/or locations have to be compared.

As an empirical rule, the probability of occurrence of a switching surge seems to be inversely proportional to the third power of its amplitude. This behaviour, which will be called the third-power law, is shown in figure 22, for different types of locations [44], [21]. However, with increasing amplitude of the switching surge, there seems to be a general tendency for some deviations from the third-power law. These deviations seem to be more pronounced for some types of locations such as, for instance, commercial.

In figure 22, the relative probability of occurrence of a switching surge of 2 500 V amplitude is about five to ten times greater than the extrapolation of the third-power line from the region of lower amplitudes. As this result is based only on a few data points, it is rather uncertain and it is given here only as an example. Due to substantial differences between the overvoltage characteristics at different locations, which is a common result of all investigations, the data should be analysed in detail separately [42].

6.5 Interactions with surge-protective devices

Because switching surges involve the response of the installation to the voltages, current, and energy stored in the circuits at the power frequency, their energy-delivery capability can be substantial. However, as mentioned above, their amplitude is often limited, giving an opportunity to avoid the risk of having an SPD attempt to clamp them. System designers and equipment designers should apply SPDs with due consideration of the possible occurrence of switching surges with high energy-delivery capability, as discussed in clause 12.



Key

- • all data
- □ industrial
- Δ commercial
- o household
- \+ laboratory

Figure 22 – Distribution of the relative frequency of occurrence of switching surges at different installations

6.6 Recapitulation on switching overvoltages

In most cases, the maximum switching overvoltages are in the order of twice the amplitude of the system voltage, but higher values can occur, especially when switching inductive loads (motors, transformers) or capacitive loads. Also, interruption of short-circuit currents can cause high overvoltages. If current chopping occurs, relatively high energy can be stored in inductive loads, and oscillations can occur on the load side of the opening switch or fuse.

The magnitude of switching overvoltages can be assessed by detailed measurements in electrical installations and their statistical evaluation. By those measurements, the frequency of the occurrence of transient overvoltages depending either on certain time periods during a year or on certain week-days or at certain times of the day can be evaluated. Beware, however, of the limiting effect of undefined SPDs that might be present in the installation. If such a time-dependent characteristic exists, the occurrence of transients may be inferred from events within the electrical installation, by staged switching or by operating appliances which can create interference because of their specific design.

These considerations make it necessary to assess the likelihood that a candidate SPD intended for mitigation of switching surges can offer effective voltage limitation. Next, it should then be determined that the SPD will have the necessary capability to deal with the current levels and durations involved in the switching surges to be expected at that location.

7 Temporary overvoltages

7.1 General

A wide range of phenomena, either resulting from normal system operation, or from accidental conditions, can produce overvoltages which must be distinguished from the switching overvoltages discussed in the preceding clause. These overvoltages occur at the power system frequency and generally require operation of some existing protective overcurrent equipment to clear the circuit, should some equipment fail under that stress. Note, however, that equipment is generally designed to withstand temporary overvoltage stresses. Surge protective devices at the present state of technology – as applied for protection against lightning and switching surges – do not have the energy-handling capability that would be required for limiting these temporary overvoltages. Therefore, when selecting the maximum operating voltage for surge protective devices (SPDs) at a particular installation, the expected magnitude and probability of occurrence of temporary overvoltages at the actual site have to be taken into consideration.

7.2 Magnitude of temporary overvoltages due to MV and LV faults

Temporary overvoltages are defined as a.c. overvoltages with a significant duration and amplitude that can appear in a system following a fault condition. They are, in general, originated by insulation faults or loss of a supply conductor in the MV or LV electrical installation. Product standards take into account these phenomena by appropriate insulation requirements and tests. IEC 60364-4-442 provides some information and data which are summarized here, with additional details in annex C.

NOTE In systems with MV and LV lines mounted on the same poles, or systems with two different MV levels also mounted on the same poles, accidental commingling of the systems can occur, causing substantial overvoltages on the LV system. In the application of SPDs to low-voltage systems, consideration of commingling is generally not included. However, if such exceptional events are to be considered, special SPDs need to be applied to survive the event or, at least fail in an acceptable manner. Further discussion of this problem can be found in annex C.

Depending on the configuration of the earthing of the MV and LV networks, the MV fault current flows into one or more earth electrodes and generates a.c. overvoltages in the LV system by earth coupling.

The main parameters which influence the value and the duration of the overvoltages are listed below.

All of these are determined by the designers of the power system:

a) the configuration of the earth electrodes of the MV and LV network:
   - one, two or three distinct earth electrodes;
   - common earthing electrodes or separated earthing electrodes for MV and LV networks;
   - the values and the number of earth electrodes of the LV distribution system;
b) the type of system earthing of the MV network:
   - isolated;
   - resonant-earthed;
   - earthed through an impedance;
   - solidly earthed;
c) the method used to clear the MV fault:
   - long time for isolated resonant-earthed or impedance-earthed types;
   - short times (<5 s) for low-impedance earthed types;
   - shorter time for solidly earthed types.

Temporary overvoltages appear at different places and apply in different ways.

– In the MV/LV substation, the overvoltage stresses the insulation of the LV equipment between live parts and exposed conductive parts if there is no common MV/LV earthing.

– In the low-voltage electrical installation, the overvoltage stresses the insulation of low-voltage equipment, between live parts and exposed conductive parts if the neutral is not connected to the local earthing electrode.

– An overvoltage appears between the local earth of the low-voltage installation and remote earth which can stress, for example, the double insulation of Class II equipment used outside a building or service entrance which would not be connected to the main earthing terminal.

Table 6 provides some information on the maximum values and durations which might occur depending on the MV/LV earthing electrode configuration and the LV system configuration. Note that the values of 250 V and 1 200 V specified in some columns of this table are the maximum values allowed according to IEC 60364 for connecting the MV earth and the LV earth together. In actual practice, much lower values occur.

Table 6 – Maximum values of overvoltages allowed to occur during MV faults to earth

Type and earthing MV-system with single earth fault	Earthing arrangement according to IEC 60364-4-442	Maximum r.m.s. stress voltage on equipment within LV-installations			Fault duration	Maximum duration
		L-PE	N-PE	L-N	s	A
3 wires, isolated	TN, TT, IT	U_0	0	U_0	>>5	Some tens
3 wires, resonant earthing or 3 wires, impedance earthing	TN, TTb) ITa), c), d)	U_0	0	U_0	>>5	Some hundreds
	TTa), ITb), e)	≤250 V + U_0	≤250 V	U_0	>>5	
Low impedance earthing (France)	TN, TTb) ITa), c), d)	U_0	0	U_0	<5	Some hundreds
	TTa), ITb), e)	≤1 200 V + U_0	≤1 200 V	U_0	<5	
3 wires/direct earthing	TN, TTb) ITa), c), d)	U_0	0	U_0	<5	Some thousands
	TTa), ITb), e)	≤1 200 V + U_0	≤1 200 V	U_0	<5	
4 wires, direct earthing (USA practice)	TN	≤2,45 U_0	0	≤2,45 U_0	<5	Some thousands

NOTE 1 If there is no distinction made between TTa) and TTb), for example, but only stated for TT, this means that this subclassification has no influence on the maximum r.m.s. stress voltages given in the table.

NOTE 2 U_0 is the nominal voltage line to earth of the low-voltage system.

NOTE 3 For overvoltages above 1,5 to 2 times U_0, SPDs can be prone to failure or even destruction. Therefore, product standards for SPDs require that the devices fail in a safe way without endangering persons or the risk of fire in such cases. This condition can be ensured by means of a suitable automatic disconnection device, acting for a short duration or permanently, such as a dedicated protective device called SPD disconnector.

NOTE 4 Double faults might need special consideration.

NOTE 5 The information given in table 6 presents maximum values allowed according to IEC 60364; if earth fault tripping is used in isolated or resonant earthing systems, fault durations less than 5 s can be obtained.

Temporary overvoltages could occur from the effect of ferro-resonance within a distribution transformer when one phase of the incoming MV supply is lost upstream of any appreciable phase-to-earth capacitance.

7.3 Temporary overvoltages due to defects in the LV electrical installation

7.3.1 Temporary overvoltages due to a short circuit between a line conductor and the neutral conductor

After the transient situation, the magnitude of the short-circuit current is limited only by the supply and building wiring impedances. The currents involved can be very high, ranging between one hundred and tens of thousand amperes. A protective device operates to clear the fault. During this period of a few milliseconds to a few hundred milliseconds, but in all cases lower than 5 s, a temporary overvoltage condition occurs. The value of the overvoltage can be calculated from the supply and building wiring impedances. The value of 1,45 U_0 is considered to be a representative upper limit (see IEC 60364-4-442). The conditions are very similar in the case of an insulation fault to earth in a TN-system.

7.3.2 Temporary overvoltages due to LV insulation faults to earth

After the transient situation, a temporary overvoltage occurs during such a fault.

– In a TN system, earth faults can produce overvoltages comparable to those occurring in circuits where the fault is between phase and neutral. Indeed, the return path to the neutral of the transformer consists of a cross-section comparable to that of the phase conductors.

– In a TT system, earth fault currents flow through the PE conductors and two earth electrodes. These earth electrodes are separated, or at least not intentionally connected. Consequently, the fault current remains relatively low. The fault is generally cleared by the residual current circuit-breakers. The corresponding overvoltage is considered to remain lower than $\sqrt{3}\ U_0$.

– In an IT system, the earth fault current in case of a first fault is very low: it is the capacitive leakage current of insulated conductors of the distribution system including the installation, and of the filters in electrical equipment. The first phase-to-earth fault is unlikely to operate any form of protective device but will cause transients and establish an overvoltage condition close to the phase-to-phase supply voltage.

NOTE Resonance phenomena can occur in IT systems earth faults involving high reactances (fluorescent lamp reactors, motors, etc.), when the oscillating frequency (for the reactance of the circuit in series with the system capacitance) is close to the operating power frequency. This phenomenon can produce temporary overvoltages two to three times the normal line-to-earth voltage, or even higher. This type of overvoltage occurs for all installations supplied by the same MV/LV transformer, and SPD failures due to this phenomenon are experienced in some IT systems.

7.3.3 Temporary overvoltages due to the loss of a live conductor

In three-phase systems, loss of any conductor can give rise to various conditions such as unbalance, faults and temporary overvoltages, that can indirectly result in transients. For example, loss of a neutral conductor in an unbalanced star-connected supply can result in a temporary overvoltage condition where two phases attain the phase-to-phase voltage with respect to neutral. This can cause a fault and possible transients associated with initiation or clearing of the fault. In that case, it is generally considered that the permanent stress voltage is the line-to-line voltage.

7.4 Probability of occurrence and severity of harm

7.4.1 Temporary overvoltages due to faults between MV and earth

AC insulation faults to earth are likely to occur on overhead MV lines during thunderstorms or due to other incidents. Failures due to temporary overvoltages need only be expected when any of the main risk parameters occurs with a sufficient severity. These parameters are listed below, together with the most adverse conditions which can occur:

– location of the MV earth fault: in the substation;

– earth fault current: due to adverse momentary system conditions;

– resistance of the substation earthing: at the upper end of the tolerance band;

– LV system configuration: TT-a;

– momentary condition of the stressed item: energized or not.

As already stated in 5.2, when lightning strikes the MV system, operation of an SPD located on the MV side initiates a current flow through the corresponding earth electrode. In many existing networks, SPDs (“surge arresters”) are still of the air gap type and the surge current starts the flow of an MV fault current at the power frequency, which is not interrupted at the first zero crossing.

Utilities strive to minimize the numbers of MV earth fault events to those associated with severe weather conditions, such as thunderstorms, ice, and wind. If a substation has an indoor location, measures to avoid earth faults can be most effective and earth faults can then be considered as having a very low probability.

Medium-voltage system configurations are well defined so that their earth fault currents can be predicted by calculation even though they vary depending on the location of the earth fault. The current calculated for an earth fault in a specific substation will be the basis for the determination of the resistance of the earthing arrangement to comply with the requirements of IEC 60364-4-442. This excludes the location of the earth fault to be a risk parameter. Other parameters, such as the number of temporarily switched-off feeders call for consideration only if they lead to higher currents for MV earth fault in the substation.

The above considerations regarding the occurrence of adverse conditions are the basis for estimating the probability of a harmful event in the LV system as a consequence of an MV earth fault in the substation. This probability of harm is one of the factors of the risk to be considered.

If surge arresters are installed on the MV side, close to an MV/LV substation, they normally decrease the number of earth faults. The current flow through the SPD to earth is restricted to a short surge if the surge arrester is of the metal-oxide type. In case of gapped arresters, a short-duration a.c. current follows. In case of gaps alone, an a.c. follow current occurs, to be cleared by the MV protective devices after a duration that depends on the type of device used.

Among the LV systems, the TT-a configuration (common LV and MV earthing system) is the most critical. Generally, the rules of the utilities enforce the use of TT-b (separate MV and LV earthing systems), and the TT-a configuration is not often applied due to lack of space or difficult earthing conditions. In urban and industrial areas, the local earth at the consumer's premises and the station earth are usually closely linked in electrical potential due to extended metal items like pipes between the substation earth and low-voltage earth. Consequently a reduced voltage drop is developed across the station earthing arrangement which practically extends to the user's premises.

Finally, the immunity specification of an item which is likely to be subjected to temporary overvoltages depends on its mode of application. An SPD, for instance, is permanently energized, whereas, at the lower end of the severity scale, a portable tool is connected to the LV system only for a very short fraction of its lifetime; in the latter case, the probability of coincidence with an MV earth fault in the substation is then extremely low and the immunity specification is likely to be correspondingly low.

7.4.2 Temporary overvoltages due to faults in the LV installation

The likelihood of LV insulation faults cannot be neglected in normal installations. This possibility increases for old installations and equipment which is not permanently energized or is installed in humid or polluted areas. Generally, insulation faults are more likely to occur between active conductors and earthed conductive parts than between the active conductors considered hereafter. The effects of these earth faults (voltage drops and in particular overvoltages) affect the SPDs. These effects are determined by the location of the fault and, in the case of a fault to earth in TT systems, the impedance to earth of the earth electrodes.

If the SPD has been selected with a maximum continuous operating voltage (MCOV, U_c) lower than the overvoltage generated by the LV insulation failures or the loss of a supply conductor, the current flowing through the SPD increases very quickly and thermal destruction of the SPD occurs. The effects of this failure are limited to the SPD itself by its incorporated thermal protection. This SPD failure can then leave the installation or equipment without other overvoltage protection.

It is recognized that if the maximum continuous operating voltage (MCOV) of the SPD, U_C, is chosen equal to or higher than 1,45 U_0 for TN systems and higher than √3 U_0, for TT systems, a tolerable risk of SPD failure and resulting loss of protection against overvoltages is achieved in most situations. Furthermore, this tolerable risk can be obtained for lower U_C values in some system configurations, or by suitable SPD designs. As noted in 7.3.2, however, an exception is the case of an IT system where high values of MCOV might be necessary because of resonance phenomena.

For the remaining cases, when the possibility of a loss of protection is deemed acceptable, other risks have to remain covered; in particular, an appropriate protection against short circuits should be specified by the manufacturer and requested by the end-user.

Concerning the loss of the neutral conductor, the overvoltage is independent of the earthing system, but can reach values close to √3 U_0 in a three-phase system, applied between line conductors and neutral. The overvoltage can reach 2 U_0 in a single-phase, three-wire system whenever the loads in each side of the neutral are not balanced; this overvoltage is then applied across an SPD intended for surge protection of loads connected line-to-neutral. In the case of the loss of the neutral conductor, damage to the SPDs can be disregarded in comparison with the damages suffered by other equipment in the installation, as long as the SPD failure occurs in an acceptable mode.

In IT systems, due to the occurrence of a voltage close to the line-to-line voltage after the first fault, a full protection of the SPD can be achieved, but only if U_C is chosen equal to, or higher than, √3 U_0. Note, however, that other equipment have probably been selected similarly. As noted in 7.3.2, resonance phenomena can occur for earth faults in IT systems having high reactances.

7.5 Recapitulation on temporary overvoltage

Temporary overvoltages are a type of abnormal event which is extremely difficult – if not impossible – to prevent in the normal course of operation of a power system. The probability of such occurrence and the levels of overvoltages that can be reached depend on the design of the power system. This design is generally determined by overriding system constraints other than the consequences of applying an overvoltage to an SPD.

Therefore, SPDs have to suffer the consequences of an overvoltage, and various scenarios are possible, ranging from an SPD selected with a high MCOV that will make it immune to most temporary overvoltages (but at the price of diminished surge protection), down to a low MCOV selected by a wish to provide surge protection with low limiting voltage for loads perceived as needing such low limiting voltage, but at a greater risk of destruction under temporary overvoltage conditions.

This dilemma cannot be solved by mandatory practices imposed by one of the parties involved in the design, operation, and protection of power systems and connected loads. Rather, the situation requires cooperation among the parties, recognizing the limitations of the technology and weighing the options and consequences, depending on the specifics of the installation and its mission.

8 System interaction overvoltages

8.1 General

The title of this technical report might imply that its scope is limited to the occurrence and control of overvoltages in a.c. power systems. However, it is also necessary to consider another type of overvoltage associated with interactions between two different systems, such as the a.c. power system and a communications system, in particular during the flow of surge currents in one of the systems.

This consideration of an interaction is necessary because field experience has demonstrated that equipment failures are often summarily – and incorrectly – attributed to a surge impinging on the power port of a multi-port equipment, a power-line surge in the language of the media. The fact of the matter is that the stress on the equipment which produced the failure (upset can also occur at lower stress levels) is the result of the flow of surge current in one of the systems, either inherently, or as a side-effect of the flow of surge current resulting from the intended diverting action of an SPD.

Understanding the nature of the phenomenon is important because the system interaction stress can occur even if both ports of the equipment – power and communications – are protected by SPDs, one at each port or upstream in the systems, raising expectations of adequate surge protection being provided. When failure or upset of the equipment still occurs, questions are then raised on the adequacy of the existing SPDs. However, the answer will be found, not in providing improved SPDs installed separately on each of the ports, but by understanding the interaction scenario and providing effective remedial measures to address that stress.

8.2 Interaction between power system and communications system

As electronic equipment enters the home and business environment more and more, this often involves a communications port as well as the usual power-cord port. Typical examples involving a connection to the power system and the telephone system are a personal computer (PC) with modem connection, or a fax machine. Although each of the power and communications systems might include a scheme for protection against surges, the surge current flowing in the surged system causes a shift in the potential of its reference point while the reference point of the other, non-surged system remains unchanged. The difference of potential between the two reference points appears across the two ports of the PC/modem. Depending on the nature of the PC/modem and its immunity, this difference of potential can have some upsetting or damaging consequences.

Figure 23 illustrates the example of a PC equipped with a modem powered from a branch circuit which includes a protective earth conductor, with a three-wire cord that bonds the chassis to the earthing point of the power panel. The modem is connected to a telephone outlet in the room, wired to a protective device installed by the telephone company at the telephone service entrance (called Network Interface Device (NID) in North American practice).

For a worst-case scenario – often encountered – the power service and the telephone service enter the house at opposite ends of the house. In such a situation, the earthing connection of the NID is made to the nearest point of the earthing system, typically a cold water pipe (obsolete practice), a dedicated earthing wire, or an equipotential bonding conductor. In either case, the length of this earthing connection can be substantial. The result can be a large shift in the reference potential during the flow of surge currents.

The very same scenario applies to other equipment connected to the power system and to the telephone system, such as a fax machine or an answering machine. The difference, however, might be that a PC/modem is often assembled by the user or by a retailer from uncoordinated elements often obtained from different manufacturers, while the fax machine or answering machine are designed from the start as one unit. In the case of the PC/modem assembled from these uncoordinated components, immunity against the shifting reference potential is not assured. In the case of the fax machine or answering machine, one might expect that the design, under a single organization, should anticipate and make provision for these reference shifts. Field experience, however, indicates that problems still occur. Annex D provides further details on this example.

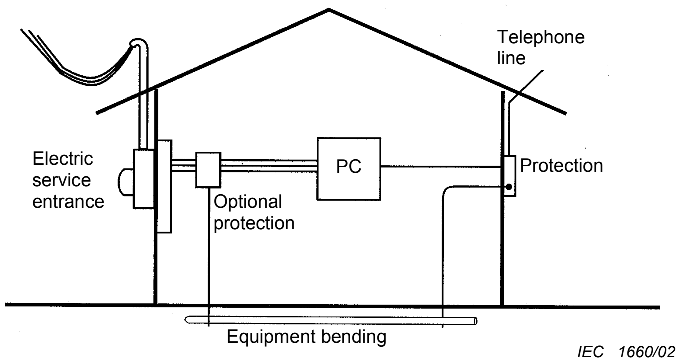


Figure 23 – PC/modem connections to the power system and to the communications system

8.3 Other interactions

A similar scenario can develop for a TV receiver or VCR, with the power supplied from a branch circuit and the video signal supplied from a CATV system or a satellite dish located outside the house. The difference would be that, instead of the symmetrical and balanced configuration of a telephone pair, the video signal is carried by a coaxial cable for which the shield would be the prime carrier of any surge current. The same observation as that made in the preceding paragraph applies to the TV or VCR, the product of an integrated design rather than uncoordinated assembly of separate components. Nevertheless, with the fast-paced evolution of satellite antenna systems for consumer applications, coordination of earthing practices appears a difficult goal to reach.

Another scenario can unfold in facilities such as an industrial installation where process control and sensor signals are carried by separate systems other than the power system on which this technical report focuses. Mitigation possibilities include provision of suitable hybrid multi-port SPDs, as discussed in annex D, as well as good earthing and cabling practices as described in IEC 61000-5-2.

8.4 Recapitulation on system interactions

System interactions occur at the interface of two different systems, such as the power system supplying equipment with its needs for power, and a communications system supplying the signals to be processed by the equipment. This multi-port equipment can be exposed to overvoltages occurring not only in differential mode at each of the ports, but also between the reference terminals of the two ports.

It is essential for proper operation and survival of the equipment to take into consideration the effects of this phenomenon, often unrecognized or incorrectly attributed to one of the systems, leading to unsuccessful attempts at mitigation applied separately at one or both ports.

9 Observations on surge overvoltages and failure rates

9.1 General

The preceding discussions of overvoltages have presented quantitative information on these phenomena, based in part on theory that makes assumptions on the prevailing situation, and in part on measurements. Field measurements can only reflect local conditions at the time of the measurement; laboratory measurements can only provide conclusions based on the assumptions underlying the experimental set-up.

Notes have been included in this report, that broad generalizations from limited data should not be made without some caution. Such caution is more a qualitative than quantitative process, calling for a reconciliation between predictions on the frequency of occurrence of large surges and the reality of field performance of equipment that are subject to the surges that actually occur in their environment.

Another qualitative caution is the reconciliation between the conclusions drawn from the sometimes simplified assumptions made for computations and the basic laws of physics. Any conclusion based on these simplifications, generalizations, or assumptions, which does not match reality, should be a call for caution on the validity of these simplifications, generalizations, or assumptions. Therefore, the following observations are presented as a measure of experience-based caution. They do not purport to deny the occurrence of large surges, but only to suggest that these large surges do not occur as frequently as the limited available information might suggest.

9.2 Using field failure data

Unfortunately, there are no extensive failure statistics available for LV equipment, and it is difficult to estimate the failure rate in an objective way. Nevertheless, some investigations made by insurance companies [29], [11], based on their internal statistics, indicate that equipment failures (video equipment, refrigerators, etc.) occur relatively frequently during thunderstorms, especially in areas with overhead LV distribution. Indications are also found that minor damages caused by leakage currents occur without breaker or fuse operation, producing the ultimate failure hours or days after the initial surge event. The reasons for these equipment failures include

- insufficient surge capability at the equipment power port;
- lack of insulation coordination;
- ageing of equipment;
- system interaction, in particular for video equipment (see clause 8).

While manufacturers are sometimes reluctant to publish their failure data, anecdotal information does often transpire to provide some indication on the success (survival) of generic equipment under actual field conditions. If the surge immunity levels, or failure levels, of these equipment are known, one can make inferences on the order of magnitude of the frequency of occurrence of surges above that immunity level. A high rate of failure occurrence would indicate a corresponding rate of occurrence of surges above that level. When the field experience shows in fact a low failure rate, one can infer an equally low rate of surge occurrence above the equipment failure level. However, that inference should be tempered by the fact that failure data are not systematically collected nor published by manufacturers.

One example of such inference is the historical record of incandescent lamp failures attributable to surges – over and beyond the normal end-of-life of these lamps. The qualifier “historical” is attached to the inference because nowadays the proliferation of SPDs and load equipment with a rectifier-capacitor [33] has considerably reduced the occurrence – and the observation – of surges in excess of two to three times the peak voltage of a power system [9], [37], [1]. Investigations on the failure mode and levels of incandescent lamps [4] have shown that a typical threshold above which incandescent lamps fail is between 800 V and 2 000 V for 120 V lamps, and between 1 800 V and 2 200 V for 230 V lamps, depending on the energy-delivery capability of the impinging surge. The higher the energy-delivery capability, the lower the threshold.

From this observation, one can infer that the rate of occurrence of surges above these thresholds in the line-to-neutral mode (the usual connection of lamps, as opposed to line-to-earth mode, which is the concern of insulation coordination) was not high, as the generally acceptable life rating for lamps in LV systems is being achieved. The relationship between energy-delivery capability of the surge and the threshold of failure is also consistent with earlier discussions, where it was noted that surges with high energy-delivery capability (such as surges from direct flashes) are considerably less frequent than surges with low energy-delivery capability (such as induced surges). This inference was valid before the proliferation of SPDs, and should remain valid as the mechanisms at the origin of surges have not changed in spite of the proliferation of SPDs.

Another example of observation relevant to the frequency of occurrence of large surges is the apparently low failure rate of metal-oxide varistors in LV systems, according to existing knowledge. Very high numbers of these devices have been installed since their introduction in the mid-seventies. While anecdotal failures have been reported [1)], the vast majority of these varistors is claimed to operate successfully when applied in an environment commensurate with their known capability, although these claims might lack the strength of a solid statistical basis. Proposals for requiring general immunity to large surges (IEC 61000-4-1) were not consistent with the known (and limited) capability of typical varistor ratings. Therefore, the inference could be made [19] that these proposed requirements for general requirement of immunity to large surges were not supported by actual experience – another observation applicable to discussion of the frequency of occurrence of large surges.

It should also be noted that the large surges that have been discussed, especially in clause 5, are prospective overvoltages, assuming no voltage limitations by the system itself. In reality, the large overvoltages will cause flashover and/or operation of SPDs in the utilities distribution system. Accordingly, there are practical voltage limitations in the supply system that, to a great extent, will reduce the number of large surges in the users installations.

9.3 Recapitulation of observations on failure rates

Although extensive and objective data on failure rates of LV equipment clearly attributable to overvoltages are not available, some inferences on the frequency of occurrence of large surges can be made from the available data. There is no conflict or contradiction, only a need for caution, between the expectations of surges resulting from the phenomena described in clauses 5 and 6 on the one hand, and the limitation on their occurrence discussed in the present clause.

As stated in the introductory comments to this clause, the preceding experience-based examples do not infer that large surges do not occur at all. There are also many anecdotal histories of SPD failures due to inadequate capabilities, occurring at locations where high stresses are imposed. Information from well-documented case histories can be usefully applied to the future applications of SPDs.

10 Considerations on system outage/equipment failure/fires

10.1 General

SPDs are installed in power supply systems to ensure protection of equipment by limiting overvoltages and thus enhance the reliability of the system. This clause provides some perspective on the consequences of inadequate surge protection, which range from momentary interference to massive failure.

Reliability of an end-user operating system involves two distinct considerations:

– avoiding interference (upset) in the operation of the system;

– preventing permanent damage to the system equipment and components.

For many situations, interference in the operation of equipment by an overvoltage cannot be mitigated by SPDs because the interference is associated with the frequency spectrum of the disturbance and the response of the equipment to this frequency spectrum, rather than the amplitude of the overvoltage. Generally, SPDs act upon the amplitude of the overvoltage, not their frequency spectrum. Another way to describe this situation is to state that interference can occur during the rise of the surge voltage or surge current, before the voltage reaches the level at which the SPD will intervene. On the other hand, SPDs are widely applied for protection against permanent damage, enhancing the reliability of a system when selected in the appropriate manner, a topic that will be discussed in clauses 11 and 12.

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1) Furthermore, anecdotal (undocumented) information tends to attribute the majority of these (rare) failures to the occurrence of temporary overvoltages rather than to large surges.

10.2 Avoiding interference in system operation

The impact of interference in the operation of an end-user system depends on the type of end-user, ranging from annoyance to severe economic consequences. Avoiding such interference is essentially the goal of EMC considerations in system design. In the language of EMC, the term disturbance is reserved to the concept of a change in the electromagnetic environment in which equipment operates, and is not used to describe a malfunction of an equipment, an event that non-EMC engineers would readily label disturbance. Hence, the heading of this subclause uses the term interference to avoid the ambiguity of disturbance when EMC specialists interface with non-EMC engineers.

Briefly, the essence of EMC is to ensure a sufficient margin between the level of electromagnetic disturbances in the environment in which equipment operates on the one hand, and on the other hand the immunity level of equipment to these disturbances. Furthermore, the equipment should not introduce disturbances above an agreed-upon level. In the context of the present technical report, emphasis has been on defining the conducted disturbances taking the form of overvoltage control, primarily surge protection.

Other phenomena are involved in producing electromagnetic disturbances, which can be mitigated by different approaches including reduction of the disturbances at their source, mitigation of those over which there is no control – lightning being the prime example, and increasing the immunity of equipment either by raising its inherent immunity level or by providing an interface – such as an SPD when the disturbance is a conducted overvoltage.

Clause 5 contains information on how disturbances in the environment associated with lightning events ultimately interact by direct injection of current into the power system – a conducted phenomenon in EMC terms – or by inducing overvoltages in the power system circuits – a radiated phenomenon in EMC terms. These considerations are discussed in the vast EMC literature and in the IEC 61000 series. Annex F presents examples of avoiding overvoltages and the resulting problems by application of sound EMC practices that do not involve the use of SPDs.

10.3 Preventing permanent damage

Application of SPDs is generally focused on the second consideration, prevention of damage caused by the amplitude and energy-delivery capability of a surge (involving the duration of the surge) while the interference generally reflects the parameters of the front of the surge. When the situation involves an overvoltage resulting from inductive effects associated with a surge current, the rate of current change – the front of the surge – is the relevant factor for the resulting overvoltage.

Of course, preventing permanent damage can also be achieved by raising the inherent immunity level of the equipment. This is the approach suggested in IEC 60664-1 where the equipment withstand voltage is defined and several categories of withstand levels are identified, as discussed below.

It should be kept in mind, however, that insulation withstand generally refers to overvoltages occurring in the line-to-earth mode (a form of common mode), while sensitive electronic components are generally connected line-to-neutral (also described as differential mode). Neutral grounding practices, which vary from country to country, also play a role in the relative levels of surge stresses in the common mode versus the differential mode. For instance, in TN systems, the bonding of the protective earth neutral and earth at the service entrance prevents further propagation of common mode surges impinging upon the installation by converting them to differential (line-to-neutral) surges. Many IEC publications defining surge environments, such as IEC 61000-4-5 suggest that immunity tests should have a level for common mode surge higher than that for differential mode. This situation does not occur in a TN system, but the overvoltages to be expected in a TN system are generally lower compared to a TT system, due to the multiple earthing of the neutral conductor.

Notwithstanding these subtle differences, the following paragraphs summarize the approach taken in IEC 60664-1, where a direct relation is established between equipment impulse withstand voltages and an overvoltage category assigned to the equipment. This relation is independent of the geographic location of the equipment in the installation of interest.

The overvoltage category, which characterizes the impulse withstand level of equipment, allows the classification of equipment and their selection according to the necessity of service continuity and an acceptable possibility of harm. Jointly with the preferential rated impulse voltages, they make possible the achievement of an appropriate insulation coordination for the whole installation, reducing the possibility of failure to an acceptable level and providing a basic overvoltage withstand capability.

A higher level of overvoltage category indicates a better withstand of the equipment and provides wider choice of a method for overvoltage protection. After their front, for which characteristic impedances prevail, overvoltages of atmospheric origin are not subject to significant attenuation downstream from the service entrance when relatively high impedance loads are connected on the branch circuits. Studies show that it is reasonable to use probabilistic analysis to evaluate the need for a protection.

Protective measures may have been taken inside the equipment. In this case, information should be provided by the manufacturer to allow appropriate assessment of the need for further surge mitigation. Misguided perceptions on the surge environment can lead to counter-productive inclusion of inadequate SPDs, decreasing the overall system reliability. Some electronic devices, in particular those with switch-mode power supply that include a large input capacitor are an example where little is gained over inherent immunity and much can be lost when SPDs that are unsuited for the environment are incorporated in equipment just for the sake of quoting some enhancement of surge immunity.

10.4 Costs of surge-related interruptions and failures

In case of surges occurring in an installation and equipment not protected by SPDs, there is a higher probability that the equipment will be damaged, or that the power supply will be interrupted by the operation of the protection devices (for example RCDs) of the installation. Four types of events can be involved with cost-related consequences.

a) Service degradation or loss of service: Disruption and damage cause operational difficulties to business. Service degradation can have a qualitative element that is additional to direct financial losses. For example where extensive automation or computer-based operation is involved, reversion to manual operation can be virtually impossible.
b) Loss of operations: This cost covers the real-time expense of service unavailability of equipment, computers, communications, and information technology systems including associated losses of operational revenues and/or business productivity. Critical systems such as emergency services, certain central information systems, etc. can have very high direct and indirect expenses associated with loss of operations. Commercial enterprises lose direct revenue through down time. Expected time to repair and restore operations will depend upon availability of staff, spares, procedures and information.
c) Repair or replacement of equipment or facilities: This cost is the expense of physical damage, including equipment replacement and direct and indirect expenses of reinstallation. Gradual degradation of components in equipment can also occur, through repeated small magnitude pulses which cause seemingly random faults. Such events cannot be associated immediately or directly with a lightning storm or switching event at the time of failure. Increased expenses of routine or preventive maintenance can result from such cumulative effects.
d) Emergency services: Damage of equipment or injury to people can necessitate use of emergency services such as fire, ambulance, police, etc. which are an expense to a firm, person, or community. Breakdown of fire alarm systems and emergency services telecommunications decreases the efficiency and credibility of such services.

To calculate the interruption and failure costs, these types of events need to be addressed, depending of the use of the installation. Typical parameters to be taken into account for interruption (outage) cost estimation are

– season in which it occurs;
– type of day (weekday or weekend);
– start time;
– duration;
– total or partial loss of service.

An estimation is then made of the costs that would be incurred within various loss categories (for example, cost of lost production or sales, cost of idle labour, costs of rescheduling, damage costs, etc.).

The basic equation is

total outage cost = value of lost production + outage related costs – outage related savings

where

– the value of lost production is equal to the expected revenue without outage;
– the outage-related costs are those directly incurred because of the outage (labour costs to make up production, labour cost to restart production, material cost to restart production, damage costs to material, damage costs to physical plants, cost of re-processing materials and cost to operate backup generation equipment);
– the outage-related savings are costs savings that result because of the outage (cost of wages unpaid to workers, cost of raw material unused, cost of fuel unused and scrap value of damaged material).

The failure rate of SPDs is expected to be low when they are tested according to the relevant SPD product standard and carefully selected according to the characteristics of the network and the expected stress parameters such as available short-circuit current, temporary overvoltage (TOV), etc., and the consequences of the failure of the SPD with regard to safety are minimal.

Regarding the consequences of the failure of an SPD on the protection of equipment, several cases have to be addressed and options for the mode of operation of the SPD disconnector should be considered.

a) The SPD disconnector is in series with the SPD and the combination is in shunt with the power supply. Opening of the SPD disconnector removes the failed SPD from the system and maintains continuity of the load, albeit unprotected.
b) The SPD disconnector is in series between input and output ports of the SPD. Opening of the SPD disconnector removes the failed SPD and the load from the power supply.
c) It may be possible to use two SPDs in parallel, each provided with a separate SPD disconnector: one of the SPDs will fail first and be disconnected, but the second one will maintain protection, with time allowed to make a replacement. (This option may be appropriate for surges, but does not work for TOVs.)

Clearly, the option to be selected depends on the mission of the facility, cost of equipment left unprotected, and all the associated intangibles. Furthermore, there is the issue of overcurrent protection coordination between the SPD disconnector characteristics and the upstream overcurrent protection existing in the installation.

– The SPD disconnector, internal or associated with the SPD in line with it, can operate before the overcurrent protection devices of the installation operate. In this case, the SPD failure will involve the choice a), b) or c) described above
– The SPD disconnectors a) or b) above are not fast enough to operate before the protection devices of the installation. In this case, power supply is interrupted when the SPD has failed. Additional devices, such as an automatic reclosing circuit-breaker can be used to solve this problem, but in some cases the SPD disconnector is perhaps not yet open, leading to another opening of the protection device of the installation.

A more detailed discussion of these options for failure modes can be found in SPD product standards such as IEC 61643-12.

10.5 Recapitulation on outages and failures

All of the tangible cost parameters depend on the type of installation, process involved, local conditions, etc.

In addition, the intangible costs are by definition difficult to assess. Therefore, it is beyond the scope of this technical report to attempt a presentation of numerical data on costs, but the trade literature is replete with industry-specific examples. Facility designers and planners should be made aware of the generic considerations discussed in this clause.

11 Considerations on the use of surge protection

11.1 General

Providing surge protection at a given installation is a decision that only the installation owner can make, either as the result of some local mandatory regulation, if any, or on the basis of informed decision. Two significant elements in this decision-making process are the following.

– The perception of the need for protection, depending on the type of installation, the type of equipment, its purpose, and an assessment of the risks.
– The trade-off of protection against the severe but rare direct stroke, versus protection against less severe but more frequent indirect stroke. The latter can occur either by inducing overvoltages into the circuits of the installation, or by injecting currents through striking the MV or LV systems at some distance from the installation. A similar trade-off is applicable to switching overvoltages.

11.2 Power system configuration

Regarding direct and induced surges on the power lines, overhead lines are more exposed than underground cables. However, one should not conclude that underground lines are shielded from exposure. Furthermore, the consequence of a direct lightning stroke to an underground line is likely to be permanent damage rather than the insulator flashover of an overhead line which can be cleared by the system circuit-breakers.

Overhead lines on the top or sides of high hills or mountains are more susceptible to direct lightning flashes than similar lines in valleys and areas of lower natural exposure. In addition, low-rise overhead lines might be shielded from direct flashes by adjacent taller objects. For example, measured values on MV networks show that the number of direct flashes to the line can be considerably reduced when this line is surrounded by tall trees.

A coefficient in the risk analysis should take care of both phenomena (topography: coefficient higher or lower than 1; surroundings: coefficient lower than 1).

In the case of a system where the power is supplied to the consumer via underground cables, two different cases should be considered.

a) Direct flash to the building: Only part of the total lightning current flows to the earthing system of the building. The rest of the lightning current exits the building via the power supply cables to other buildings of the same LV power system (see 5.7).
b) Direct flash to the soil, close to the building: Cables leading to another building can be hidden at the point where the direct stroke contacts the soil. Consequently, part of the lightning current flows along the inner conductors and/or the shield of the cable. This current flow produces a potential difference between the active lines and local earth.

Underground cables can be influenced by direct flashes to the ground especially through their sheath which will offer a path of lower resistivity compared to the ground itself and then will lead this surge to the installation. Induced surges on underground cables exist, but they have a lower probability than that of overhead lines and they are in general negligible compared to nearby direct flashes to the earth. Underground cables should then be addressed specifically in the risk assessment method.

The probability of a direct flash to the phase conductors or of an induced overvoltage into the phase conductors is not influenced by the system earthing, but the magnitude of the overvoltages is. For the same flash density, it seems that a TT system is subjected to overvoltages with a magnitude about three times that of a TN system.

11.3 Types of installation

Four types of installation may be considered. In the first three: residential; small and medium commercial or industrial; and large commercial or industrial, the financial costs of failure or interruptions (see 10.2) are different for each. The fourth type, critical installations, not only has the potential for financial loss, but also for human and environmental costs.

a) Residential installations: Equipment such as personal computers, audio and video systems, electronic-control appliances, etc. can be particularly sensitive to overvoltages and need to be considered. Attention should also focus on consequences, in addition to the equipment itself.
b) Small or medium commercial or industrial installations: In addition to equipment failure, outage costs have to be addressed. In case of a home-based business, it should be considered as a small commercial activity.
c) Large commercial or industrial installations: The same parameters as those of smaller installations have to be addressed, but the number and cost of equipment involved is much larger. In addition, the consequences are more important and the weight of this parameter is then more important.
d) Critical installations: In addition to financial consequences, a transient overvoltage can directly cause life hazard (hospitals), indirectly cause life hazard (petrochemical plant) and/or environmental hazards (nuclear or petrochemical plant).

11.4 Occurrence of surges

General information on the occurrence of lightning surges and switching surges has been given in clauses 5 and 6 respectively.

Clause 5 provides general information on the occurrence and point of impact of lightning strokes on the structure of interest – be it a building or the power system lines. Additional details are provided in annex A.

The probability of direct flashes to a building is given by multiplying the equivalent collection area of the building by the lightning flash density of the area. These parameters and the related computations are discussed in detail in IEC 61024-1-1. The probability of direct flashes to the lines is given in the same way. The collection area is calculated as three times the height of the line multiplied by its length. The probability of induced surges on the lines is given typically by figure 10.

The occurrence of switching surges has been discussed in clause 6, emphasizing that local conditions can vary over a wide range. Annex B provides further details. These conditions, imprecise as they are, should govern considerations on the application of SPDs in these local conditions.

The occurrence and severity of temporary overvoltages (TOVs) have been discussed in clause 7. It is generally not possible for an SPD to mitigate a TOV, given the energy-delivery capability of a power system TOV. Therefore, the selection of an SPD should take into consideration selecting a protective level appropriate to the trade-off between the presumed (and possibly unnecessary) benefits of a low protective level but involving the risk of TOV-induced failures, versus immunity against TOVs but at a higher protective level [41].

11.5 SPD disconnector

Because it is unrealistic, for economic and practical reasons, to provide an SPD capable of withstanding all possible scenarios of surges, provision shall be made for a rare but not impossible failure of SPD components. To guard against unacceptable consequences, an SPD disconnector is generally specified, with the choice determined by the nature of the installation as discussed in 10.4.

There are three basic functions which are needed according to SPD standards such as IEC 61643-12 to disconnect the SPD from the LV power system in case of failure of the SPD:

- thermal protection;
- short-circuit protection;
- protection against indirect contact.

These three functions are associated with different failure modes of the SPDs and reflect different needs of protection of the SPD circuit. A single SPD disconnector might be capable of performing these three functions or it might be necessary to provide up to three SPD disconnectors to cover the three functions. Some other disconnecting functions might be needed, for example in situations where very high temporary overvoltages are likely to occur.

The disconnecting devices can be fitted inside the SPD itself or associated to it (in series in the load-carrying lines, or in the SPD branch). Some functions may be performed by the back-up protection of the system and then may be located at a certain distance from the SPD. The choice of disconnecting devices in the SPD branch or in line with the mains depends on coordination with other overcurrent protection devices and on the need for continuity of power supply versus continuity of surge protection. An SPD disconnector can be an ordinary fuse, a circuit-breaker or an RCD, or a device especially developed for this application. SPDs have to satisfy the requirements of, and be tested according to, the relevant standards, such as IEC 61643-1.

11.6 Risk assessment

The purpose of risk assessment is to help in the decision whether or not the protection is required and, if it is, to select the proper measures of protection to limit the risk below a given value, defined as the tolerable level of the risk. The following subclauses deal with protection against transient overvoltages due to lightning striking directly a structure or the ground near the structure, or the incoming power supply lines (see figures 1 and 2), and also switching overvoltages originating in power supply networks or in the user installations.

11.6.1 Risk associated with lightning

Depending on the local environment, type and extent of the low-voltage distribution system, lightning flashes to other buildings or structures in the neighbourhood can also produce overvoltages of similar magnitude. These kinds of overvoltages are discussed in 5.7, together with their probability of occurrence.

a) Lightning current of direct flashes to the structure can affect the electrical installations and the equipment internal to the structure. This effect occurs through resistive coupling (for example, due to earth termination impedance or cable screen resistance) or through inductive coupling due to loops formed by the installations or bonding conductors. Overvoltages arising through these couplings can cause
   – a discharge between internal installations and metallic parts with a consequence of fire of the structure and/or its content;
   – a failure of the installations and equipment internal to the structure.
b) Lightning current of flashes to the ground surrounding the structure can affect the electrical installations and sensitive equipment through resistive and magnetic field coupling. Overvoltages arising through these couplings can cause failure of electronic systems internal to the structure.
c) Lightning flashes to or near the lines supplying the structure can cause overvoltages which penetrate into internal installations and equipment.
   – Direct flashes to the line conductors can cause overvoltages which could trigger a discharge between internal installations and metallic parts (in particular at the service entrance panel of the line into the structure if the front is steep [32]) with a consequence of fire of the structure and/or its content. Furthermore, these overvoltages by direct flashes to the line can cause failure of internal installations and equipment.
   – Flashes to ground near the line can induce overvoltages which can be transmitted to the internal installations and can cause failure of electrical and electronic equipment.

The assessment of the risk due to lightning is treated in IEC 61662. According to IEC 61662, the risk is defined as the probable annual loss (human and goods) in a structure due to lightning. The effects are considered for both lightning striking directly a structure and for lightning to ground near the structure. The effects of lightning striking directly the line supplying the structure or striking the ground near the line and causing lightning overvoltages (induced overvoltages) are also treated in that technical report.

11.6.2 Risk associated with switching overvoltages

Switching overvoltages can originate outside the internal installations and be transmitted by the supply line, or they can be created inside the structure when the installation includes equipment generating these overvoltages.

As discussed in clause 6, there are two types of switching overvoltages.

a) Repetitive overvoltages (intentional operation of circuit breakers, switching of capacitor banks). These occur quite frequently, initiated by a manual or automatic intervention. Their frequency of occurrence ranges from several in a second (welding) to a few per day (capacitor switching). The parameters of these overvoltages, as well as their potential effect on equipment are in general known or predictable, based on experience. The decision to provide protection is then based on a deterministic analysis and in general no risk analysis is necessary.
b) Random overvoltages (fault clearing and system recovery). Their frequency of occurrence, rather low, is not known but statistical results discussed in clause 6 and annex B provide some information toward a risk assessment analysis. Their magnitude and effect on equipment are not defined for specific installations. Therefore, the decision to provide protection is likely to need a risk analysis.

11.6.3 Types of damage

A lightning stroke can cause damage depending on the characteristics of the structure, among which the most important are:

– type of construction;
– contents and application;
– services and lines entering the structure;
– measures taken for limiting the risk.

Moreover, the damage might be limited to a part of the structure or might extend to the whole structure and might even involve the surrounding structures or the environment (for example, chemical or radioactive emissions). For practical applications of risk assessment it is useful to distinguish the type of damage which can appear as the consequence of lightning stroke. Four types of damage have to be distinguished, namely:

– loss of human life;
– loss of services to the public;
– loss of cultural heritage;
– loss of economic values: structure, content and loss of activity.

If one of the first three types of risk is present, the decision to take protection measures should not be made at the designer's discretion. This decision should be made by comparing, for each type of risk, the risk due to lightning with a maximum tolerable value.

If the risk is solely economic, the decision to adopt protection measures may be taken by the designer on the basis of purely economic convenience, by comparing the annual cost of any protection measures with the annual cost of probable loss due to lightning, taking into account not only the loss of the structure and of its content, but also the consequences (for example, loss of activity).

11.6.4 Data required for risk assessment

For the assessment of the risk the following data are required:

– lightning flash density of the region where the line and the structure are located;
– type, characteristics and length of the line (overhead or underground; MV or LV);
– characteristics of the structure supplied by the line; type and characteristics of the content;
– type of internal installations;
– characteristics of equipment (rated impulse withstand voltage);

– protection measures provided against overvoltages;
– protection measures provided against the propagation of the fire;
– cost of the equipment damage;
– amount of the consequential loss and social and environmental impact of damage;
– measures to limit the consequences of equipment damage (for example, redundancy of electrical system, alternative power supply line, etc.).

11.7 Recapitulation on the need for surge protection

The need for surge protection is influenced by objective as well as subjective factors. Objective factors can be expressed through a risk assessment, but ultimately the selection of what is a tolerable risk becomes a subjective matter. In many cases, the actual decision to provide surge protection can be taken away from the end-user as regulatory requirements may be promulgated.

In most cases, switching overvoltages are less damaging than lightning overvoltages and the means of protection (namely SPDs) effective for protection against lightning surges are also effective against switching surges. Therefore, protection against switching surges needs in most cases to be discussed specifically only when protection against lightning surges is found not to be necessary.

12 Surge protection application

12.1 General

The majority of lightning overvoltages within an installation are induced by distant lightning in the area. The resulting current surges are generally small and low-energy surge protective devices (SPDs) are adequate for protection against these moderate stresses. If protection against direct or near flashes is considered, high-energy SPDs are needed to deal with the higher stresses. An evaluation of the probability of these different stresses, including their tangible and intangible consequences, is recommended.

When discussing lightning current stresses propagated along cables or wires of some length, it is pointed out that in the case of steep rate of rise, high voltages will occur at the cable end at which the current is injected. These overvoltages can exceed the withstand capability of wiring devices and equipment, resulting in a flashover. Consequently, SPDs at the other end of the cable are not subjected to the high stresses associated with the injection of surges of large amplitude and long duration when their front is steep [32].

If stresses caused by direct or near flashes are taken into account, these stresses are in most cases decisive for the energy requirements of the SPDs. The identification of appropriate devices and their optimum point of connection are discussed in the following subclauses. These include a general description of the SPDs, the relationship between basic system characteristics and requirements for SPDs, an assessment of SPD effectiveness, coordination among multiple SPDs, and compatibility with other protective means. See also annex F for examples of overvoltage control accomplished by sound EMC practices rather than by application of surge protective devices.

12.2 Surge protective devices in power distribution systems

12.2.1 Function of an SPD

The SPDs considered in this document are those installed external to the equipment to be protected. Under normal conditions, the SPD has no significant influence on the operational characteristics of the systems to which it is applied. Under abnormal conditions (occurrence of surge), the SPD responds to surges by lowering its impedance and thus diverting surge current through it to limit the voltage to its protective level. Upon return to normal conditions, the SPD recovers to a high impedance value after the surge and a possible power follow current. Detailed information on normal conditions and requirements are provided in applicable SPD product standards of the IEC 61643 family.

An SPD can fail or be destroyed when surges are larger than its designed maximum energy and discharge current capability. Failure modes of SPD are divided roughly in open-circuit mode and short-circuit mode. For an open-circuit mode the system to be protected is no longer protected. In this case, failure of the SPD is usually difficult to detect because it has almost no effect on the system. To ensure replacement of the failed SPD before the next surge, an indicating device of the SPD failure may be required. For a short-circuit mode the system is severely affected by the failed SPD. The short-circuit current flows through the failed SPD from the power source. Thermal energy can be produced there and can result in a fire hazard before burning out and open circuit.

In case the system to be protected has no suitable device to disconnect the failed SPD from its circuit, a suitable, additional disconnecting device may be required for an SPD with short-circuit failure mode.

NOTE In this subclause, the term “short-circuit mode” is used. If the short circuit were in fact zero impedance, the situation would be less difficult than it is for typical voltage-limiting SPDs where this so-called “short-circuit mode” is a substantial lowering, but not to zero, of the impedance. There can be sufficient residual resistance in the failed SPD to limit the current to a value that might or might not cause operation of an overcurrent protective device. Even if the overcurrent protective device does operate, its time response might be such that significant heat is generated in the residual resistance of the failed SPD, all in a confined space, with the potential of high temperatures being produced.

12.2.2 Classification of SPDs

SPD product standards specify classification characteristics such as:

- number of ports: one or two;
- design topology: voltage switching, voltage limiting or combination;
- class I, II and III tests (see IEC 61643-1);
- location: indoor or outdoor;
- accessibility: accessible, non accessible;
- mounting method: permanent or portable;
- SPD disconnector: location and function;
- back-up overcurrent protection: specified or not;
- degree of protection provided by the SPD enclosure.

The above choices are in fact linked to the technology and are defined by the manufacturer. The main components of SPDs belong to two categories:

- voltage-limiting components: varistors, avalanche or suppressor diodes, etc.;
- voltage-switching component: gaps in air, gas discharge tubes, silicon controlled rectifiers, etc.

Based on these components, the basic SPD designs are

– single-voltage limiting component: limiting type SPD;
– single-voltage switching component: switching type SPD;
– combination of different technologies: combination type SPD.

Many SPD designs cannot be defined by a simple arrangement of basic components. They could incorporate indicators, disconnecting devices, fuses, inductors, capacitors and the like. Another way to describe SPDs is to use the terms one-port SPD, two-port SPD, or combination multi-port SPD, as defined in clause 3.

12.2.3 Electrical characteristics of SPDs

Proper selection of an SPD requires knowledge of the following characteristics, as defined in SPD product standards of the IEC 61643 family:

– maximum continuous operating voltage and continuous operating current;
– temporary overvoltage withstand versus time curve;
– nominal discharge current (only for Class I and for Class II tests);
– I_{max} for Class II tests and I_{imp} for Class I tests;
– U_{oc} for Class III tests;
– U_p voltage protection level;
– durability;
– failure modes;
– short-circuit withstand;
– maximum continuous load current (for two-port SPD or one-port connected in line with the mains);
– voltage regulation (for two-port SPD).

12.3 Basic system characteristics for SPD selection

This subclause provides guidance on the general concepts involved in applying SPDs for protection of a power system. Additional details are provided in annex E.

12.3.1 Systems and equipment to be protected

In addition the nominal voltage of the system, one of the relevant parameters for characterizing a power distribution system is the type of system earthing (TN-C, TN-S, TN-C-S, TT, IT). Concerning the electrical installations, it is recognized that the wide variety of intended use be grouped in four major categories:

– protected installation including sensitive equipment such that a protection against overvoltages, at least galvanic separation and appropriate cabling, is provided in any case;
– current-using equipment in normal applications (domestic and light industry);
– equipment for the fixed electrical installations in normal applications (domestic and light industry);
– special conditions where one or more of the possible disturbances are atypical but where also some expectations exist related to the continuity of service. Examples of such cases are the heavy industry and in the electrical installations of buildings, equipment connected to outside lines, from the point of view of overvoltage surges.

Equipment serving as part of a complete electrical system is affected by the surge overvoltages and surge currents in different ways. Among those, the main characteristics which are concerned are:

– dielectric insulation withstand;

– the immunity to electromagnetic stresses.

Insulation stresses can cause a failure of the insulation which can result in damages such as insulation faults to earth, short circuits, damage to equipment, fires, etc. Safety requires that all equipment have a minimum withstand to such stresses. This issue is detailed in IEC 60664-1: test methods are specified, in particular the 1,2/50 μs voltage impulse. However, the impedance of the generator to be used is not specified in IEC 60664-1, which can lead to different results for equipment, depending on their impedance.

Electromagnetic stresses generally result in malfunctioning, loss of stored data or even damage to electronic components. A minimum immunity to many electromagnetic stresses is necessary for proper functioning of equipment. This immunity is specified in the IEC 61000 series by means of numerous types of stresses with the corresponding test methods.

Immunity levels are also described in the IEC 61000 series for the use of product committees. The latter choose the appropriate immunity level according to the intended use of the product and its expected environment. Guidance for typical electromagnetic environments is given in IEC 61000-2-5.

12.3.2 Selection of SPDs according to stresses

12.3.2.1 Lightning overvoltages and overcurrents

In most cases lightning surges are decisive for the energy requirements of SPDs. Knowledge of the waveshape and the current (or voltage) amplitude of the lightning surges is necessary to define the stress (energy deposition) imposed upon the SPD and to be sure that the expected voltage protection level is achieved by the SPD. The keraunic level discussed in 5.2 is often considered to define the severity of a location. However, this keraunic level is not a very satisfactory criterion for deciding whether to use an SPD or not. A better criterion is that of cloud-to-earth flash density (flashes per km² and per year). Modern lightning detection systems can provide such information with reasonable accuracy.

In some particular situations, even if the supply is provided by an underground cable, the use of an SPD may be recommended to provide protection of the installation. This occurs when

– the actual structure or other structures in the vicinity are exposed to direct flashes;

– the length of the cable is not sufficient to provide adequate separation (attenuation) of the installation from the overhead part of the network;

– high surges of atmospheric origin can be expected on the overhead line supplying the MV side of the transformer connected to the installation;

– an underground cable can be affected by direct lightning in the presence of high soil resistivity;

– the size or height of the building powered by the cable is large enough to significantly increase the risk for direct flashes to the building.

The risk for direct flashes to other incoming or outgoing services (telephone lines, antenna systems, etc.) that can affect the power system, should be also considered.

NOTE 1 IEC 60364-4-443 considers that if the installation is supplied by an underground cable or if it is supplied by an overhead line when the keraunic level is below 25, there is no need to use an SPD except if the acceptable risk depending on the utilization of the installation is exceptionally low. However, even though the supply is provided by an underground cable, this cable is not always sufficient to provide the protection of the installation especially in the cases of direct lightning and nearby lightning which are not considered in IEC 60364-4-443. This is why the supply by an underground cable cannot be used alone to determine the need of an SPD. In addition, the variation of magnitude of the surges occurring on an overhead line depends on the keraunic level, the line configuration, the period of the year, and so on. This is why a value of 25 for the keraunic level cannot be used alone to determine the need of an SPD. Risk analysis has to be performed. This analysis should be based on the probability of incoming surges and the economic balance between protection and consequences.

NOTE 2 Many buildings can be supplied from the same supply system. Then, SPDs may be recommended for electrical installations within any of these buildings.

For the purpose of assessing the current distribution through SPDs in case of direct lightning to the structure equipped with an external lightning protection system, it is, in general, sufficient to use the resistance of the earth electrodes, for example, earthing of the building, pipes, earthing of the power distribution system, etc. Figure 24 shows a typical example of the sharing of the current.

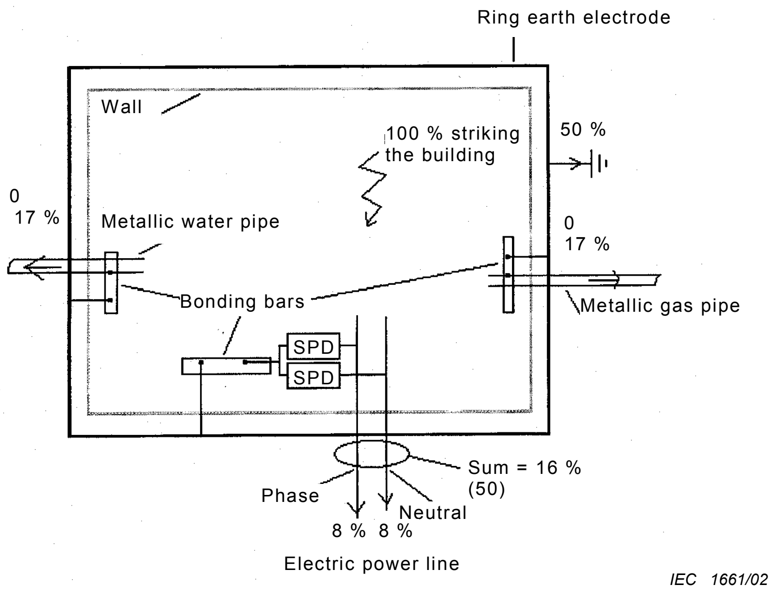


Figure 24 – Example of diversion of lightning current into the external services (TT system)

NOTE 3 The lightning impulse current combines two key parameters. The first is the fast rise time which is useful for determining the voltage value due to inductive effects. The second is the long duration which essentially refers to the available energy in the stroke. High-frequency effects are not present in this later period, allowing the resistance to be used for calculation of current distribution.

Where an individual evaluation (by calculation for example, as illustrated in 5.7.1 and in annex A) is not possible, it can be assumed that 50 % of the total lightning current I enters the earth termination of the lightning protection systems of the structure considered. The other 50 % of the current is distributed among the services entering the structure, such as: external conductive parts, electrical power and communications lines, etc. according to the ratio of the earthing impedance associated with these services. In figure 24, it is postulated that the three services offer equal earthing impedance.

In the case of a shielded power or communications cable, both ends are bonded to earth directly or via an SPD. In this case, part of the lightning current carried by that cable will flow in the shield as well as through the inner conductors. The sharing among conductors depends on the cable construction as well as on the surge parameters [5], [31]. In all cases, SPDs should be installed as close as possible to the shield bonding point.

12.3.2.2 Switching overvoltages

These stresses, in terms of energy-delivery capability and voltage, are usually lower than the lightning stresses. However, in some cases, particularly deep inside a structure or close to switching overvoltages sources, the switching stress could be higher than those stresses caused by lightning. It is necessary to know the energy-delivery capability of these switching surges for selection of the appropriate SPDs. The time duration of the switching surges, including transients due to faults, fuse operations, and capacitor switching can be much longer than the lightning duration. It is therefore difficult to specify generally applicable parameters. Site-specific studies might be necessary.

12.3.2.3 Temporary overvoltages (TOV)

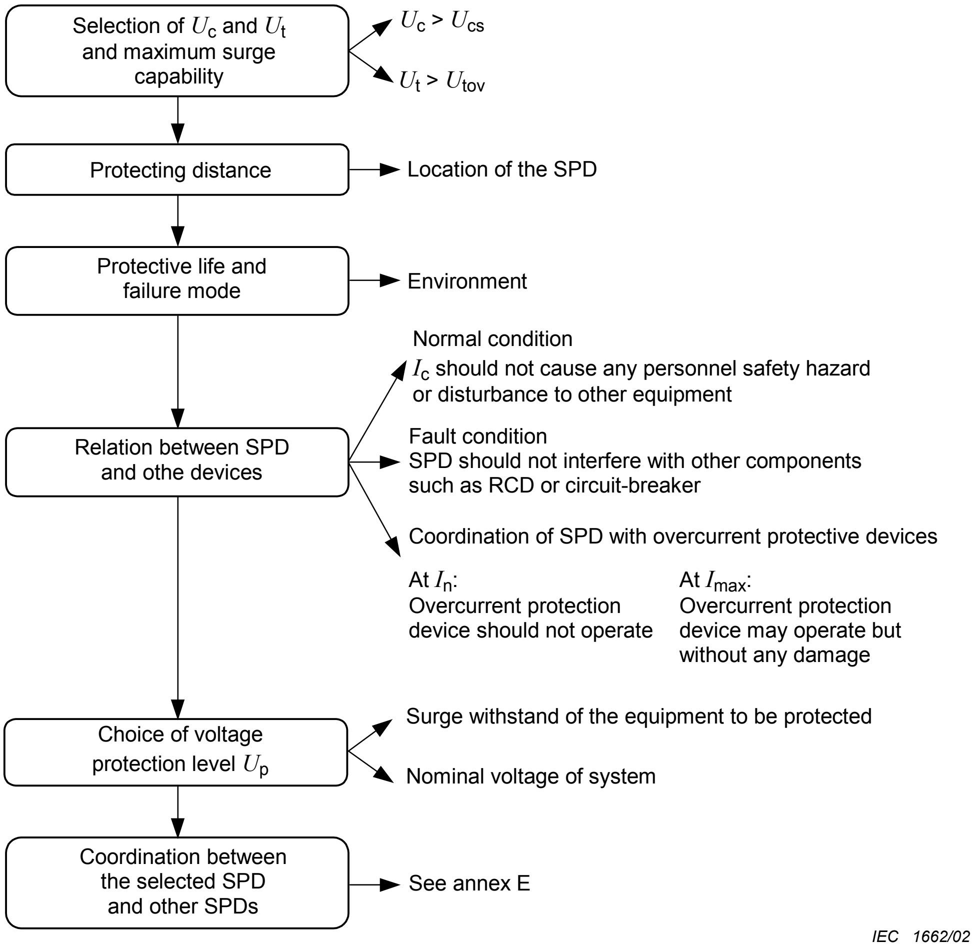
An SPD can be exposed to a TOV during its lifetime that exceeds its maximum continuous operating voltage. The temporary overvoltage capability of the SPD has two dimensions, magnitude and time.

a) For the magnitude of the maximum TOV that can occur in the system, consideration should be given to the following factors:
   - operating voltage of the LV power system;
   - configuration of the LV power system (single phase, three-phase, etc.);
   - number of distinct earthing electrodes;
   - earth coupling of the MV power system;
   - coupling of the MV-/LV-system.
b) For the time duration of the TOV that can occur in the system, consideration should be given to these factors:
   - fault location (MV/LV distribution system or LV installation);
   - protective devices used to clear the fault.

Additional factors can be important in cases of nearby HV pylons or railway tracks for example.

12.3.3 Steps for selection of SPDs

The selection of a suitable SPD requires several steps, as illustrated for example by the boxes in the chart of figure 25. Details of these considerations are given in annex E. The final step in the procedure, which is the coordination between the selected SPD and other SPDs, is discussed in 12.5, with additional information in annex E. This coordination is one of the major considerations of this technical report.



Key

U_c	Maximum continuous operating voltage of SPD
U_{cs}	Maximum continuous operating voltage of system
U_t	Temporary overvoltage of SPD
U_{TOV}	Temporary overvoltage of system
I_n	Nominal discharge current
I_{max}	Maximum discharge current
I_c	Continuous operating current

Figure 25 – Considerations required for the selection of an SPD

12.4 Considerations for installation of SPDs

12.4.1 Possible modes of protection

When the equipment to be protected has a sufficient overvoltage withstand or is located close to the entrance panel, one SPD alone can be sufficient. In this case, the SPD should be installed as close as possible to the entrance of the structure and have sufficient surge withstand capability. Typical examples are given in annex E. Table 7 lists the pairs of conductors between SPDs can be connected for the power system type in use for a particular installation. However, all these protection modes might not be necessary. The choice depends on several factors, such as:

– the type of equipment to be protected (for example, if the particular appliance is not provided with an earthing conductor, line-to-earth or neutral-to-earth protection might be not necessary);

– the withstand of the equipment according to the different modes of protection;

– the power system type as shown in the table and the specific earthing practices;

– last but not least, the characteristics of the incoming surge, to the extent that they can be defined.

Note that the installation of SPDs on the utility part of the network, before the point of entrance to the end-user installation or before the demarcation between the utility and user responsibility, should be carried out with the agreement of the electricity supplier, or perhaps by the supplier.

Table 7 – Possible protection modes

SPD connected between:	Power system type			
	TT	TN-C	TN-S	IT
Line and neutral	X		X	X[a]
Line and PE	X		X	X
Line and PEN		X		
Neutral and PE	X		X	X[a]
Line to line	X	X	X	X

[a] When the neutral is distributed.

Suitable measures should be taken to limit inductive coupling between unprotected and protected parts of the installation. The mutual inductance can be reduced by separation of the inducing source and the victim circuits, limitation of loop areas and selection of the angle of the loops. In general, it is better to separate the protected wires from those which are not protected. In addition, separation from the earth conductor is desirable. In all cases, measures should be taken to avoid cross-coupling of disturbances between power and communication cables.

12.4.2 Influence of oscillation or reflection phenomena on the protective distance

When an SPD is used to protect specific equipment or when the SPD located at the entrance panel cannot provide enough protection for some equipment, SPDs should be installed as close as possible to the equipment to be protected. If this distance is too large, oscillations or reflections could lead to voltages appearing at the equipment terminals higher than the protection level expected by the provision of the entrance SPD. This situation could cause a failure of the equipment to be protected in spite of the presence of the SPD. An acceptable distance (called protective distance) depends on SPDs type, type of systems, steepness and waveform of the incoming surge and connected loads. Oscillations at the natural frequency of the circuit can be excited by the step function of the incoming surge. Reflections at the end of the branch circuit occur in accordance with the classic transmission line theory involving the relationship between the line characteristic impedance and the terminating (load) impedance.

In particular, voltage doubling is only possible if the equipment corresponds to a very high impedance load or if the equipment is internally disconnected. In general, oscillations or reflections may be disregarded for distances less than 10 m. Sometimes the equipment has internal protective components, such as varistors that significantly reduce oscillations and reflections even at longer distances. Care is necessary in this case to avoid coordination problems between the SPD and the protective component inside the equipment.

NOTE It is generally not sufficient to use an SPD close to the equipment to be protected. For EMC reasons, it is better to divert the surge current at the service entrance of the building in order to avoid electromagnetic disturbances due to the surge currents. Furthermore, to protect the installation (avoid flashover between conductors) it is better to install the SPD at the entrance of the installation. If necessary, another SPD close to the equipment should be installed if the equipment is not within the protective distance of the SPD installed at the service entrance. Coordination studies are then necessary, as discussed in 12.5.

12.4.3 Influence of the SPD connecting leads

In order to achieve an optimum overvoltage protection, connecting conductors of SPDs should be as short as possible. Long lead lengths or significant loop area formed by the connecting leads will add an inductive voltage to the protective voltage of the SPDs, degrading its performance. Many references are found in the literature that imply that lead length is the significant factor, but overlook the loop area aspect. In an actual situation, the protective voltage impressed on the equipment will be the voltage established by the limiting action of the SPD, augmented by the voltage induced in the loop area formed by the connecting leads (figure 26).

NOTE For the example represented by this figure, with a typical standard impulse wave, di/dt is highest near the beginning of the impulse. In the case of lightning impulses, the highest di/dt can occur close to the crest value. This remark, however, does not decrease the importance of ensuring optimum lead configuration.

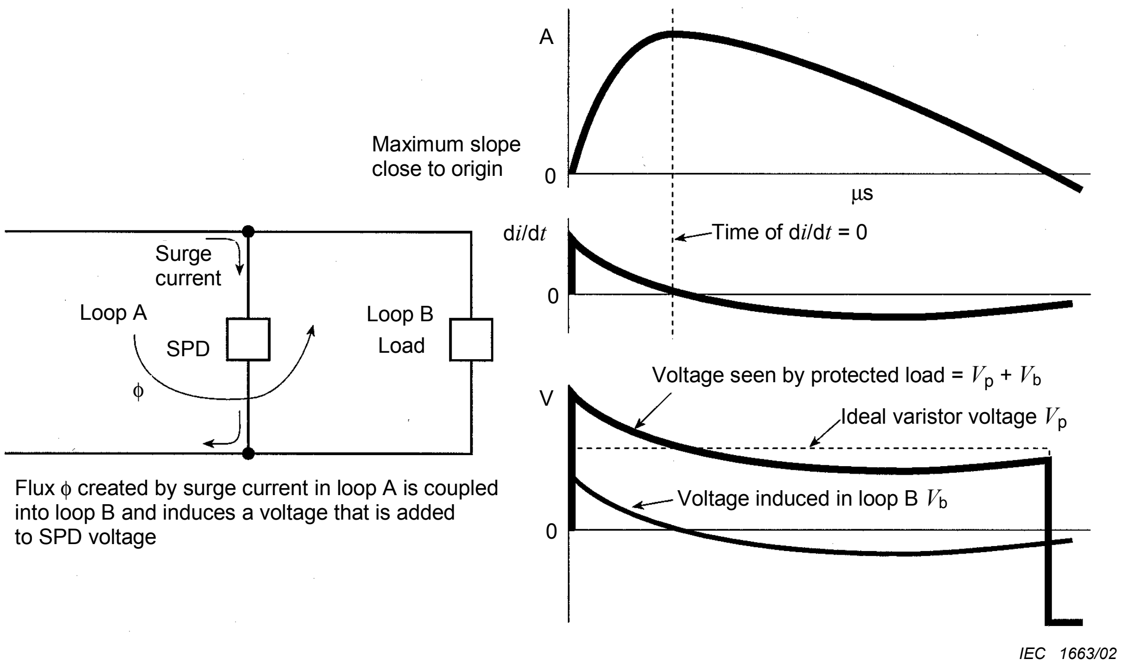


Figure 26 – Effect of additional connecting lead on the limiting voltage of a varistor

12.5 Coordination among SPDs and with equipment to be protected

When two or more SPDs are present in an installation, there will be a mutual interaction of the SPDs, and if these are not properly selected, there is a risk of overstress on the less powerful protective device. In principle, the SPD with the lower protective level will tend to draw the higher current, due to its lower effective impedance. However, the location of the SPDs in relation to the part of the installation in which the surge is generated, the surge steepness and duration, as well as the impedance between the SPDs are all significant to the sharing of current and energy stresses.

In order to explain this phenomenon and to illustrate the importance of the surge current waveshape as well as the impedance between the SPDs (including decoupling elements), results from computations for a simplified case are shown in clauses E.1, E.2 and E.3.

12.5.1 General objective of coordination

Whenever more than one SPD is used to protect equipment and after verifying that the protection level of the SPDs and their location are suitable for the equipment to be protected, a coordination study of these SPDs and equipment is needed. The general objective of the coordination is to reduce the overvoltages, by means of SPDs, to the withstand capability of the equipment to be protected and to ensure that the surge current rating capability of the individual SPDs will not be exceeded. This condition can be expressed as follows.

Given two SPDs connected in parallel, SPD1 and SPD2, separated by a decoupling impedance (figure 27), the energy coordination is achieved if, for each surge-current level and waveshape to be considered, the portion of energy dissipated through SPD2 is lower than, or equal to, the maximum energy withstand of SPD2.

Coordination between two SPDs can be demonstrated by five different approaches, described below. Whatever the approach, it is necessary that the end-user have control over the selection of the SPDs, preferably the two of them. If one is already given and beyond the control of the end-user, the coordination of the second candidate SPD can be assessed and more suitable candidates identified if necessary. Most of the time, coordination is, or might seem, a complex situation. Some of the following five procedures might then appear to the end-user as difficult to apply, due to lack of knowledge concerning some data, for example, accurate SPD characteristics. Nevertheless, coordination is necessary to ensure technically effective and cost-effective use of resources.

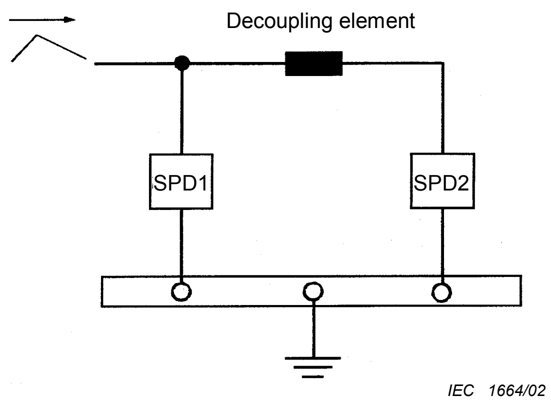


Figure 27 – Basic model for energy coordination of SPDs

12.5.2 Assessment of coordination

The five basic different ways of assessing the coordination of two SPDs are:

a) Application of preferred SPD combinations

   For the users, this is the most convenient variant as the burden of demonstration is incumbent upon the SPD manufacturer. However, this approach implies either that a sole source manufacturer be selected, or that standard methods be developed to allow determination that candidate devices from different sources are in fact equivalent.

b) Coordination computation

   By means of computer simulation, complex systems can be examined and parametric evaluation performed over a wide range.

c) Application of the let-through energy concept

   In this concept, some decoupling impedance is postulated in the upstream SPD and a computation is performed for converting the SPD characteristics on the basis of an equivalent combination wave generator. A comparison can then be made with the energy withstand capability of the downstream SPD [27]. This method is described in more detail in clause E.8 (see tables E.5 and E.6).

d) Coordination test

   A full-scale test is performed with candidate SPDs, for a postulated decoupling impedance and a range of surge currents such that blind spots, if any, are revealed. Candidate devices may include voltage-limiting SPDs, voltage-switching SPDs, or combination type SPD (voltage-switching SPD + voltage-limiting SPD).

e) Simplified rules with margin

   Simplified tables including margins for the coordination of some typical SPDs may be used when no other data are known from the SPD manufacturers. The values given in these tables are based on sufficient margins to cover discrepancies between manufacturers and manufacturing tolerances. Examples of such tables are given in annex E.

12.6 Recapitulation on surge protection application

Successful application of SPDs requires consideration of many factors, which have been briefly described in this clause. Many designs of SPDs are available, so that it is possible to select a design that matches the surge environment in which the device is to perform its protective function. This selection process involves several steps in which the characteristics of the candidate SPD are assessed:

– coordinate the maximum continuous operating voltage of the system and of the SPD;
– coordinate the temporary overvoltage of the system and of the SPD;
– coordinate the SPD surge-handling capability to the surge environment at the point of use;
– coordinate the SPD protection level and the surge withstand capability of equipment to be protected;
– consider the consequences (failure mode) for the rare case of excessive stress;
– ensure that no undesirable side-effects occur under normal or abnormal power system operation;
– coordinate the SPD response to surges with the operation of overcurrent protective devices;
– coordinate the operation of the candidate SPD with other SPDs in the installation;
– ensure that the topology and dimensions of connections do not degrade the SPD performance.

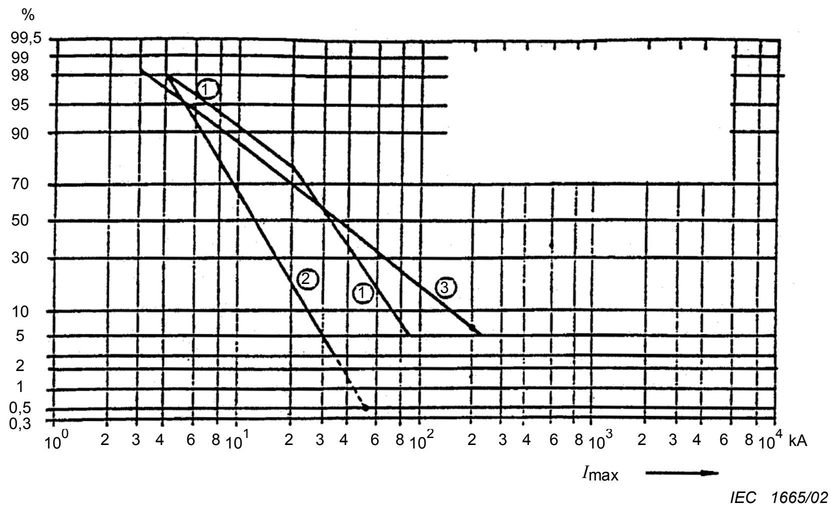
Annex A
(informative)

Complementary information on lightning-related overvoltages

A.1 Additional data on lightning parameters

Table 2 in clause 5 summarized the parameters of lightning flashes. Other percentiles for these parameters are given in the comprehensive plot of IEC 61312-1 in the form of frequency distribution plots for the following parameters:

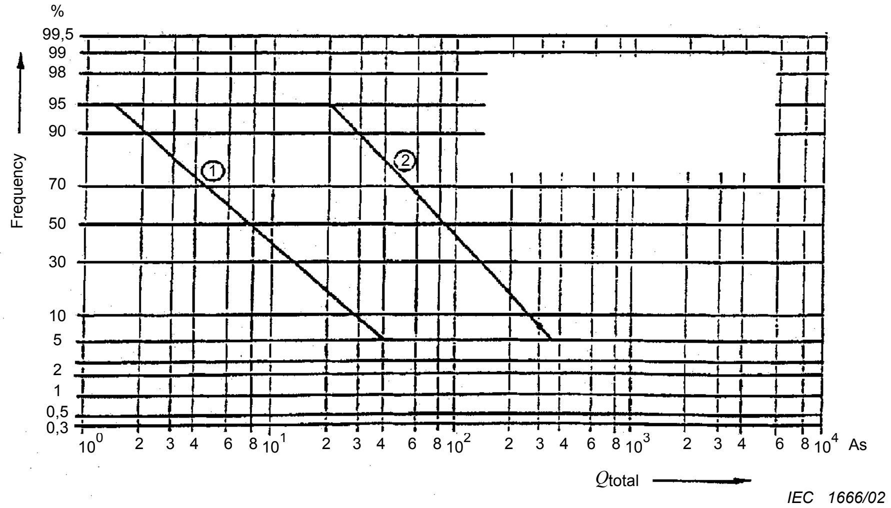
– peak current I_{max} (figure A.1);
– total charge Q_{total} (figure A.2);
– transient charge Q_{trans} (figure A.3);
– specific energy W/R (figure A.4);
– maximum slope of transient current $(di/dt)_{max}$ (figure A.5);
– slope of transient current $(di/dt)_{30/90\ \%}$ of negative subsequent strokes (figure A.6).



Key

1 Negative first strokes
2 Negative subsequent strokes
3 Positive ground flashes

Figure A.1 – Frequency distribution of the lightning peak current I_{max}

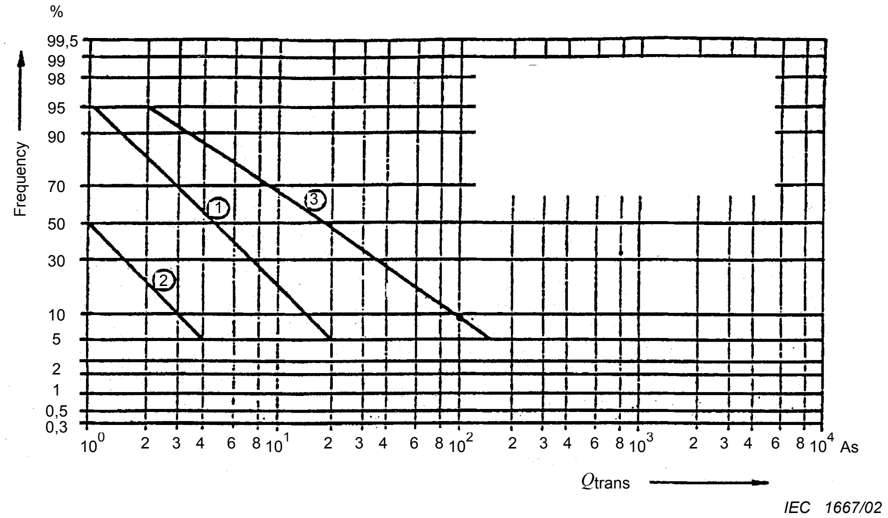


Key

1 Negative ground flash

2 Positive ground flash

Figure A.2 – Frequency distribution of the total lightning charge Q_{total}



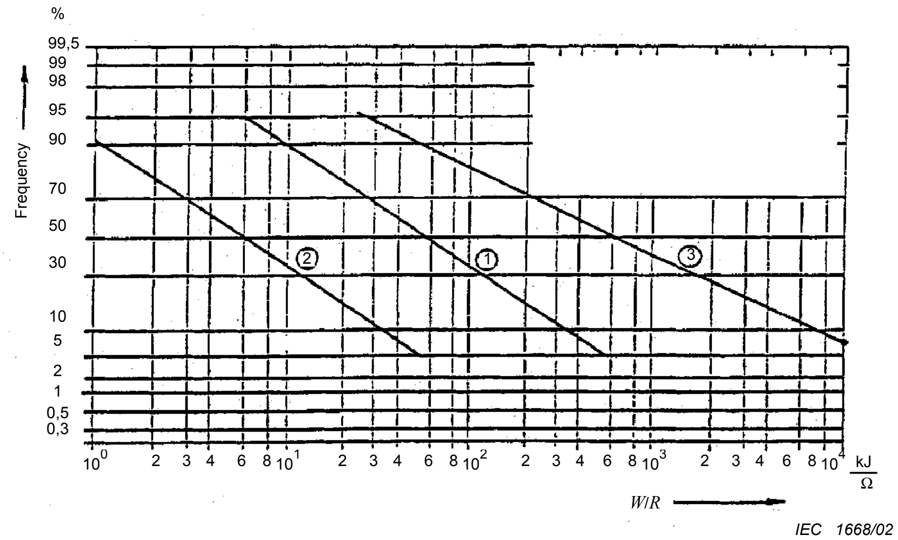
Key

1 Negative first strokes

2 Negative subsequent strokes

3 Positive ground flashes

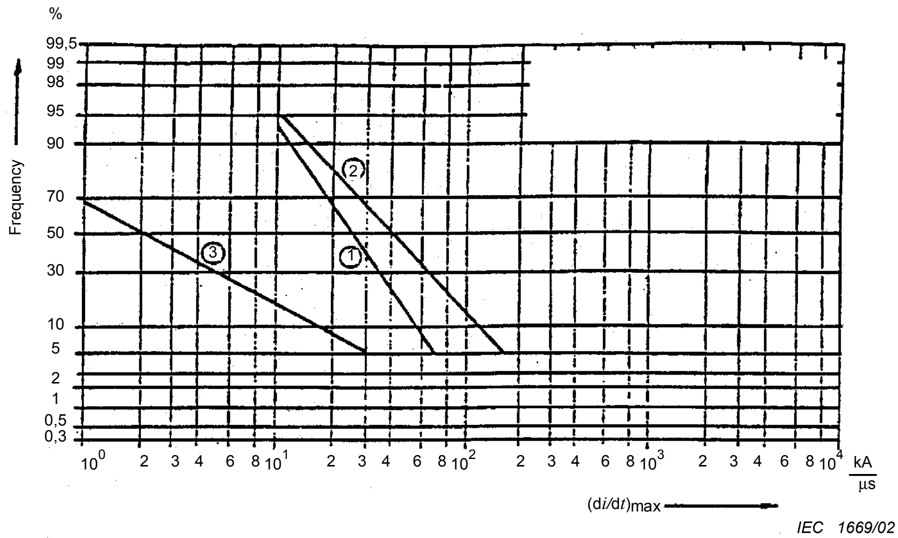
Figure A.3 – Frequency distribution of the transient lightning charge Q_{trans}



Key

1 Negative first strokes
2 Negative subsequent strokes
3 Positive ground flashes

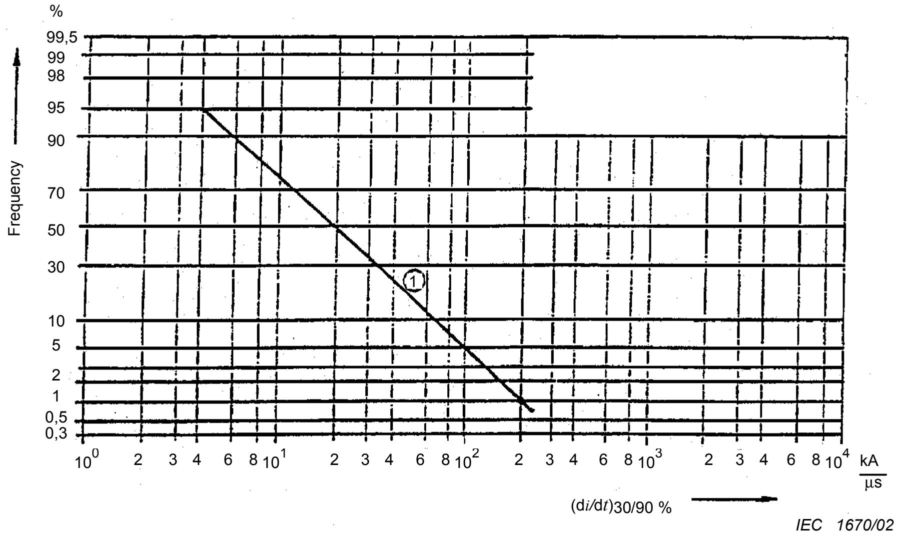
Figure A.4 – Frequency distribution of the specific lightning energy *W*/*R*



Key

1 Negative first strokes
2 Negative subsequent strokes
3 Positive ground flashes

Figure A.5 – Frequency distribution of the maximum slope of transient current $(di/dt)_{max}$



Key

1 Negative subsequent strokes

Figure A.6 – Frequency distribution of the slope of current $(\mathrm{d}i/\mathrm{d}t)_{30/90\ \%}$ of negative subsequent strokes

A.2 Prospective overvoltage example

For illustrative purposes, the simple circuit of figure A.7 is considered. A flash is assumed to occur at a pole close to the mid-point of a 150 m overhead line connecting a residential house to a distribution transformer. The postulated current magnitude is 50 kA peak, with a 2/50 µs waveform.

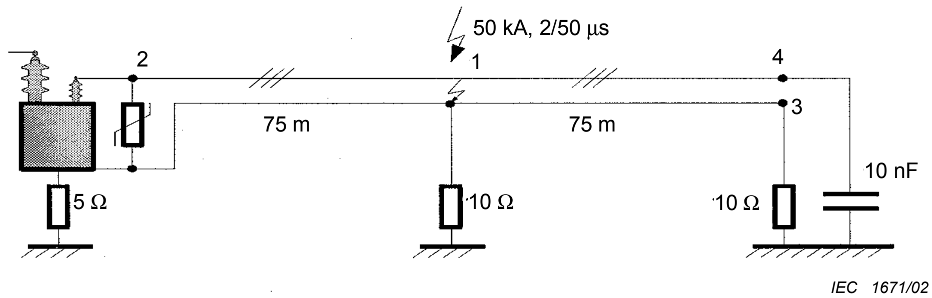


Figure A.7 – Simplified example with lightning flash to overhead LV line

Flashovers to all conductors and to earth occur immediately at a pole close to the point of strike, and it is assumed that the earthing resistance at this pole is 10 Ω. Furthermore, it is assumed that the distribution transformer is protected by surge arresters and that the earthing resistance at this point is 5 Ω. At the consumer installation the neutral is assumed earthed through a resistance of 10 Ω. Finally, in this example where the prospective voltages are considered, it is assumed that there is no SPD nor any significant load in the consumer installation and that the insulation is such that a flashover will not occur. The installation is approximated by a single capacitance of 10 nF.

Figures A.8 and A.9 show the computed prospective voltages at the four nodes of figure A.7 for the assumptions listed above. In figure A.8, the highest voltage occurs at the point of strike (node 1) and the lowest voltage at the transformer (node 2), as a result of the lower earthing resistance of that node. In figure A.9, the prospective voltage of the live conductor (node 4) is shown, together with the voltage at node 3, already plotted in figure A.8. Clearly, in a real situation, these voltages would result in an immediate flashover.

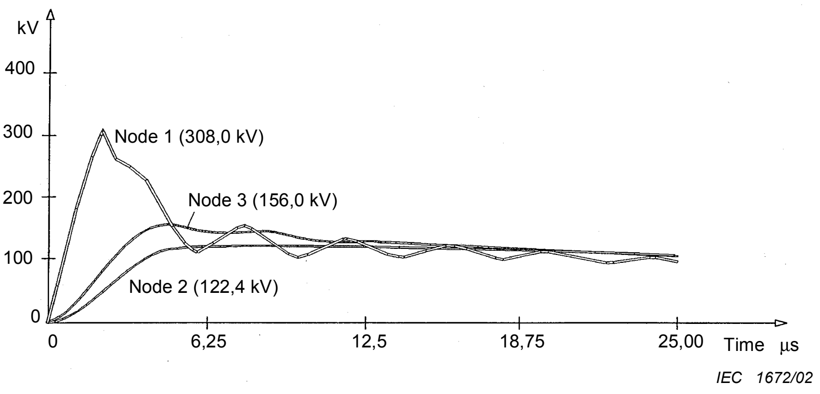


Figure A.8 – Prospective voltages between line and true earth at point of strike (node 1), at the transformer (node 2) and at the neutral conductor in the consumer installation (node 3)

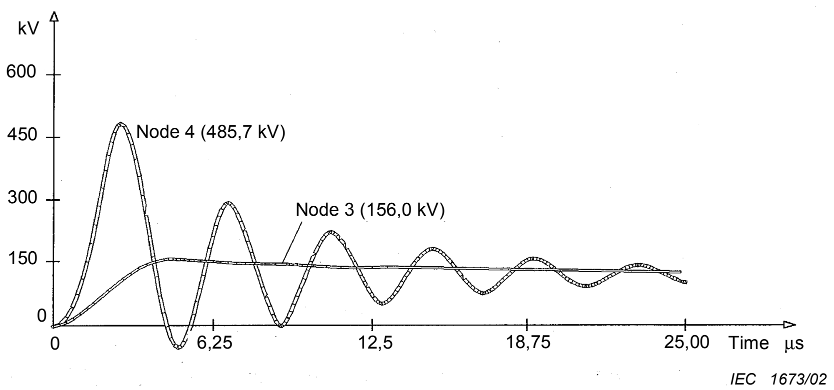


Figure A.9 – Prospective voltages relative to true earth at node 3 and at node 4

Figure A.10 shows the computed currents to earth for the scenario of figure A.7. After the initial phase, the currents divide according to the ratio of the earthing resistance, with the current at node 2 (the transformer, with an earthing resistance of only 5 Ω) about twice that of the two other nodes where the earthing resistance had been postulated at 10 Ω.

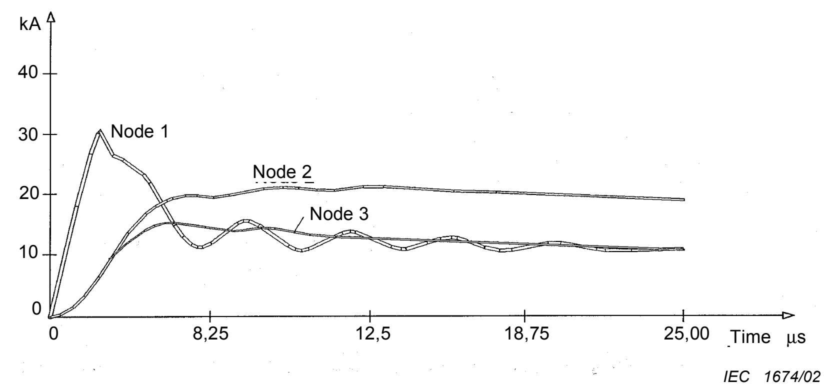


Figure A.10 – Current to earth at the point of strike (node 1), at the transformer (node 2), and at the consumer installation (node 3)

A.3 Surge propagation in MV systems

As an example of the coupling and propagation of lightning surges, this clause summarizes measurements performed on a typical MV system (20 kV) in France (where the ground flash density is about 2 flashes per km^2 per year). Figure A.11 shows a histogram of the peak magnitudes recorded at the primary of an MV/LV transformer.

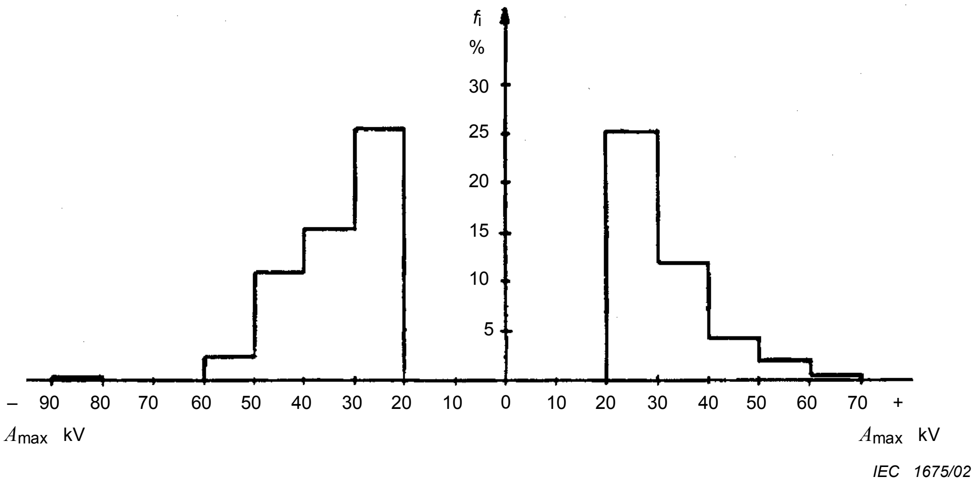


Figure A.11 – Distribution of overvoltage peak magnitudes recorded at the primary of an MV/LV transformer

The following typical quantitative values were recorded for lightning flashes to MV systems.

a) Most of the overvoltages on MV systems were generated by induced surges. Direct lightning to line conductors or system structures were only about 3 % of the observed surges.

b) Of 330 surges recorded in one year, only 10 surges had a magnitude higher than 70 kV and could be attributed to direct lightning on conductors or structures.

c) A typical MV/LV transformer can be submitted each year to 75-150 surges having a peak value between 20 kV and 70 kV, and 6 surges reaching a peak value higher than 70 kV.

d) Surge arresters rated 70 kV operated for about 4 % of the lightning overvoltages, while 80 kV rated air gaps operated only for 2 % of the lightning overvoltages.

e) The recorded wave front duration appears independent of the surge peak value. A mean value of this duration is 55 µs. The probability that a wave front duration be longer than 15 µs is 90 %.

A.4 Statistical distribution of lightning overvoltages in an LV installation

A comparison was performed between the results of measurements reported in [51] and a simulation by EMTP modelling with Monte-Carlo statistical method. Figure A.12 shows the modelled system, consisting of a 100 kVA distribution transformer supplying a four-conductor line 1 km long, 6 m above earth and 0,3 m apart. The MV line is taken as 2 km long to account for direct flashes to the MV line with transfer through the transformer.

Assuming a flash density of 2,2 flashes per km^2 per year, over a collecting area of 20 km × 30 km surrounding the line, the Monte-Carlo run was made for 1 000 000 flashes, which would take 670 years to accumulate to that number. The magnitude of the strokes was distributed according to that given by CIGRE [3], [10]. Direct flashes to the line were not counted, but assumed that they produce overvoltages above 20 kV, the upper limit of the distribution in figure A.13. In figure A.13, the results of the computation are identified as ANASTASIA [52]. Four points from the Popolansky field data [50] are also shown on the plot.

In the higher overvoltages part of the plot, the difference between the computation and the measurements can be explained by the fact that in the LV installation, flashovers can occur before the 10 kV level is reached, decreasing the incidence in the measured data versus the computed data.

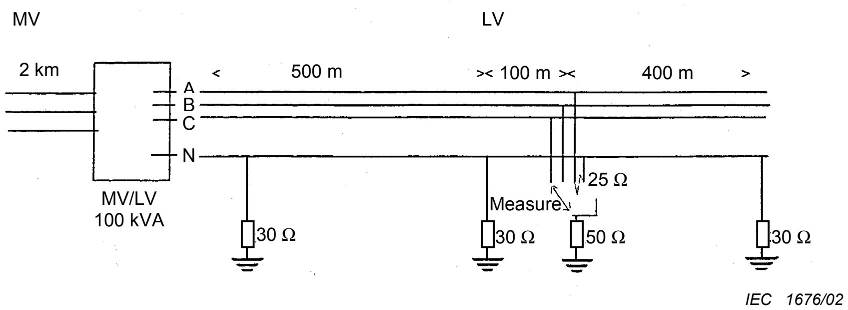


Figure A.12 – Circuit used for the statistical computation

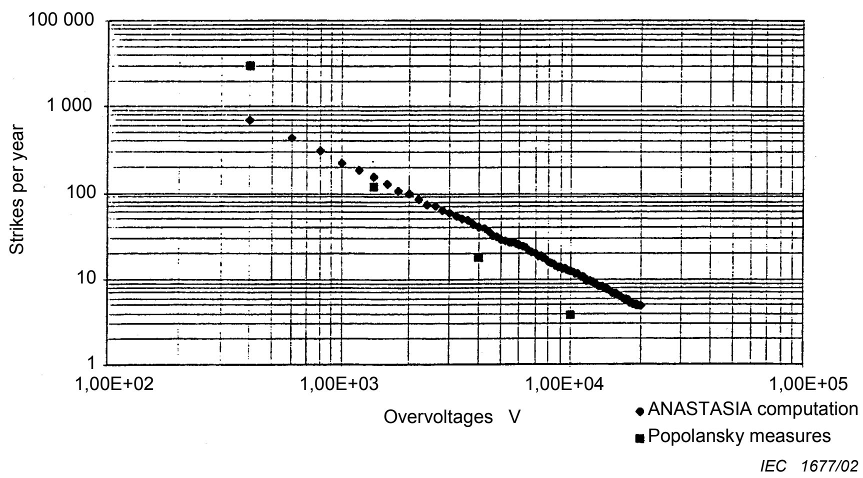


Figure A.13 – Comparison of measured overvoltages [51] **and computed overvoltages (ANASTASIA)**

A.5 Lightning current dispersion among parallel installations

When lightning strikes a structure which is one of several supplied in parallel by a LV power system, the earth-seeking current divides among the various paths available. These include local earth – the building earthing system – as well as distant earth points, through any and all metallic paths, primarily the power supply cable. To quantify this dispersion, an example is given in figure A.14 of two buildings supplied from a substation where building 1 is struck by lightning as defined in IEC 61312-1.

At building 1 of figure A.14, the injected current i_{imp} flows from the air-termination system through the down-conductor to the earth-termination system (P1). At that point, the lightning current divides into two components, $i_{Earthing}$ flowing into the local earth, and i_{Mains} flowing through the power supply cable toward the distant earth. These two currents divide according to the inverse ratio of the impedances at (P1). In the initial phase of the impulse current, the current division is determined by the ratio of the inductances, while in the tail, where the rate of change is low, the division is determined by the ratio of the resistances as in (A.1):

$$i_{Mains}/i_{Earthing} = R_{Earthing}/R_{Mains} \tag{A.1}$$

With several buildings strung in parallel, the effective resistance R_{Mains} decreases, which means, according to (A.1), that the portion of the lightning current that flows into the LV system will increase when more buildings are connected into the string.

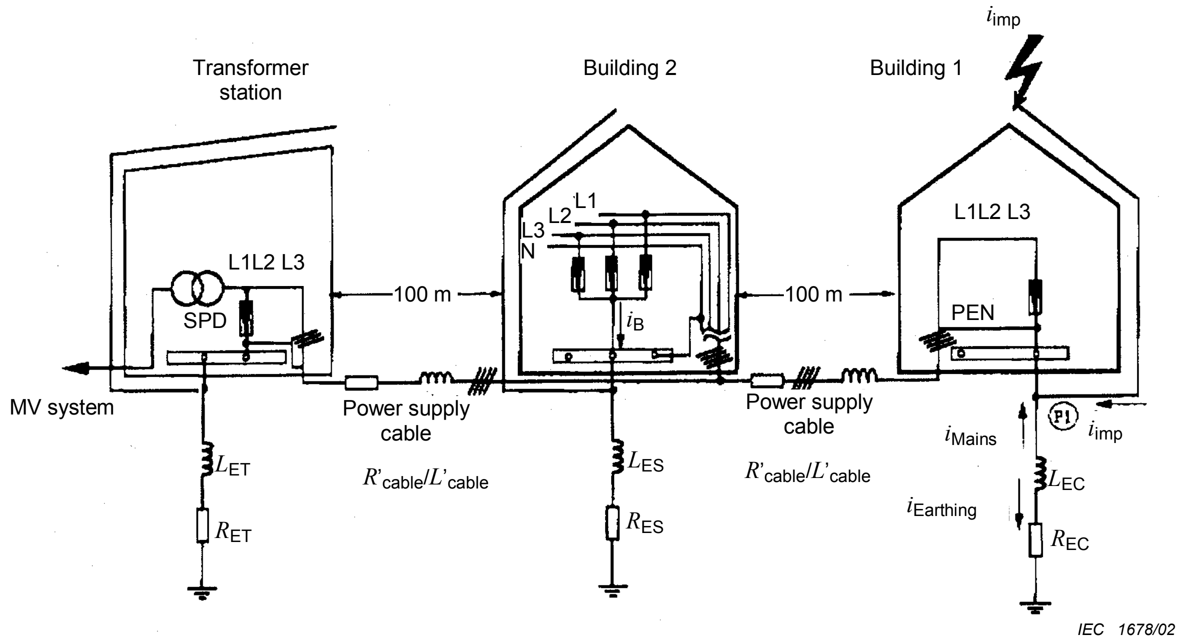


Figure A.14 – Model for computing dispersion of lightning current among parallel buildings (TN-C system) [24]

At the point of connection of building 2 to the system cable (figure A.14), the lightning current coming from building 1 and carried by the power system cable is still seeking earth and divides in two components, one entering building 2, the other flowing toward the transformer station where an earth electrode is also available. In a TN-C system, the three-phase cable includes three line conductors and the PEN conductor. The part of i_{Mains} entering building 2 is carried by all four conductors, with the PEN current directly fed to the earth electrode by way of the bonding bar. In this manner, the current flowing in the PEN provides some relief for the three SPDs provided at the service entrance, each carrying a third of the current i_B entering the building through the active conductors.

Figure A.15 shows the waveforms and amplitudes of currents at Building 1 and Building 2. From top to bottom traces, the lightning stroke current i_{Imp} (postulated at 100 kA peak), the current i_{Mains} carried away by the power cable, the current i_{Earthing} flowing directly into the Building 1 earth electrode, and the total current i_{B} in the three SPDs of Building 2. It is important to note that in this example the service entrance SPDs of Building 2 are each stressed with a peak current of more than 8 kA, even for a distance of 100 m between the two buildings. This situation is explained by the fact that the 100 m of cable add only 0,1 Ω to the path of i_{Mains} which flows through the two earthing resistances, each 10 Ω, of Building 2 and the transformer station. The model results also show that the ratio of the two inductances in the path force an initially larger current through the earthing electrode of Building 1 but that, after the inductive effects have subsided, the currents do indeed divide according to the ratio of the earthing resistances.

NOTE In the computations for the example of figure A.14 (and of figure A.16), all capacitances (wiring, cables and equipment) are neglected. If the involved capacitances were included, some oscillations would be seen on the oscillograms. However, these oscillations are of minor practical importance for this study, in which the current dispersion among the various conductors is the main issue.

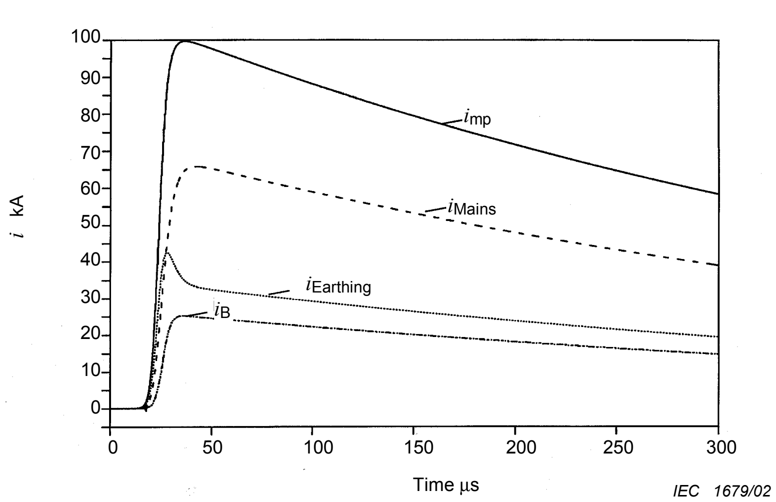


Figure A.15 – Dispersion of lightning current among the paths defined in figure A.14

The partial lightning current flowing in each earthing electrode leads to a voltage rise across the impedances, appearing between the local earth and the active lines L_1, L_2 and L_3 of building 2. To illustrate this situation, computations were also performed with the same model as that of figure A.14, except that no SPDs were provided at the service entrance of building 2, as shown in figure A.16. For that situation, as shown in figure A.17, the model indicated a prospective surge voltage of 200 kV peak (U_{B} in figure A.16) between each of the line conductors and the PEN conductor. In an actual situation, this high voltage would produce a flashover or other failures in connected equipment. Figure A.17 also shows the currents in the earthing electrodes of building 1 and building 2. Note that after the initial part, where inductance has some influence, the current can be expected to be equally divided among the three earthing electrodes of the two buildings and the transformer station, which have been postulated to have the same earthing resistance.

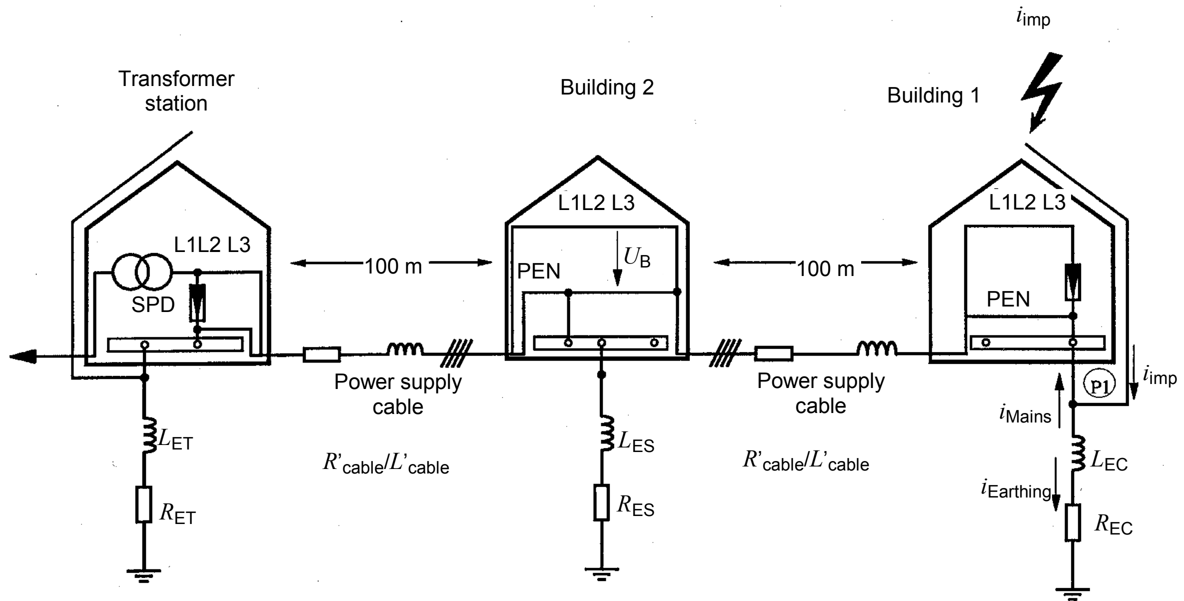


Figure A.16 – Model for computing dispersion of lightning current among parallel buildings (TN-C system, Building 2 with no LPS and no SPDs at the service entrance) [24]

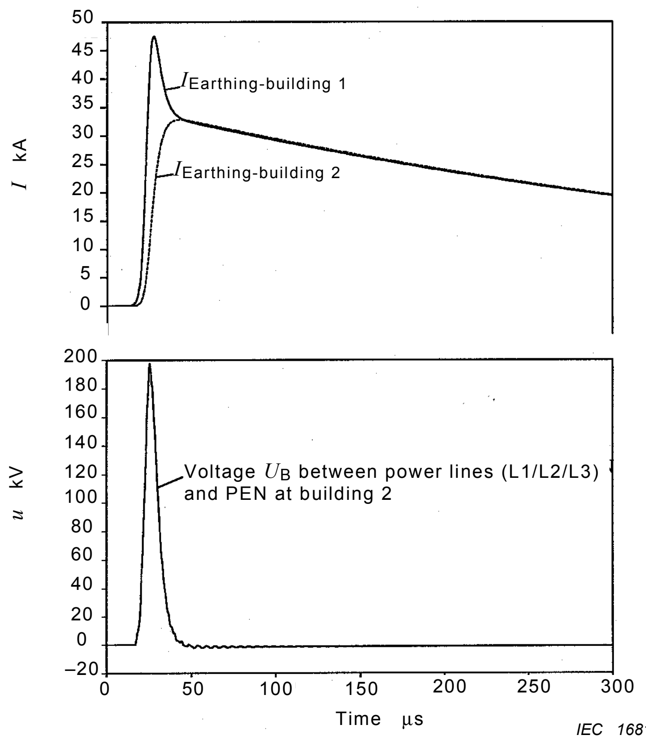


Figure A.17 – Currents and voltage for the example of figure A.16

Similar modelling of lightning current dispersion for a variety of neutral earthing configurations was also performed and reported in [31]. The modelling reported above was conducted using the well-known PSPICE programme, while the Mansoor modelling was conducted with the equally well-known EMTP programme. Good agreement was found between the two simulations [5].

As a general conclusion, the higher the density of buildings in an area, the greater the portion of the lightning current flowing to earth through the incoming LV power system cable of the building being struck. This conclusion has implications for the building being struck as well as for adjacent buildings.

Annex B
(informative)

Switching overvoltages

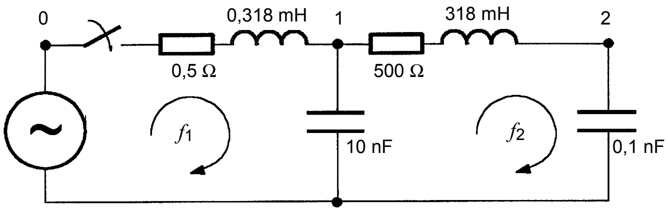
Lightning overvoltages described in clause 5 and annex A are mainly based on theoretical calculations, and the concept of prospective overvoltages (no inherent voltage limitation) was introduced in that context. In contrast, for switching overvoltages, extensive theoretical studies in the different existing low-voltage systems have not been found in the literature, and are also difficult to perform. Instead, data have been obtained from recordings of transients as they occur in existing systems, from staged field tests, or from simplified laboratory experiments.

General considerations on the occurrence of switching overvoltages have been presented in clause 6. In this annex, greater details are provided on the mechanisms leading to switching overvoltages, on the measurements (monitoring) of switching overvoltages as they occur in actual low-voltage a.c. power systems, and on staged measurements conducted on actual buildings or somewhat simplified laboratory experiments.

a) Clause B.1 describes the mechanism by which switching overvoltages can be exacerbated by transient resonance in some circuits.
b) Clause B.2 presents a brief review of a special type of switching overvoltage associated with the switching on or off of capacitor banks.
c) Clause B.3 describes the mechanism by which fuses can produce substantial overvoltages when clearing a fault.
d) Clause B.4 presents an overview of the results from transients monitoring projects.
e) Clause B.5 gives some insight on the propagation of switching overvoltages obtained by injecting standard surge waveforms into an installation model or into an actual building. (those findings are also useful for considering the propagation of lightning-related surges impinging at the service entrance).
f) Clause B.6 reports some examples of switching overvoltages observed in laboratory experiments involving circuit breaker operations.
g) Clause B.7 reports some examples of switching overvoltages observed in laboratory experiments involving fuse blowing.

B.1 Transient resonance

The frequency of the oscillations during switching operations is determined by the system characteristics, and resonance phenomena can sometimes occur. In such cases, very high overvoltages can be initiated. The probability of resonance with harmonics of the power frequency of the system is usually low. If the characteristic frequency of a switched part of a system is close to one or more resonant frequencies of the rest of the system, however, a state of transient resonance can also occur. In order to illustrate this behaviour, consider the example shown in figure B.1. The resonant frequencies of the two loops of the circuit are similar. Furthermore, the impedance of the first, driving part is low compared to the second loop. For high frequencies, frequency dependency of the system losses must be considered in order to obtain realistic results. The resistances shown on the figure are assumed to be representative for the resonant frequencies of the circuit studied.

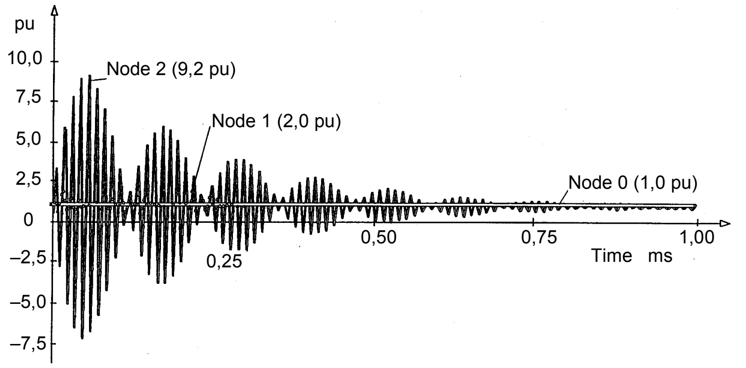


IEC 1682/02

Figure B.1 – Example illustrating transient resonance caused by switching

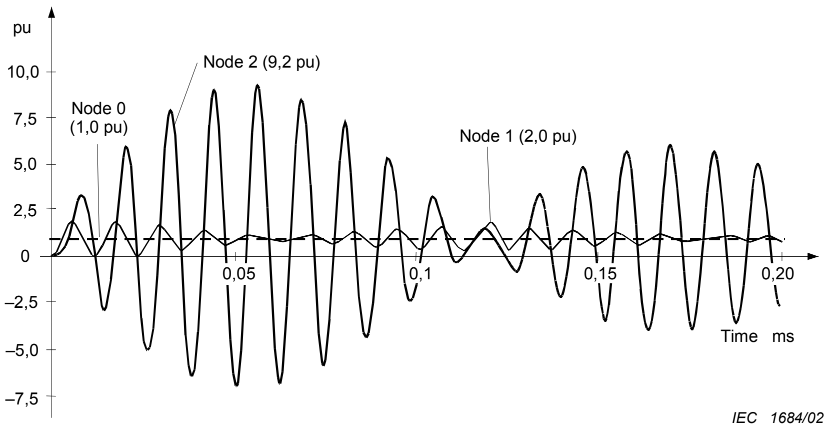
The calculated voltages at the circuit nodes are shown in figure B.2. The oscillation frequency is very high compared to the power frequency voltage, and this voltage (node 1) is practically constant in the time interval studied. Part a) of figure B.2 shows that a typical modulation takes place. The modulation frequency is basically determined by the difference between the frequencies of the two circuit loops. The details of the transients are seen in part b) of the figure.

a)



IEC 1683/02

b)



IEC 1684/02

Figure B.2 – Calculated overvoltages at the circuit nodes of figure B.1

The probability of occurrence for such overvoltages in a low-voltage system is low but the phenomenon should be noted. Also, it is noteworthy that a voltage magnification can occur for higher harmonics as well (3rd, 5th, 7th, etc.) of the characteristic frequencies of different parts of a system.

B.2 Capacitor-switching overvoltages

B.2.1 Energizing an isolated bank

Capacitor-switching overvoltages are an important type of switching overvoltage in some locations where the utility or the end-user applies capacitor banks for the purposes of power-factor correction or voltage control. These banks are switched on or off either at fixed times of the day, according to a predictable load profile, or at random, according to the need determined by a sensing control system.

Recent field observations of capacitor switching transients have shown frequencies as low as a few hundred hertz (IEEE 1036). Furthermore, the source impedance of a capacitor switching surge depends to a large degree on the amount of kvar being switched, compared to the base kvar of the system.

Figure B.3 shows an example of the overvoltage recorded on a distribution system bus during capacitor energizing. Usually, this type of overvoltage, with levels in the range of 1,2 to 1,7 p.u.V per unit is not of concern to utilities because the peak magnitudes are just below the level at which the surge protective devices (SPDs) in the utilities systems begin to operate. Because of the relatively low frequency, these overvoltages will pass through the distribution transformer and appear in the LV systems. There, SPDs with relatively low limiting voltages might become involved in attempting to clamp a capacitor switching surge of high amplitude, and be in jeopardy if the source impedance is low.

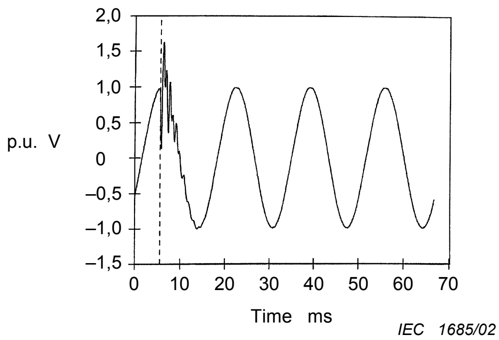


Figure B.3 – Typical overvoltage occurring during capacitor bank energizing

A low-frequency (relative to the 100 kHz ring wave or combination wave) capacitor-switching surge can deposit high energy into an SPD because of its long duration and low frequency. The low frequency results in low attenuation by line inductance, so that the effects of inductance, which are very significant when considering the propagation of microsecond-type surges, are generally far less significant when considering capacitor-switching surges [35]. For instance, in a low-voltage installation, an SPD installed at the end of a branch circuit will practically be exposed to the same surge as that experienced by the service-entrance arrester. Depending upon the relative limiting voltages of the two SPDs, coordination between the two devices might or might not be achieved.

B.2.2 Voltage magnification

The phenomenon of resonance was discussed in clause B.1 for an example of high frequencies and low values of capacitance (nanofarads). Resonance can also occur for the low frequencies and the large capacitances (millifarads) involved in an industrial installation. Figure B.4a shows an example of circuit where the phenomenon can occur, and figure B.4b shows how a 1,88 p.u. initiating transient causes a 4,65 p.u. overvoltage at the second (remote) location. Parallel-connected loads will experience that overvoltage.

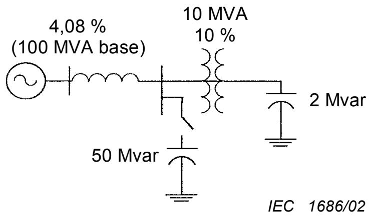


Figure B.4a – Magnification condition

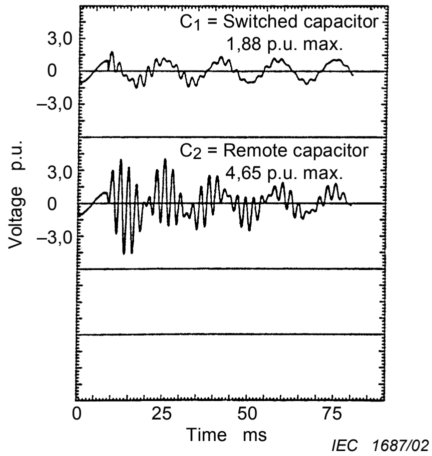


Figure B.4b – Voltage magnification effect

Figure B.4 – Magnification of capacitor switching overvoltage at remote bank (IEEE 1036)

Possible occurrence of capacitor-switching surges should be considered when SPDs are exposed to an environment near large switched capacitor banks. The ambiguity, however, is in defining what the qualifiers of near and large mean. At this stage of experience, it seems that broad generalizations are risky, and the phenomenon is best considered on a case-by-case basis, depending on the local conditions. When there is no magnification involved, special consideration in the selection of SPDs might not be necessary, except avoiding unjustified low limiting voltage, as demonstrated by the low incidence of problems in that scenario.

On the other hand, the voltage magnification scenario might be quite rare but if encountered, other remedial measures (detuning, switching in steps, resistance insertion, etc.) will be necessary to correct it because energy-absorbing SPDs do not have the capability to handle the level of energy exchanges involved in such scenarios.

B.3 Switching overvoltages produced by fuse blowing

Fuses are widely used in distribution systems and in electrical installations for protection against overcurrent and for interruption of short circuits. If a fuse is operating in a distribution system to clear a short circuit, the fuse has to generate a counter-voltage with a value above the instantaneous line voltage.

This overvoltage is also transmitted via the busbar to other equipment supplied from the same distribution system. For fuses which are operating faster than protective switchgear and thus create a higher overvoltage, figure B.5 shows the general conditions, which are explained as follows.

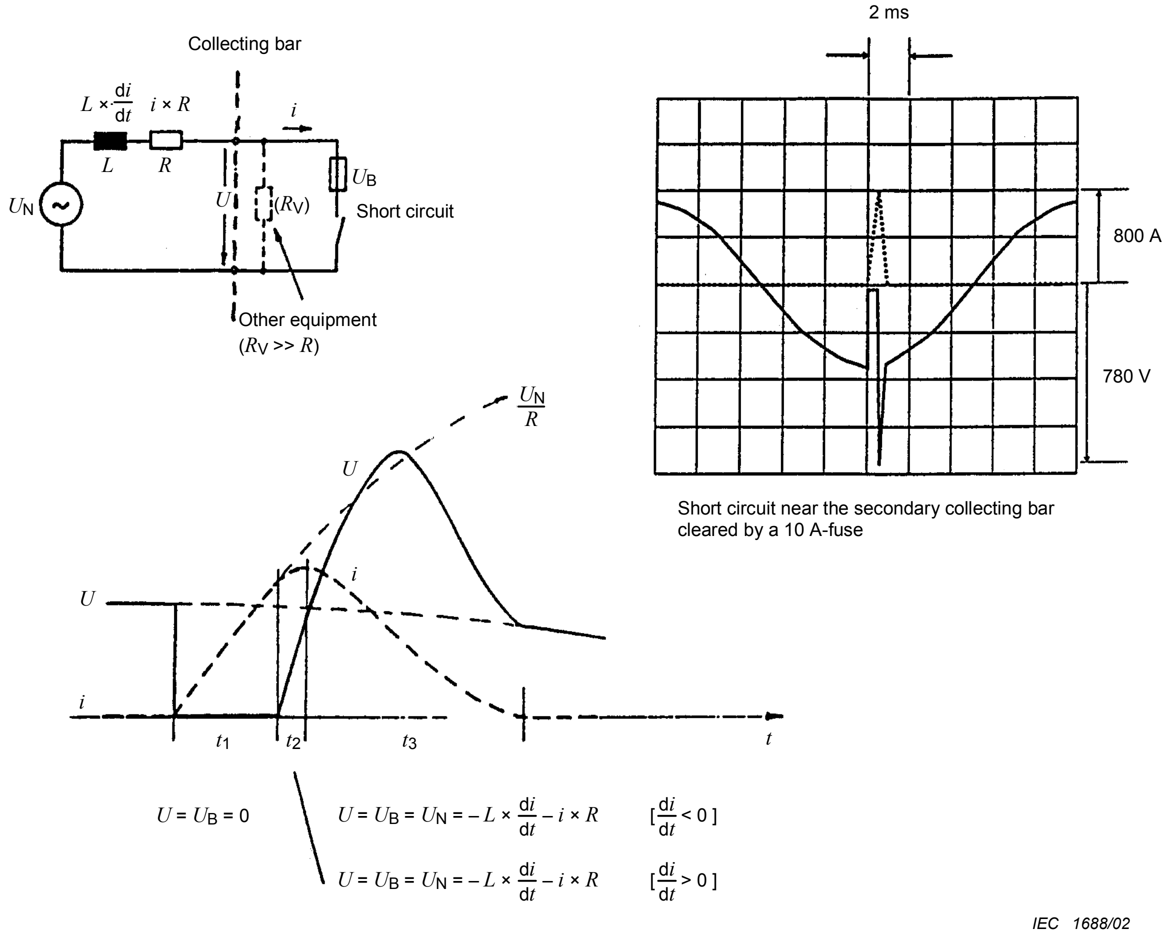


Figure B.5 – Principle of overvoltage generated by clearing a short circuit

At time t_1, the short circuit occurs and the voltage U_B across the fuse is zero until the fuse element melts at time t_2 and an electric arc occurs. When the arc voltage U_B has reached a voltage level which is equal to the line voltage reduced by the inductive and resistive voltage drops, the short-circuit current I has reached its peak value. In the time period t_3, it approaches zero the faster the higher the arc voltage is during t_3. The power consumption of other system loads has only a minor effect on this mechanism because its internal resistance R_V is large as compared with the internal resistance R of the system.

B.4 Monitoring of switching overvoltages

Overvoltages recorded in wide-scale field measurements are seldom correlated with power system disturbances, switching surges, or lightning events. Therefore, these measurements yield only the combined effects of all the phenomena, not just the switching overvoltages, although in some measurements, the absence of lightning activity at the time of the recorded event was reported. Measurements have also been conducted in real systems during staged switching tests, but the results are then limited to the particular conditions of the test. An interesting development in the technology of lightning location detection is now emerging, with the support of insurance companies, for the purpose of reconciling claims for lightning damaged appliances with the actual occurrence of lightning strokes in the area. Such pin-pointing of lightning events might eventually allow separating lightning-related surges from switching surges among the results of overvoltage monitoring projects.

On the other hand, all overvoltages in actual systems are limited by the insulation withstand level of the system and of the connected equipment. In addition, SPDs installed in the system (and also built-in SPDs incorporated within connected load equipment) will limit the measured voltages [37]. This significant change in the power system conditions, emerging in the early eighties and now well established, should be borne in mind when considering the numerical values cited in the most recent surveys. For future surveys, researchers would be well-advised to consider monitoring the currents that a surge event might produce in a candidate SPD to be installed at the point of interest, rather than monitoring the voltages that only reflect the mitigation of nearby SPDs.

Monitoring transient overvoltages has been done by many researchers since the 1960's. The assessment of switching overvoltages in low-voltage installations requires long-time measurements and their statistical evaluation [8], [38], [51], [20], [43], [44], [21], [42], [47], [2], [49], [54], [9], [1]. These measurements were first performed with oscilloscopes and camera systems until the mid-eighties, and are now performed by use of automatic recording systems based on digital storage oscilloscopes or on entirely digital data-collecting systems.

The results, of course, are influenced by the maximum measurable amplitude and by the bandwidth (corresponding to the maximum measurable rate of rise) of the measuring system. In [51], [43], 44], a rather large bandwidth (20 MHz) was used but the maximum measurable amplitude was only 3 kV. In [47] and [49], the bandwidth was only 5 MHz, but amplitudes up to 5 kV could be measured and surges with larger amplitudes could be recorded. Today, systems with both higher bandwidth (50 MHz) and maximum measurable amplitude (>6 kV) are being used. In addition, the results are greatly influenced by the location of the measuring system, the kind of installation, the total measuring time and many more parameters.

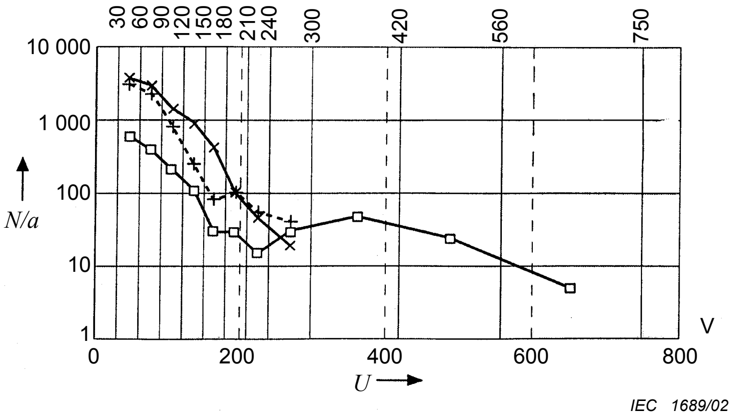
Another factor which has to be taken into account is that the measurements were conducted in different systems (TT or TN) and the reported results are line-to-local-earth for some surveys, but line-to-neutral for other surveys.

In [8] the survey was conducted with peak-detection counters installed in various locations of the United Kingdom. While representing an early attempt at characterizing the environment, limiting the data to peaks only – no information on waveshape – was a limitation, unavoidable for the type of portable field instrumentation available at that time. Nevertheless, the findings were useful to draw attention to the phenomena.

In [38], two stages of monitoring in North American systems were reported. One involved a simple level detector, a simplified version of the Bull and Nethercot instrument, capable of counting transient occurrences above 1 200 V or above 2 000 V. For those locations where such occurrences were recorded, an oscilloscope-camera system was then installed. These oscilloscope-camera systems were also used to check locations where equipment failures had been reported. The results of the monitoring indicated that a small percentage of locations – those not selected because of reported problems – did (in the 1960s) experience a few voltage surges above 1 200 V, and very few above 2 000 V. On the other hand, surges in the range of 2 kV to 5 kV were found in locations that had experienced equipment failures. It should be noted that these measurements were conducted before the proliferation of SPDs in low-voltage consumer systems.

In [51] and in [43], [44], many industrial locations were investigated, primarily in Germany, but the measuring time at each location was rather short. In commercial installations, similar amplitudes were recorded. However, as during the total measuring time of 1 202 h the number of events (3 401) was comparatively low, the probability of occurrence of switching surges is significantly lower. The results of these measurements were published in English by [21]. Figure 22 shows a frequency of occurrence vs. peak level for diverse locations, as reported in the referenced paper.

In [47] and [48], households, offices and laboratories in Germany were monitored. Figure B.6 shows a plot of the results from these two investigations.



Key

□ Household

\+ Office

X Laboratory

Figure B.6 – Example of survey of switching overvoltages in three types of installations

An industrial location was added later on. The additional measurements were performed over a period of more than three month at each location. Table B.1 shows a summary of these measurements, which are rather well in line with the previous data reported in [51], [43] and [44], especially if the different locations and the limited amplitude measuring range of the earlier ones are taken into account.

Table B.1 – Minimum, maximum and mean values of the amplitude and rate of rise of the recorded switching surges at different locations [48]

	Household	Office	Laboratory	Industrial
Minimum amplitude, V	35	35	35	50
Maximum amplitude, V	644	294	257	4916
Mean amplitude, V	97	80	86	280
Minimum rate of rise, V/µs	4	1	2	270
Maximum rate of rise, V/µs	1 690	1 190	1 385	10 766
Mean rate of rise, V/µs	255	253	216	600

In an industrial installation, equipment can be located at rather short distances from distribution transformers and the collecting bar. Under those conditions switching surges of up to 5 kV amplitude have been recorded. As can be seen from the evaluation of the absolute probability of occurrence of switching surges (*N/a* = events per year) shown in figure B.7, there seems to be a superposition of the regular distribution according to the third-power law with a special event causing switching overvoltages of approximately 5 kV amplitude.

The latter ones could be allocated to the switching-on and off of one distribution transformer at every weekend. It is evident that such special situations also require special protection measures.

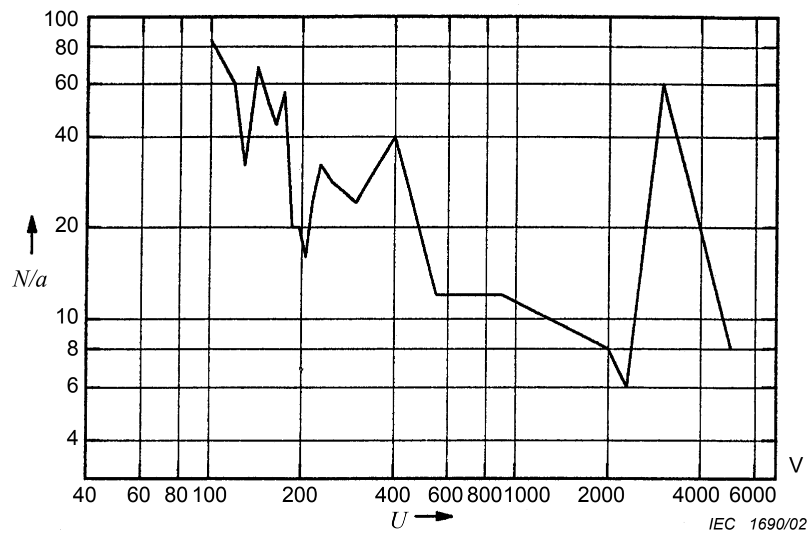


Figure B.7 – Switching surges in an industrial plant measured near the collecting bar

In [9], the emphasis was more on dips and interruptions than on surges as the survey was part of an attempt to characterize power quality in low-voltage end-user systems in North America. The results for recorded transients are shown in table B.2. A significant finding in that survey, however, was the relatively rare occurrence of high-amplitude transients, which Dorr suggests to be the result of the proliferation of SPDs in low-voltage end-user systems.

Table B.2 – Distribution of recorded transients

NOTE One hundred and thirty sites were monitored, that is a total of 1 200 site-months of monitoring. Half of the monitors were in place for a full year and half were in place for six months.

Range of recorded transients, volts	<1	1-2	2-3	3-4	4-5	5-10	10-20	20-30	30-50	50-100	100-150	150-200	200-250	250-300	300-400	400-500
>1000	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0
901-1000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
801-900	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
701-800	0	0	0	0	0	0	2	0	0	1	0	0	0	0	0	0
601-700	1	2	0	0	0	1	2	1	0	0	0	0	0	0	0	0
501-600	0	0	1	3	0	1	0	1	0	0	0	0	0	0	0	0
451-500	0	1	2	4	0	0	1	1	0	1	1	0	0	4	1	0
401-450	1	2	4	12	0	1	3	1	1	1	10	0	1	16	0	0
351-400	0	6	10	14	3	2	2	2	1	5	10	7	2	11	1	2
301-350	1	10	15	15	4	3	6	3	25	21	23	9	9	19	8	1
251-300	3	5	14	20	6	15	39	6	58	67	79	23	15	31	8	8
200-250	5	25	60	23	13	130	473	78	116	158	210	86	15	58	20	9
150-200	19	89	187	728	687	976	1702	1975	749	832	887	513	214	197	99	36
100-150	140	503	1350	3875	2488	11108	7035	3816	3352	12193	4162	2536	811	393	357	234

Duration of transients, microseconds

The Dorr measurements, as well as those of [38], were made on single-phase or polyphase systems, between line and neutral, for the purpose of assessing the stress applied to electronic components connected between line and neutral. Because the North American practice is to bond the neutral to the local earth at the service entrance, these measurements also represent the line-to-earth stress. In contrast, some of the measurements reported by other researchers cited in this narrative were made from line to the local earth, for the purpose of assessing the stress applied to the equipment insulation.

In [1], recent monitoring performed in Germany are reported. This monitoring covered two stages, one of general characterization and one of high-risk locations. The aim was to monitor maximum overvoltages stressing the insulation of low-voltage equipment.

In the first part of the investigation during a two-year period, 40 measuring points were monitored, covering commercial and industrial locations, as well as office buildings and residential buildings. Figure B.8 shows the frequency of occurrence per year for the recorded events. The source article does not provide information on waveshape, except a statement that a duration of at least 1 μs was required to register. Because the main objective was to assess the stress on insulation, the waveshape was less important than the peak values.

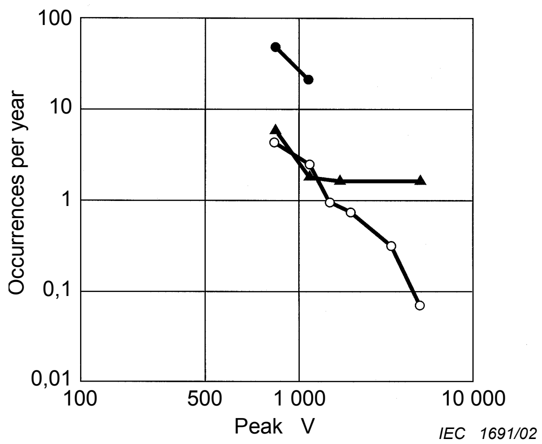
In the second part of the investigation, overvoltages were measured at 25 locations where frequent and severe overvoltages might be expected. The locations selected were rated 400 V and the measurements were made from line to protective earth. According to the report of this investigation, all SPDs that were detected at the measuring point were removed. Nevertheless, it is difficult to guarantee that all SPDs were disconnected, considering the widespread practice to have built-in SPDs in modern equipment.

Most of the recorded overvoltages were in a range of 500 V to 1 000 V but only those above 1 000 V were considered for evaluation. The expectation that frequent and severe overvoltages would be found at the high risk locations were not validated. At some locations, not even the 500 V threshold was exceeded.

Table B.3 shows a summary of the findings. For most of the recorded transients, the maximum voltages were much lower than previously expected, raising, once again, the issue of proliferation of undetected SPDs. For those low-voltage systems where no protection is presently provided, greater risks can be avoided by using equipment with higher withstand capability or by providing suitable SPDs.

Table B.3 – Measurement points and results of the long range measurement (second part) [1]

Measurement points	Installation type	Network type	Measurement results					
			0,5 kV	1 kV	1,5 kV	2 kV	4 kV	6 kV
Municipal hall	Household	Overhead line	X					
Automotive industry	Industry	Cable						
Producing firm No. 2	Industry	Overhead line						
SPD-factory	Industry	Cable	X					
Lignite open cast mining	Industry	Cable						
Chemical factory No.1	Industry	Cable	X	X	X			
Chemical factory No. 2	Industry	Cable						
Fibrous material factory	Industry	Cable	X					
High rise ware house	Industry	Cable	X					
Chipboard factory	Industry	Cable	X					
Producing firm No. 1	Industry	Cable	X					
University laboratory	University	Cable	X					
Surface technique factory	Industry	Cable	X					
Factory	Industry	Cable	X					
Switchgear factory	Industry	Cable	X					
TV-transmitter	Miscellaneous	Cable	X					
Telecom-station	Miscellaneous	Cable	X					
Mains network No.1	Utility network	Overhead + cable	X					
Mains network No.2	Utility network	Overhead line	X					
Residential building	Household	Cable	X	X	X	X		X
District office	Office	Overhead line						
Tower station	Utility network	Overhead line	X					
Farm	Miscellaneous	Overhead line	X					
Radio-transmitter No. 1	Miscellaneous	Overhead line	X					
Radio-transmitter No. 2	Miscellaneous	Overhead line	X					



Key

- • Chemical plant
- Δ Residence
- o Overall results

NOTE Transients below 1 000 V are not considered a threat to equipment insulation.

Figure B.8 – Frequency of occurrence at selected sites and overall results

B.5 Propagation of switching overvoltages

A worthwhile consideration is a possible attenuation or increase of switching overvoltages within low-voltage installations. This effect has to be considered together with the shape of the switching overvoltages involved and the configuration of a typical low-voltage installation. Possible effects are travelling wave phenomena and/or attenuation by transmission losses and branching of lines. The first phenomenon is only of significance if the travelling time along the transmission line is at least one-third of the rise time of the switching surge. This means that for the standard impulse with 1,2 µs front time, the line length would have to be in the order of 70 m to cause travelling wave effects.

One might expect that lines of such length could exhibit attenuation caused by dielectric losses or by skin effect. However, measurements have shown that even for a line of 75 m in length, for the standard impulse of 1,2/50 µs, attenuation by losses is not an important effect as far as the maximum amplitude of switching overvoltages is concerned [39].

As the combined effect of reflections, attenuation and branching is rather complex, extensive measurements of surge propagation in a model installation were performed, as reported in [49]. The model installation included 10 branch circuits of various length and characteristic impedances, supplied from a main service panel and several sub-panels. All measurements were made single phase to earth with the surge applied from a generator with 25 Ω source impedance. The maximum line length selected for the model was such that reflections might occur even for the standard impulse. Indeed, some modest overshoot caused by reflections was observed at some nodes of the model, but the waveform remained essentially un-attenuated.

In a similar experiment, performed on a new building before it was placed in service, propagation measurements were conducted with injection of a combination wave surge as well as a 100 kHz ring wave [36]. For the combination wave (a 2 Ω source impedance), the results are similar to those cited above. For the ring wave, significant reflection effects were observed at the open ends of the longer branch circuits (40 m to 70 m).

On the other hand, steeper overvoltages, such as those implied in the electrical fast transient burst (EFT) of IEC 61000-4-4 are significantly attenuated by a line length of a few metres [40]. Therefore, the event of contactor switching and bouncing, which is the source of these fast transients, is more an EMC issue than an overvoltage concern. Furthermore, the interference effects of these fast transients are generally not mitigated by conventional SPDs that focus only on voltage amplitude mitigation.

B.6 Examples of circuit-breaker operation

B.6.1 Circuit-breaker and switch operations in the customer's premises

During switching-off of equipment, the switching overvoltage on the load side has a higher amplitude and energy delivery capability than that which appears on the line side. However, this is mainly a problem with respect to the design of the particular equipment being switched. If other equipment is connected in parallel, it will also be stressed. The overvoltage on the installation side is of greater importance for the whole system and for the equipment connected to it. Therefore, this aspect is pursued in greater detail: both switching-on and switching-off can induce overvoltages [48]. The switch-on overvoltage will be increased if equipment with high inrush current is switched on.

Usually higher amplitudes are generated by switching-off of equipment. Amplitudes of 1,9 kV have been observed in staged tests, with rates of rise up to 5 kV/µs. Switching-on of contactors can induce overvoltages with amplitudes of up to 600 V. The rate of rise will be in the order of only 50 V/µs. Switching-off of contactors can induce much higher surges on the load side. Amplitudes as high as 2,3 kV have been observed. A scenario for contactor operation that might be described as switching-on can in fact involve switching-off when the contacts bounce and effectively produce an electrical switching off, the very phenomenon addressed by the electrical fast transient burst test.

Switching of miniature circuit-breakers with rated currents of some amperes seems to be a minor problem as far as switching overvoltages are concerned. Even a short-circuit interruption will induce rather low overvoltages on the installation side. In general, the amplitudes of the overvoltages on the installation side are below 500 V. An example of test results for the different current ratings of typical miniature breakers is given in table B.4.

Table B.4 – Amplitude and rate of rise of switching surges versus rated current of miniature circuit-breakers [47]

Rated current, A	2	4	6	10
Mean amplitude, V	208	224	201	232
Maximum amplitude, V	379	399	332	285
Mean rate of rise, V/µs	33	36	21	22
Maximum rate of rise, V/µs	190	135	48	28

However, a much more severe event is the operation of a miniature circuit-breaker in case of high inrush current. This is especially true if the rated current of the circuit-breaker is too low. As an example, a measurement made when a power tool was switched on in a circuit with a miniature circuit-breaker with a current rating of only 2 A (figure B.9). The unavoidable interruption of the inrush current as the breaker tripped under these conditions produced very high overvoltages with very long duration and high energy delivery capability. The maximum overvoltage in this test was 2,8 kV.

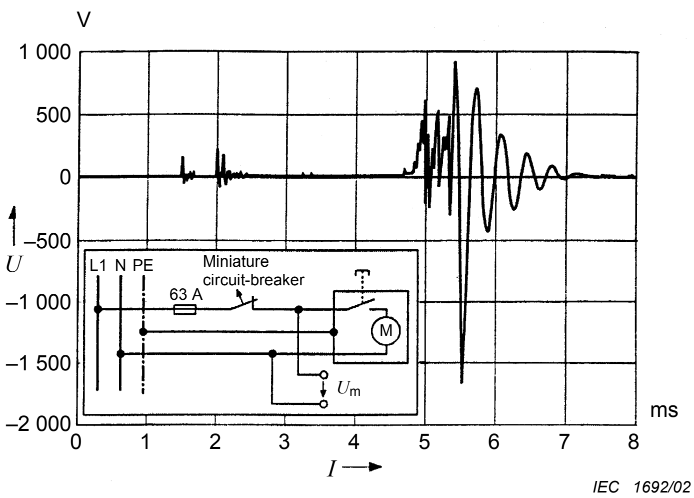


Figure B.9 – Test circuit and surge during trip of a miniature circuit-breaker due to inrush overload

B.6.2 Circuit-breaker and switch operations in the supply system (LV and MV)

Transient overvoltages stressing the electrical equipment can be observed in every supply system. In underground supply systems, nearly all transients are generated by electromechanical switchgear of similar sources. In LV and MV installations, the switching of inductances such as transformers, impedance coils, contactor coils and relays installed in parallel to the supply source can cause switching overvoltages with an amplitude up to several kilovolts. However, the frequency of the occurrence is quite low, as switching in supply networks usually occurs in case of faults or maintenance. Such events are very rare as compared with switching of loads in the customer's installation. The same phenomenon exists when switching off longitudinal inductances such as conductor loops and longitudinal impedance coils, or even when switching off the supply system itself together with the inductances of wiring. On the supply side, switching overvoltages can also be caused by the operation of gating controls, by brush arcing of slip ring motors, by sudden load decrease of electrical machinery or transformers and by operational switching of capacitor units used for power factor correction.

The frequency and energy delivery capability of the overvoltages of such kind can be considerably higher than those of atmospheric origin as far as the influence on low-voltage installations is concerned. Transient overvoltages due to switching in the low-voltage supply can reach amplitudes of several kilovolts, though it may be assumed that the maximum values are limited due to certain conditions when operating the low-voltage supply network. In those supply systems where overvoltage control by protective devices is installed, it can be expected that a maximum amplitude of 6 kV in general is not exceeded within the low-voltage customer's installation.

B.7 Examples of fuse operation

The principle of overvoltage generation during a fuse operation has been explained in clause B.2, and an example of operation of miniature fuses has been described in 6.3. In this part of annex B, additional examples are given of such overvoltage generation.

Figure B.10 shows the overvoltage at the secondary collecting bar of a 230/400 V transformer substation when blowing 100 A fuses. The short-circuit overvoltage has an approximately triangular wave shape and occurs between the line conductors of the system. Of course, it does not occur frequently, compared with overvoltages caused by switching of operating currents.

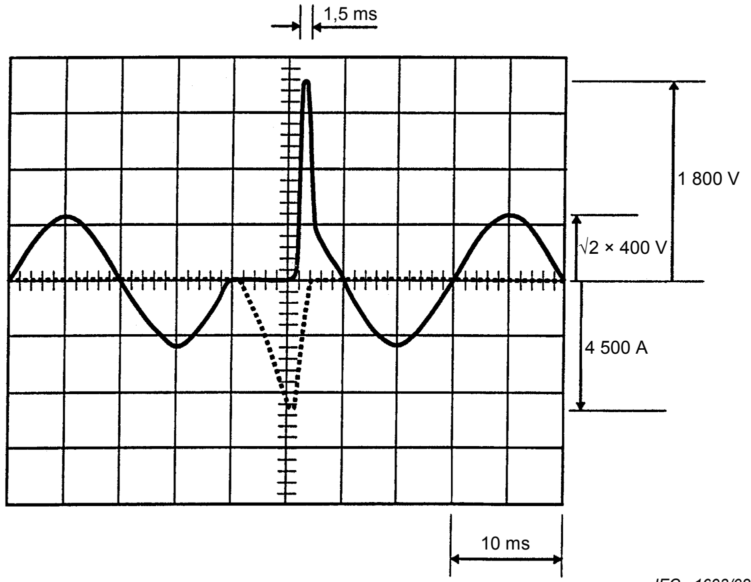


Figure B.10 – Example of overvoltage at the secondary collecting bar of a 230/400 V transformer substation when blowing 100 A fuses of a feeder

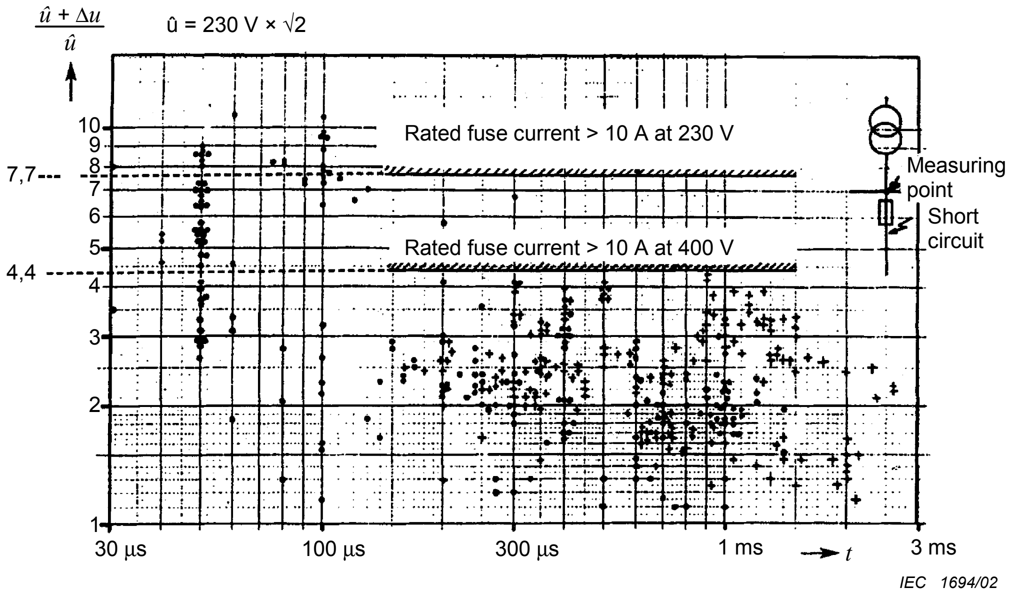
For the industrial field, figure B.11 shows the magnitude and time duration of overvoltages occurring at the busbar and thus stressing the connected loads when a short circuit located immediately behind the circuit fuse is switched off. The data are based on measurements taken at a variety of measuring points in different industrial installations.

These measurements were performed with fuses from different manufacturers having rated currents of 10 A, 35 A, 100 A and 355/400 A. From the distribution of the measured data in figure B.11, it appears that the lower the rated current of the fuse, the higher the overvoltage, but the shorter its duration.

The measurement results are expressed by the overvoltage factor which is the effective maximum of the transient overvoltage expressed as a multiple of the peak of the nominal supply voltage. The overvoltage factor is between 7,7 and 10,5 in only 3 % of the cases measured. For a 230 V single-phase supply, this means that in case of a short circuit between line conductor and neutral conductor, an overvoltage of 2,5 kV to 3,4 kV occurs.

For a 400 V three-phase supply and a short circuit between line conductors, the overvoltage factor is below 4,4, and hence the overvoltage remains below 2,5 kV. According to the relevant fuse standards, the switching voltage of fuses with a rated current greater 10 A should not exceed 2,5 kV. This value corresponds to an overvoltage factor of 7,7 for a 230 V supply and 4,4 for a 400 V supply. The horizontal bars in figure B.11 show that the specified limit of the switching voltage is nearly kept in both cases.

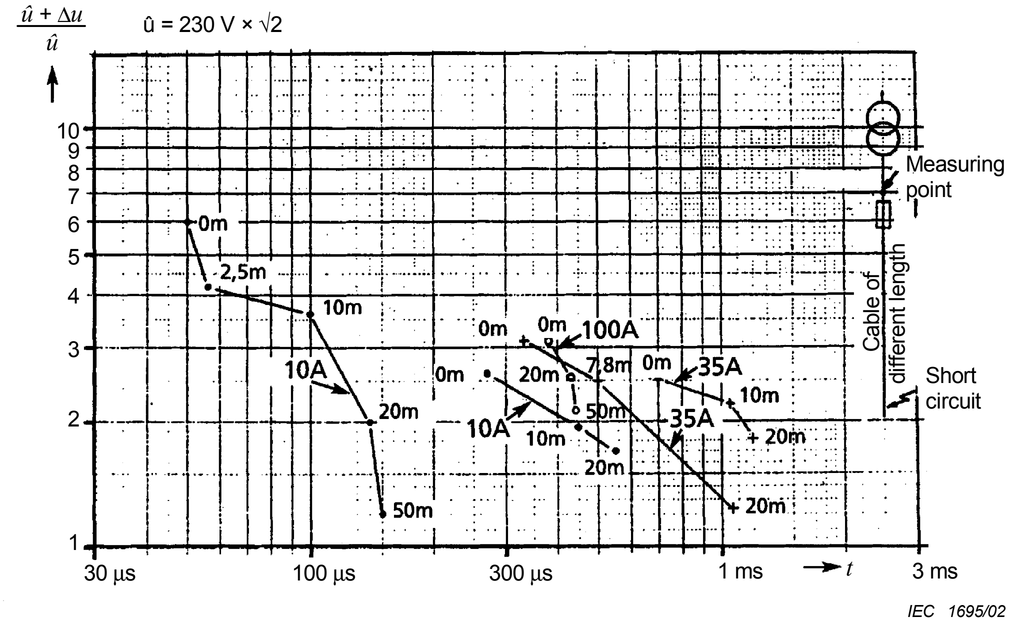
If the short circuit does not occur near the busbar where the circuit fuse is located but at the far-away termination of the circuit, which is the more probable case, the switching overvoltage level reduces but its duration increases as shown in figure B.12. For each rated current being investigated, two data sets are shown. They refer to products from two different manufacturers and give some indication of the spread of amplitude and duration of the surges to be expected.



Key

//////	Limit value of switching overvoltage by low-voltage fuses according to the standards for fuses
•	10 A-fuse
+	Fuses >10 A

Figure B.11 – Overvoltage factor versus time duration of switching surges in a distribution system – Short circuit near a feeder fuse



Dimensions in millimetres

Figure B.12 – Overvoltage in a distribution system depending on the cable length for different fuse ratings – Short circuit at the end of the cable

Annex C
(informative)

Complementary information on temporary overvoltages

C.1 Temporary overvoltages caused by faults

One of the sources of temporary overvoltages (TOVs) in LV power systems is the occurrence of faults in the MV system. The characteristics of these TOVs depend on the type of the power system and the nature of the faults. Tables C.1 and C.2 summarize the possibilities outlined graphically in the schematics provided in IEC 60364-4-442. Table C.1, already included in clause 7 as table 6, is reproduced here for the convenience of the reader. It represents the maximum values allowed to occur, as a design requirement for the installation. These values are an upper limit, and in practice the TOVs that do occur are likely to have lower values. Table C.2 shows the maximum values that can occur in case of a fault in the LV system.

The IEC 60364 information is complemented by the schematic of figure C.1 representing the North American practice, which is not included in the current edition of IEC 60364-4-442.

Table C.1 – Maximum values of overvoltages allowed to occur during MV-faults to earth

Type and earthing MV-system with single earth fault	LV-system according to IEC 60364	Maximum r.m.s stress voltage on equipment within LV-installations			Fault duration	Maximum fault current
		L-PE	N-PE	L-N	s	A
3 wires, isolated	TN, TT, IT	U_0	0	U_0	>>5	Some tens
3 wires, resonant earthing or 3 wires, impedance earthing	TN, TTb) ITa), c), d)	U_0	0	U_0	>5	Some hundreds
	TTa), ITb), e)	≤250 V + U_0	≤250 V	U_0	>>5	
Low impedance earthing	TN, TTb) ITa), c), d)	U_0	0	U_0	<5	Some hundreds
(France)	TTa), ITb), e)	≤1 200 V + U_0	≤1 200 V	U_0	<5	
3 wires/direct earthing	TN, TTb) ITa), c), d)	U_0	0	U_0	<5	Some thousands
	TTa), ITb), e)	≤1 200 V + U_0	≤1 200 V	U_0	<5	
4 wires, direct earthing (USA practice)	TN	≤2,45 U_0	0	≤2,45 U_0	<5	Some thousands

Table C.2 – Maximum possible values for TOVs in LV-installations due to LV-faults

Type of fault in the LV-system	Type of LV-system	Maximum r.m.s stress voltage on equipment within LV-installations			Fault clearing time
		L-PE	N-PE	L-N	s
Earth fault	TN	U_0	0	U_0	<5
	TT If $R_B/R_E \le 50$ V/(U_0-50 V) is fulfilled in the distribution system[a]	≤40 V + U_0	≤50 V	U_0	>5 if fault occurs in distribution system
		≤√3 U_0	U_0	U_0	<5 if fault occurs in user's installation
	TT If $R_B/R_E \le 50$ V/(U_0-50 V) is not fulfilled in the distribution system[b]	≤1,45 U_0	≤U_0/2	U_0	>5 if fault occurs in distribution system
		≤√3 U_0	U_0	U_0	<5 if fault occurs in user's installation
	IT	≤√3 U_0	U_0	U_0	>>5
L-N short circuit	TN	≤1,45 U_0	0	≤1,45 U_0	<5
	TT	U_0	≤U_0/2	≤1,45 U_0	
	IT	U_0	≤U_0/2	≤1,45 U_0	
Loss of neutral	TN, TT	U_0	≤U_0	≤√3 U_0	>5

NOTE 1 In some countries, a distinction is made between TT-systems:

[a] TT system with reliably earthed neutral conductor

[b] TT-system where the neutral conductor is not reliably earthed

where

R_B is the total earthing resistance of the neutral conductor in the low-voltage system;

R_E is the lowest earth resistance to be expected for conductive parts which are not connected to the protective conductor, but may be subject to an earth fault;

50 V is the conventional touch-voltage limit;

U_0 is the nominal voltage line to earth of the low-voltage system.

NOTE 2 For IT-systems the max. r.m.s. stress voltages due to MV faults and due to LV faults have to be added because of the possible long durations.

As an example, a three-wire MV system resonant earthed, with earth fault duration longer than 5 s, and LV earth fault duration longer than 5 s, the maximum r.m.s. stress voltage that can be produced is equal to or less than 250 V + √3 U_0 for the L-PE voltage.

NOTE 3 TOVs due to loss of neutral in the LV system can be disregarded when selecting SPDs, because no equipment is required to withstand such a stress. However, such a TOV can destroy the SPD, in which case, of course, the normal design criteria of the SPD should be satisfied, that is, that the failure mode be acceptable.

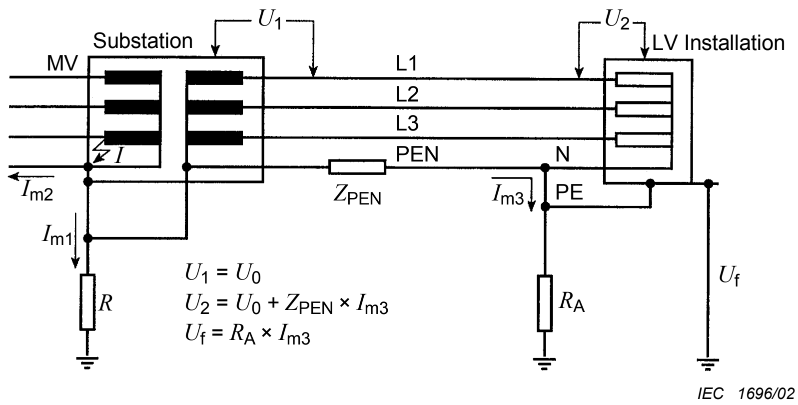


Figure C.1 – Temporary overvoltage resulting from a fault in the primary of the distribution transformer in a TN system according to North American practice

C.2 Commingling of systems

Some overhead distribution systems, for a number of compelling reasons, use the same pole to carry sub-transmission lines and distribution lines on the side of roadways, an arrangement sometimes described as overbuilt. This close proximity can lead to commingling of the two systems if the sub-transmission lines were to fall upon the distribution lines. This type of accident can occur during storms or when an out-of control vehicle knocks down a pole, a real concern in the face of repetitive occurrences in some locales. A similar situation, but with much less exposure than the long roadside overbuilt, occurs at points of crossing of the two systems. This condition can also exist in buried distribution systems where the practice of random lay (all power and communication cables in same trench) is employed.

Depending upon the overvoltage protection schemes implemented on the distribution system, this commingling can have disastrous consequences for equipment connected to the low-voltage system supplied from the distribution system through distribution transformers. Typical arresters cannot survive exposure to the relatively long time (a few cycles) of the power-frequency overvoltage, awaiting the trip of the sub-transmission circuit breaker. In fact, this inability of the arrester to dissipate the energy associated with this overvoltage leads to destruction of the arrester but initiation of a power arc which effectively provides a limiting voltage lower than the protective level of the arrester.

In this manner, customer equipment connected to the low-voltage system might be protected, albeit at the cost of the arrester which is destroyed and must be replaced. This replacement is a small expenditure compared to the cost of repairing the downed pole and broken lines. Compared to the massive failure of equipment on the low-voltage side that would otherwise occur, the one-shot protection scheme by the sacrificial arrester is an option which several electric utilities have considered and some have applied.

As an example of a commingling incident, consider a structure where a 23 kV distribution voltage circuit (13,9 kV line-to-earth) is installed above a 4,16 kV distribution circuit. Should the 23 kV line accidentally contact the 4 kV line, the voltage impressed on this line exceed the system voltage by a factor of 5,5. With wood cross-arms, the 4,16 kV circuit can easily withstand this overvoltage, thus imposing the 13,9 kV upon the distribution transformers supplied by this circuit. With arresters installed at the transformer primary, and possible saturation of the transformer, one might expect that the limitation of overvoltages on the LV side of the transformer to be sufficient to avoid serious damage to the connected LV equipment. Anecdotal data report however that massive equipment failures have occurred in some cases. That situation might be explained by inappropriate earthing practices for the transformer case and neutral.

Annex D
(informative)

Complementary information on system interaction overvoltages
(see clause 8)

D.1 The general problem

As electronic equipment enters the home and business environments more and more, this often involves a communications port as well as the usual power cord port. A typical example is a personal computer (PC) with modem connection. Although each of the power and communications systems might include a scheme for protection against surges, the surge current flowing in the surged system causes a shift in the potential of its reference point while the other, non-surged system reference point remains unchanged. The difference of potential between the two reference points appears across the two ports of the PC. Depending on the nature of the PC/modem and its immunity, which is not often defined, this difference of potential may have some upsetting or damaging consequences.

Various mitigation schemes have been proposed to remedy upsetting or damaging potential differences. The most effective would be a fibre optic decoupling inserted in the communications link, but the expense and involvement would be objectionable for the typical home office application. Increasing the withstand capability of the PC system by the manufacturers is unlikely to happen, given the market economics, and actually might not be practical for some of the voltages that can appear. The following example, drawn from North American experience (hence the use in this example of terms typical of the telephone industry), illustrates the problem, which, depending on particular national practices, is likely to be encountered in other installations.

NOTE IEC 61663-2 deals with the protection of telecommunication and signal lines using metallic conductors against lightning, including system interactions. The lines considered are:

– telecommunication lines connecting a switch with a network termination;
– telecommunication or signal lines connecting equipment located in different buildings, for example, ISDN lines or signal lines between computers.

D.2 Example of PC/modem reference potential shift

In figure D.1, a PC equipped with a modem is powered from a branch circuit by a three-wire cord which includes an earthing conductor that establishes the potential of the chassis as that existing at the earth bus of the power panel. The modem is connected to a telephone outlet in the room, and the telephone service entrance is provided with an optional surge protection installed by the telephone company. For a worst-case scenario (often encountered) the power service and the telephone service enter the house at opposite ends of the house. In such a situation, the earthing wire of the entrance protection is connected to the nearest point of the earthing system, if one is available, as shown in the figure. Alternately, a dedicated earthing conductor could be run all the way to the power panel.

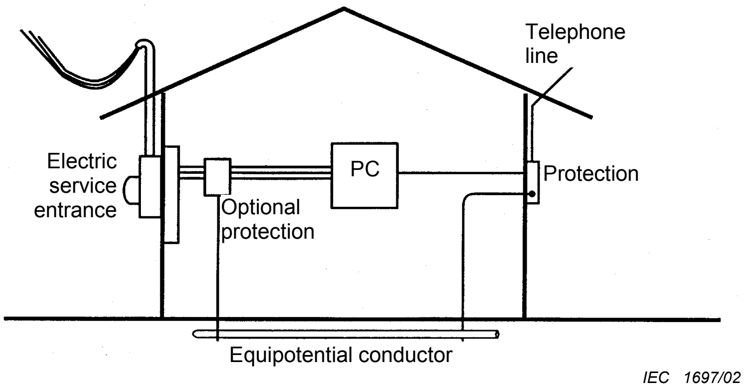


Figure D.1 – PC/modem connections to the power system and communications system

As will be shown below, this alternate routing would not make a difference in the outcome during a surge event affecting the telephone service. Note that in figure D.1, the surge-protective device on the power side of the PC – the side where the user is most likely to think about providing protection from surges expected to come from outside – is shown as optional. Whether or not there is an SPD on the power side would have no effect on the outcome of the present scenario.

Figure D.2 shows the scenario where a surge from the telephone service impinges on the service entrance where the telephone company has provided a dedicated SPD, as part of its installation. Such a device is referred to as a Network Interface Device (NID)[1]. The impinging surge is diverted by the NID through the equipotential conductor toward the earthing electrode. In this worst case of poor installation practice, the two services entrances are located at opposite ends of the house so that the equipotential connection can in fact have a significant length. For the sake of explaining the statement that the presence of an SPD on the power side makes no difference in this scenario, figure D.2 includes an SPD provided by the user and the possibility of an arrester upstream, for instance at the service panel or at the meter base.

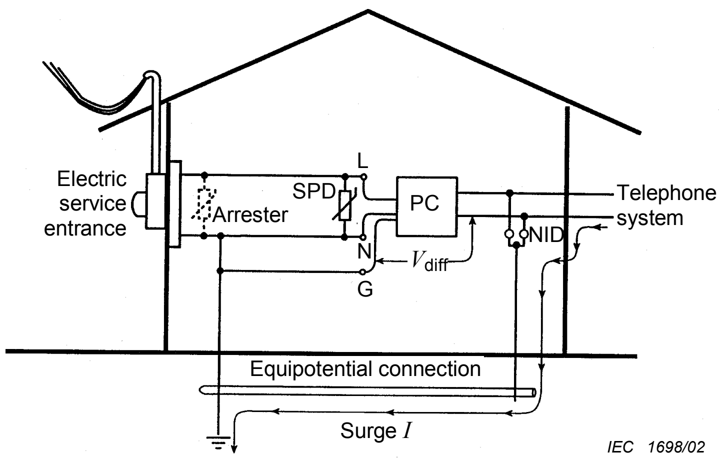


Figure D.2 – Voltage difference appearing across PC/modem during surge current flow

The surge current "Surge I" in figure D.2 flows in the pipe, creating a magnetic flux which is embraced by the loop formed by the pipe and the conductors on the upper part of the circuit – the telephone wire connecting the PC to the NID and the branch circuit connecting the PC to the power entrance. The rapidly changing surge current induces a voltage in the loop, which appears across the point where the loop is open – the insulation between the modem terminals and the power terminals of the PC.

1) The NID is provided by the telephone company to protect its outside equipment from overvoltages or surges arising in the subscriber's circuit. It is not provided to protect the subscriber from impinging surges, although the perception might exist that it is so. Nevertheless, the NID is involved in this scenario of an impinging surge.

Another way to explain the induced voltage difference, but based on the same electromagnetic laws, would be to consider that the long pipe has an inductance L which results in a voltage $L \times di/dt$ which appears along the length of pipe and hence across the PC ports. However, the explanation based on flux linkage is more useful because it points out the effect of the geometry of the loop, not just the length of the pipe. Theoretically, if the loop were extremely narrow by having the wires run close to the earthing conductor (as good EMC practice recommends – see annex F), its area would be small and the flux linkage considerably reduced. The reality, however, is that the loop area in an actual installation will always be substantial.

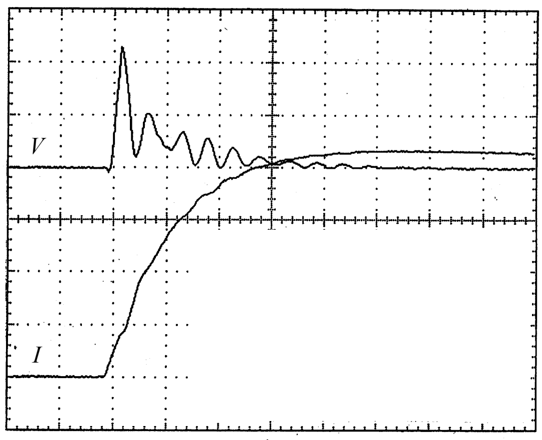
Note that in this circuit, the potential difference appears between any of the two telephone wires on one side of the PC and the neutral N or earthing conductor G on the other side of the PC, without involving the SPD or the arrester, justifying the statement that the presence of an SPD installed at the power port of the PC has no effect on the outcome on the scenario of a surge arriving from the telephone plant and – in a perverse way – being diverted by the normal operation of the NID.

In a similar manner, a surge impinging from the power system side and not diverted at the service entrance, may propagate all the way to the receptacle where the PC is plugged, and where the prudent homeowner has provided an SPD for protection against power line surges. There again, the perverse situation arises where the surge current, diverted through the SPD is returned to earth by the earthing conductor or/and the neutral conductor. This surge current will radiate magnetic flux into the same flux-collecting loop as that of the first scenario, with the same possible result of damage or upset.

D.3 Example of remedial action

To demonstrate the side-effect of uncoordinated surge protection and the benefit of a proposed solution, measurements were conducted in a full-scale replica of a house wiring system, including power, telephone, and the copper water pipe of figure D.2. The telephone wires were routed in a typical manner, at some distance from the pipe.

Figure D.3 shows the recording obtained when injecting upstream from the NID a surge such as specified by telephone industry standards. For a rate of change in the surge current of 75 A/µs, a peak of 4,3 kV was induced in the loop, as measured across the open-circuit loop. In an actual installation, this voltage would appear between the two ports of a PC connected there – but none was connected in the experiment, to avoid needless damage.



IEC 1699/02

Key

I Current impinging NID 50 A/div: di/dt = 75 A/µs

V Voltage between telephone port and protective conductor (PE) 2 kV/div: 4,3 kV max.

Horizontal sweep: 2 µs/div

Figure D.3 – Voltage recorded across reference points for the PC/modem during a surge

Inspection of figure D.3 reveals a significant fact: the peak voltage occurs during the very front of the surge current, not at the time of peak current. Thus, the peak amplitude is significant only by its influence on the initial rate of rise, not by the peak value in itself. This behaviour is indeed characteristic of an inductive effect and is another example of the remark made on several occasions in this technical report that considering the average rate of current rise computed from the 10 % and 90 % points can be quite misleading. This effect is likely to occur even for a slow-rising surge because the gas tube(s) in the NID will not spark over before the surge has developed a high voltage, meaning that by that time the capability of a fast current rise will have increased over what it would be if the current had begun flowing at the beginning of the surge voltage. This example also shows how a scheme using a gas tube can act as a generator of steeper fronts than the original impinging surge. In this case, this effect will be mitigated by the equalization of the reference voltages, as described in the following.

If now the loop were closed by a path other than the insulation between the two ports of the PC, no voltage would appear across the ports and the PC would not be in jeopardy. Closing the loop is what can be accomplished by a hybrid multi-port SPD package, called surge reference equalizer, installed between the power receptacle and the telephone receptacle, inserted in the power cord and the telephone cord upstream from the PC input connections. Figure D.4 shows such an arrangement.

To illustrate the effectiveness of the solution, figure D.5 shows the reduction of the voltage obtained in the same circuit as that used for recording figure D.4, but with insertion of a typical surge reference equalizer (available in many electronic stores, but not necessarily under this name, see 3.17) in the power and telephone lines at the point of connection of the PC.

The generic design of such a device includes insertion, in the two telephone wires, of two matched gas tubes, two series resistors, and two silicon avalanche diodes, with a direct bond or an appropriate SPD to effect a common or nearly common earthing reference.

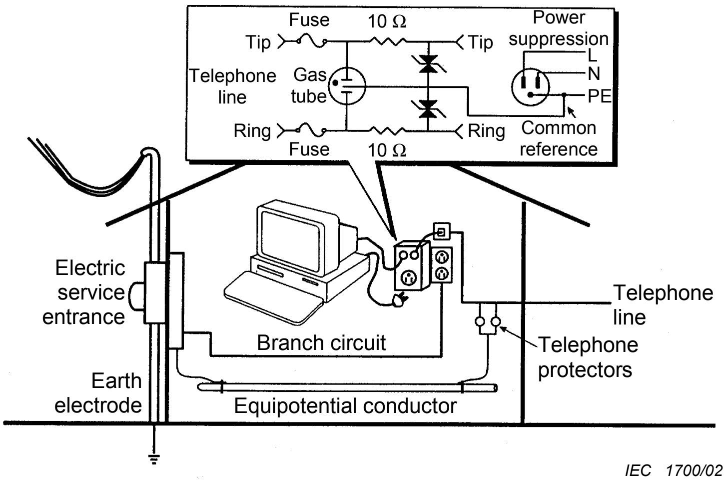
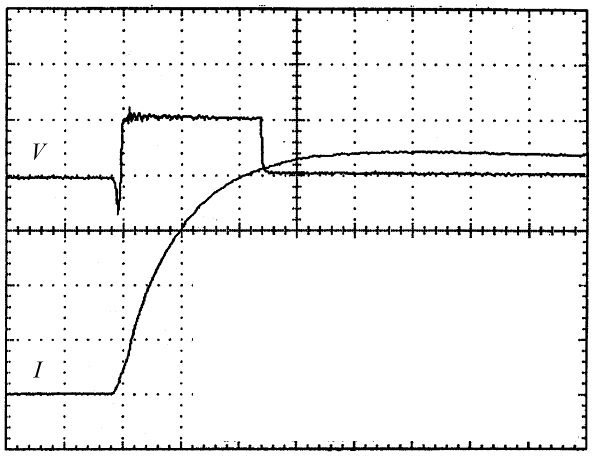


Figure D.4 – Insertion of a surge reference equalizer at the PC/modem ports



Key

I Current impinging NID 50 A/div: di/dt = 75 A/µs

V Voltage between telephone port and protective conductor (PE) 200 V/div: 200 V max

Horizontal sweep: 2 µs/div

Figure D.5 – Reduction of voltage difference between ports by a surge reference equalizer

In figure D.5, one can see the immediate clamping effect of the diodes down to 200 V from the unmitigated 4,3 kV shown in figure D.3, followed by a further reduction of voltage as the gas tube sparks over 5 µs later.

The surge reference equalizer will have similar benefits for the scenario of the surge arriving from the power system. A subtle difference may be that in the first scenario, the two wires of the balanced telephone circuit are effectively connected to the earthing system by the action of the NID, making the problem immediate. In the second scenario, the two telephone wires remain galvanically isolated from the earthing system until the NID gas tubes spark over, which they might not do. Even if the NID does not spark over, there might be sufficient capacitance between each of the telephone wires and earth to hold these two wires at the earth potential during the initial part of the surge and thus develop a reference potential difference with respect to the power port. As a result, the hazard might be less severe, but still present when large potential differences cause sparkover of the NID, justifying the investment of a surge reference equalizer against both scenarios.

A smaller loop would exist if the telephone and power service entered at the same end of the house, the recommended practice. With such a configuration, a reduction in the voltage difference to about 75 % of the large loop value was found in the test series, still a potential risk for the hardware, so that the surge reference equalizer would help there as well.

Annex E
(informative)

Complementary information on SPD application

E.1 Implementation of coordination principles

Two schemes are possible for implementing coordination with presently available SPDs:

a) Coordination without any additional specific decoupling element

   This scheme makes use of the wiring of the installation as a decoupling element

   – voltage-limiting type: based on the current/voltage characteristic of SPDs and the voltage drop of the wiring;

   – voltage-switching type: based on the dynamic voltage drop of the wiring and the sparkover voltage of the SPDs.

b) Coordination by use of decoupling elements

   For coordination purposes it is possible to use inductances or resistances as decoupling elements which should have a sufficient surge withstand capability:

   – inductances are primarily used for power system applications;

   – resistances are primarily used in telecommunication system applications.

E.2 Coordination between voltage-limiting SPDs

E.2.1 Principle

The energy coordination of two SPDs without decoupling elements can be obtained by means of their current/voltage characteristic for the relevant range of currents. For waveshapes with a long time at half value (for example, 10/350 μs), inductances are not very effective. If possible, it is useful to obtain the coordination by application of resistive decoupling elements (or the inherent resistance of cables). In power circuits, however, the deliberate insertion of a power-dissipating resistance would be limited to low-power applications, such as feeding an electronic control power supply.

If inductances are used as decoupling elements, as in the example of figure E.1, it is necessary to take into consideration the waveshape of the surge current (for example, 10/350 μs, 8/20 μs). An example of this consideration is given later in this annex.

In the coordination of two voltage-limiting SPDs, for instance metal oxide varistors (MOVs), both SPDs should be selected for the respective surge current wave, according to their I/V characteristic (see figure E.2). The current wave duration will not be significantly shortened, compared to the impinging current, as shown in figure E.3, which presents a case of MOV application. For increasing impinging currents, the energy dissipated in the MOVs increases as shown in figure E.4. As can be seen in this example, the knowledge of only the reference voltage U_{ref} of the MOV is not sufficient to establish coordination. Further computations might be necessary, as detailed in clause E.6.

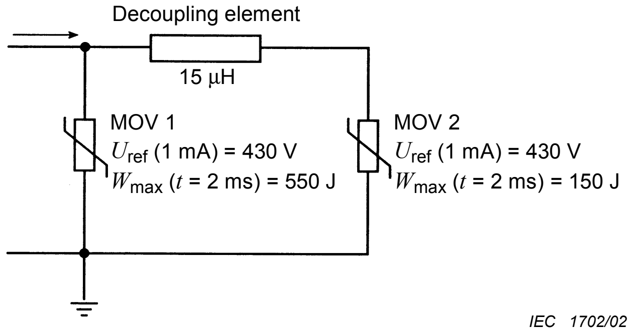


Figure E.1 – Example of coordination for two voltage-limiting SPDs (MOV1 and MOV2)

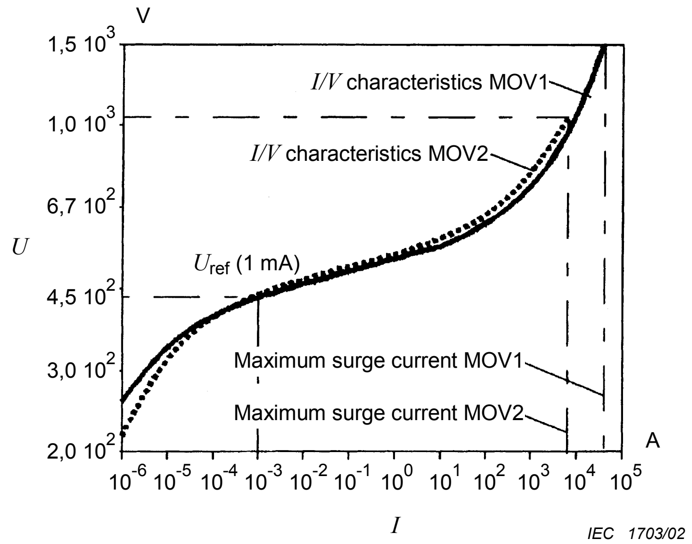


Figure E.2 – Comparison of the *I/V* characteristics of the two MOVs

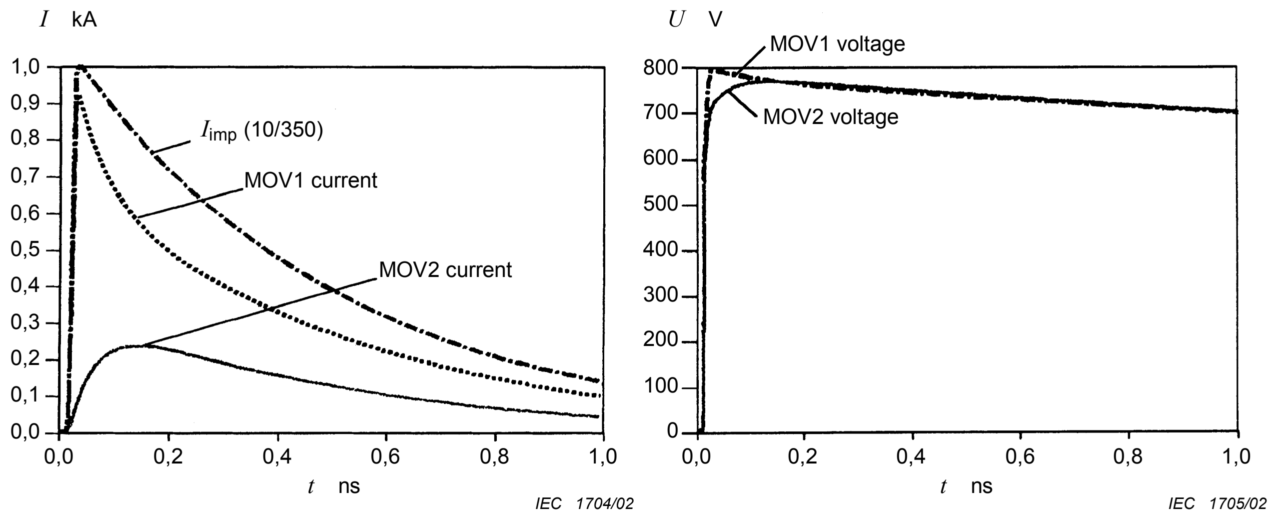


Figure E.3 – Current and voltage versus time characteristics for the two voltage-limiting SPDs

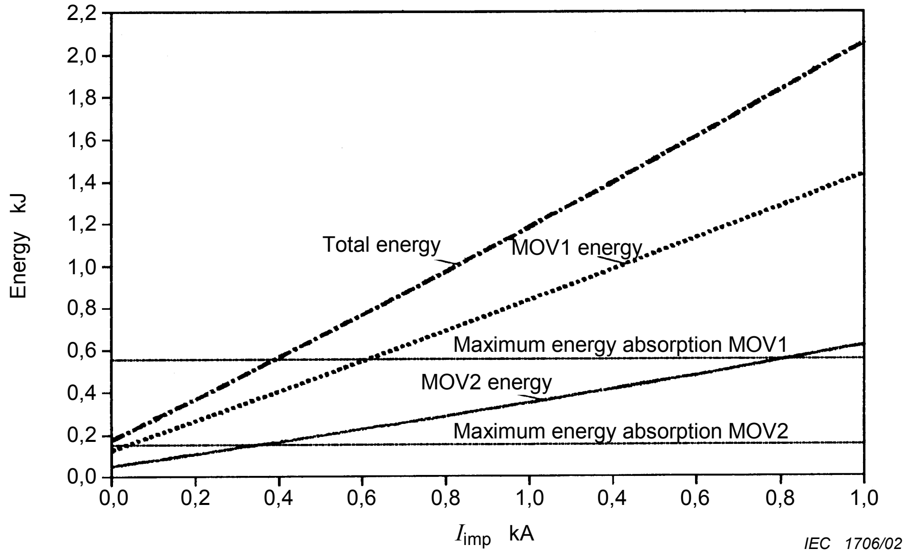


Figure E.4 – Energy distribution among two voltage-limiting SPDs versus impinging current

To illustrate these interactions, computations were performed for the simple circuit shown in figure E.5. In this circuit, two voltage-limiting SPDs (varistors) with ideal current-voltage characteristics are connected, respectively at node 1 and node 2. The protection level is postulated to be 2,5 kV (U_{p1}) at node 1 and 1,5 kV (U_{p2}) at node 2. The length of the wiring between the SPDs was assumed about 10 m, with a total inductance of 10 µH. To have a complete model, the characteristic impedance (300 Ω) and a length of 10 m of the wiring were used in the calculations. This implies a total wiring capacitance of about 100 pF.

In reality, impulses with various waveshapes will occur. Two representative lightning current pulses were selected: a short 2/20 µs impulse and the standardized 10/350 µs from IEC 61312. For simplicity, triangular waveforms were postulated. Each in turn was injected first at node 1 and, in a second set of simulations, at node 2.

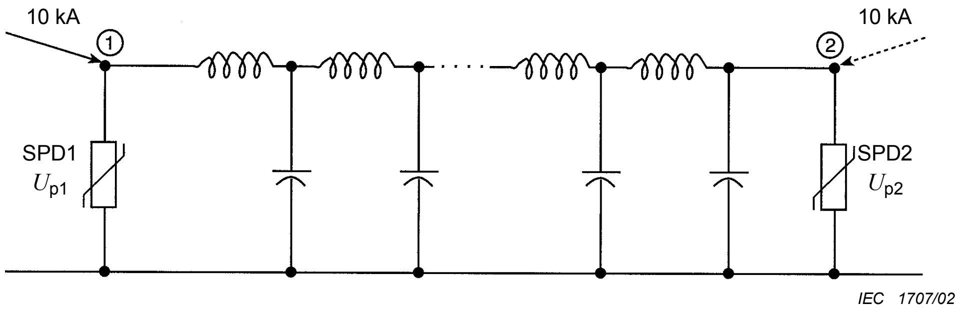


Figure E.5 – Idealized example for illustrating SPD coordination aspects

Figure E.6 shows the calculated voltages and currents for a 2/20 µs current impulse injected at node 1. For this relatively short impulse, the major current stress is applied to SPD1. The voltage U_{p1} is:

$$U_{p1} = U_{p2} + L\,(dI_{p2}/dt) \qquad \text{(E.1)}$$

where

I_{p2} is the current in SPD2;

U_{p2} is the voltage across SPD2 when conducting I_{p2}.

Accordingly, this U_{p1} voltage is negative on the tail of the current I_{p2}, where the current derivative is negative (see figure E.6).

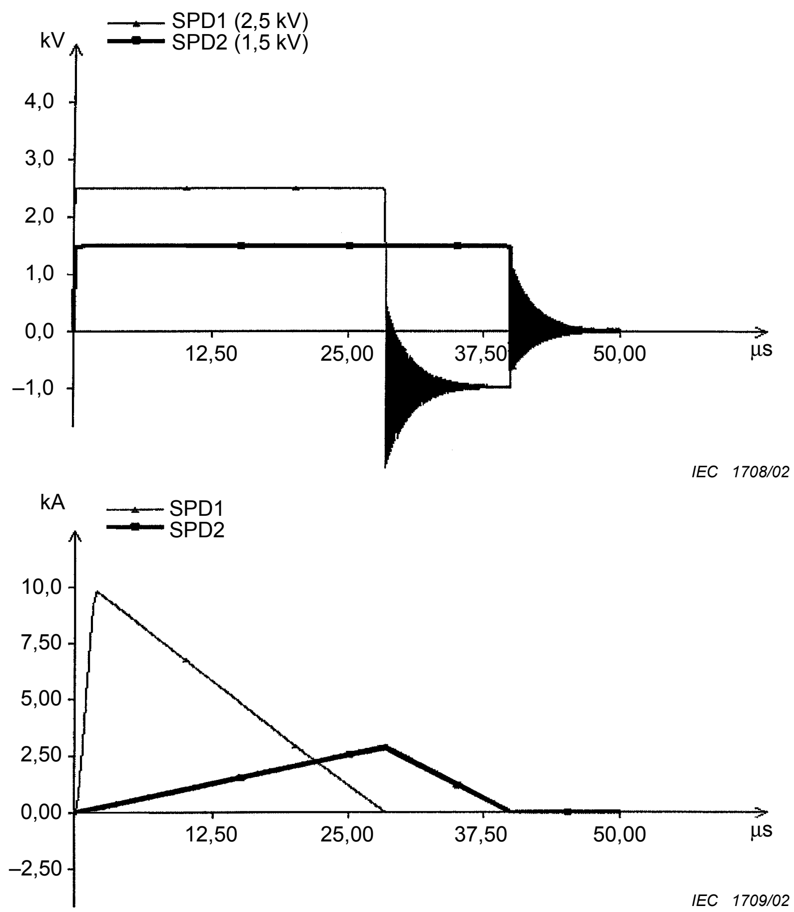


Figure E.6 – Calculated SPD voltages and current for a 2/20 µs impulse injected in node 1

Following the abrupt change of di/dt for this idealized example, high-frequency oscillations (ringing) occur for the voltage, especially at node 1, due to the inherent capacitance of the wiring (figure E.5). On the tail of the current through SPD2, di/dt is about 0,25 kA/µs. Accordingly, the voltage at node 1 suddenly changes from its value of 2,5 kV (U_{p1}) prior to the current peak to a new value, as defined by (E.1):

$$\begin{aligned} U_{p1} &= U_{p2} + L\,(dI_{p2}/dt) \\ &= 1{,}5\text{ kV} + 10\ \mu\text{H} \times (-0{,}25\text{ kA}/\mu\text{s}) \\ &= 1{,}0\text{ kV} \end{aligned}$$

excluding the initial oscillations that are superimposed on this value.

Figure E.7 shows the corresponding voltages and currents for the case of a 10/350 µs impulse, also injected in node 1. For this impulse of long duration, most of the current and energy stresses are applied to SPD2, due to its lower protection level. For comparison, the calculations were repeated for the case where the current is injected at node 2. It was then found that practically all the current was drawn through SPD2.

This example shows that especially the duration of the current impulse is of major importance for the sharing of current and energy between SPDs with different protective levels. If more than one set of SPDs are present in an installation, the SPDs with the lower protective level (for instance inside equipment) can be exposed to high stresses unless sufficient precautions are taken.

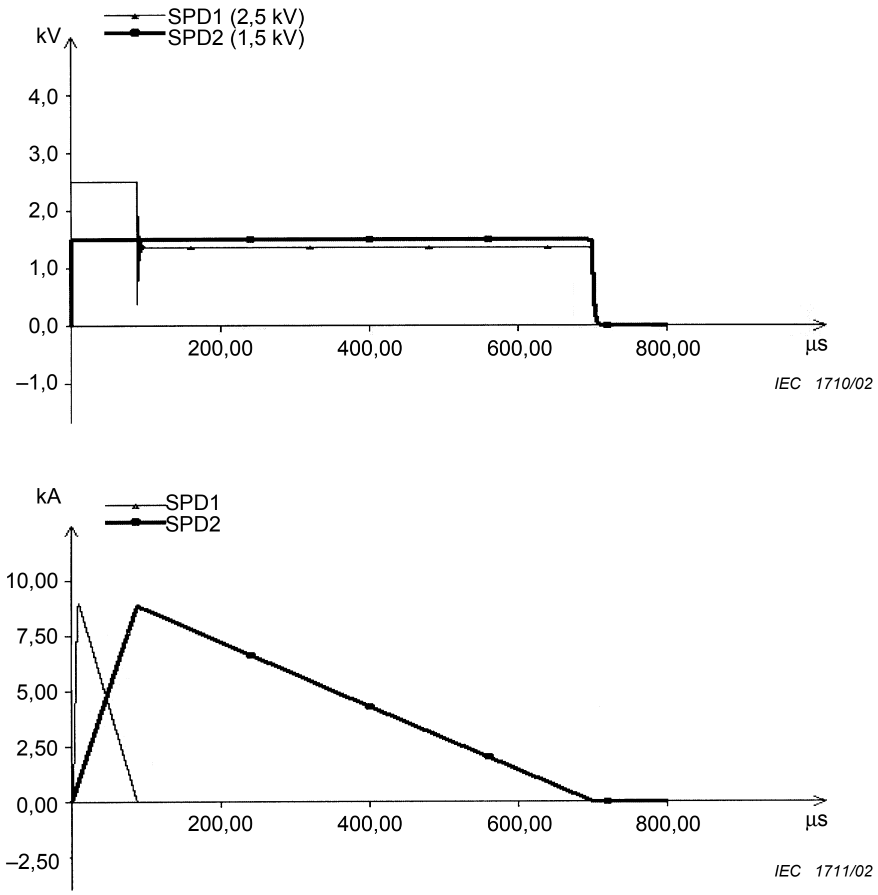


Figure E.7 – Calculated SPD voltages and current for a 10/350 µs impulse injected in node 2

As discussed later in this clause, one possibility is to add a decoupling element between the SPDs. To illustrate this possibility, the example with 10/350 µs impulse current was repeated with an inductance of 100 µH as the decoupling element. Figure E.8 shows the result of this simulation. In this case the higher current is flowing in SPD1, but still there is a rather severe stress also imposed on SPD2.

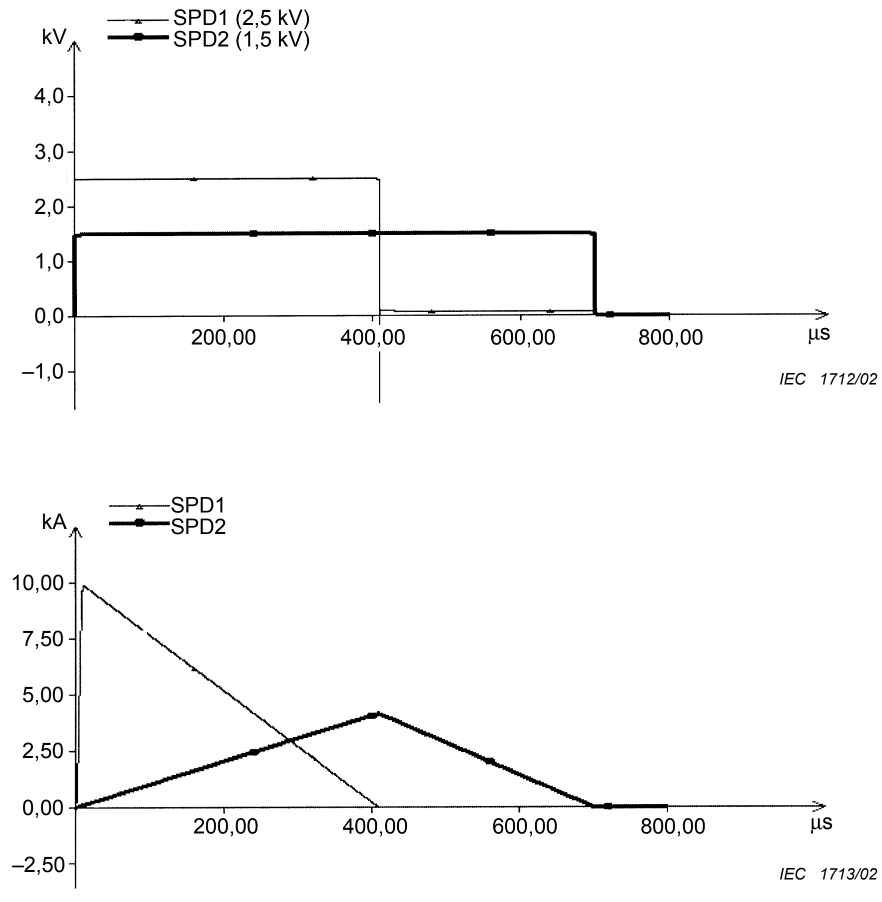


Figure E.8 – Calculated SPD voltages and current for a 10/350 µs impulse injected in node 1

E.3 Coordination between voltage-switching and voltage-limiting SPDs

E.3.1 Principle

Figure E.9 shows the basic circuit diagram of this coordination variant. The sparkover of the spark gap (SPD 1) depends on the sum of the residual voltage U_{ref} across the MOV (SPD 2) and the dynamic voltage drop across the decoupling element U_{DE}.

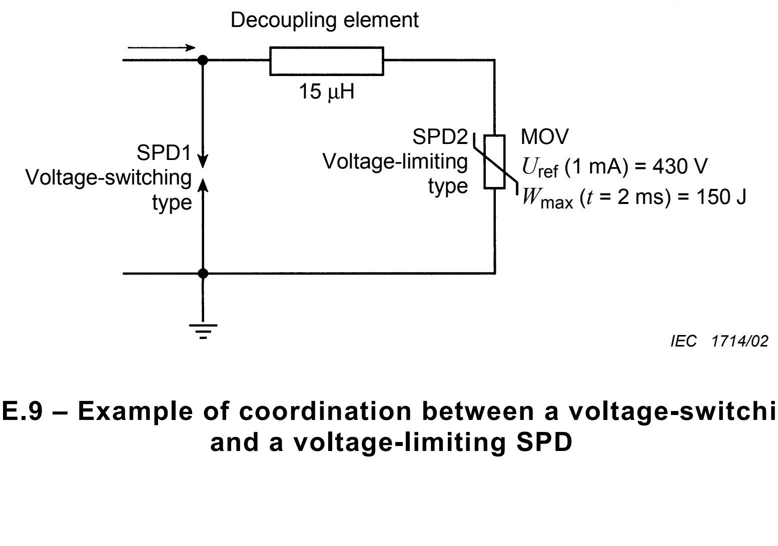


Figure E.9 – Example of coordination between a voltage-switching SPD and a voltage-limiting SPD

Before sparkover, the voltage distribution between the SPDs follows the relation (E.2):

$$U_{SG} = U_{res} + U_{DE} \tag{E.2}$$

where

U_{SG} is the voltage at the terminal of the spark gap;

U_{res} is the voltage across SPD 2 for the surge current i;

U_{DE} is the voltage drop across the decoupling element for di/dt.

When U_{SG} exceeds the dynamic sparkover voltage of the spark gap, the coordination is achieved.

This condition depends only upon

– the characteristics of the MOV (for example, U_{ref} (1 mA); W_{max} (t = 2 ms);
– the rate of current change of the incoming surge;
– the behaviour of the decoupling element (inductance in this example);
– the dynamic sparkover voltage of the spark gap.

NOTE In such an arrangement, the intention is to obtain gap sparkover early during the rise of the surge current. Therefore, it is the actual rate of current rise di/dt that determines the behaviour of the circuit, not an average rate of current rise computed as $\Delta I/\Delta T$. In actual circuits, the maximum rate of current change occurs during the rise, somewhere between the 10 % and 90 % points generally used to define the rise time. Using $\Delta I/\Delta T$ instead of the actual di/dt in the assessment might be overly pessimistic. See table E.1 for a comparison between precise computations and rough estimates based on the use of $\Delta I/\Delta T$, and further discussion of this issue in E.7.4.

Two outcomes are possible, depending on the respective parameters of the SPDs, current surge, and decoupling impedance:

a) No sparkover of the spark gap, a "blind spot"

   All the surge current is flowing through the MOV. Therefore, the MOV has to be dimensioned for the energy deposited by this surge current (see figure E.10).

b) Sparkover of the spark gap

   Sparkover of the spark gap modifies the surge waveform that stresses the downstream MOV.

As can be seen in figure E.11, the duration of the current in the MOV is greatly reduced. When a gap with a low arc voltage is used, the choice of the U_c of the following (downstream) MOV will not be important for the coordination with the spark gap.

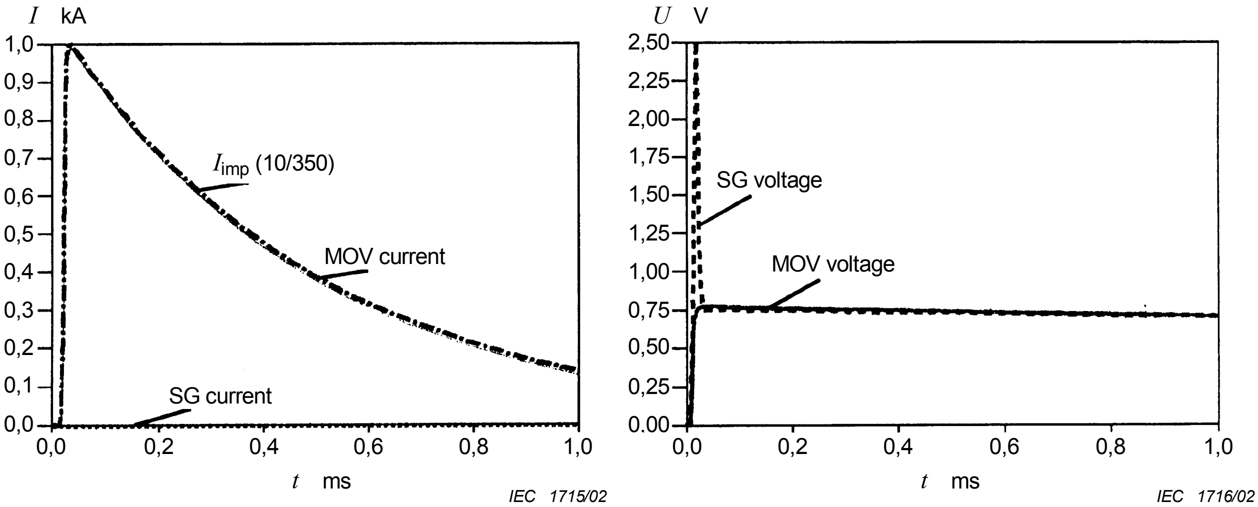


Figure E.10 – Current and voltage characteristics in the scheme of figure E.9 for no sparkover

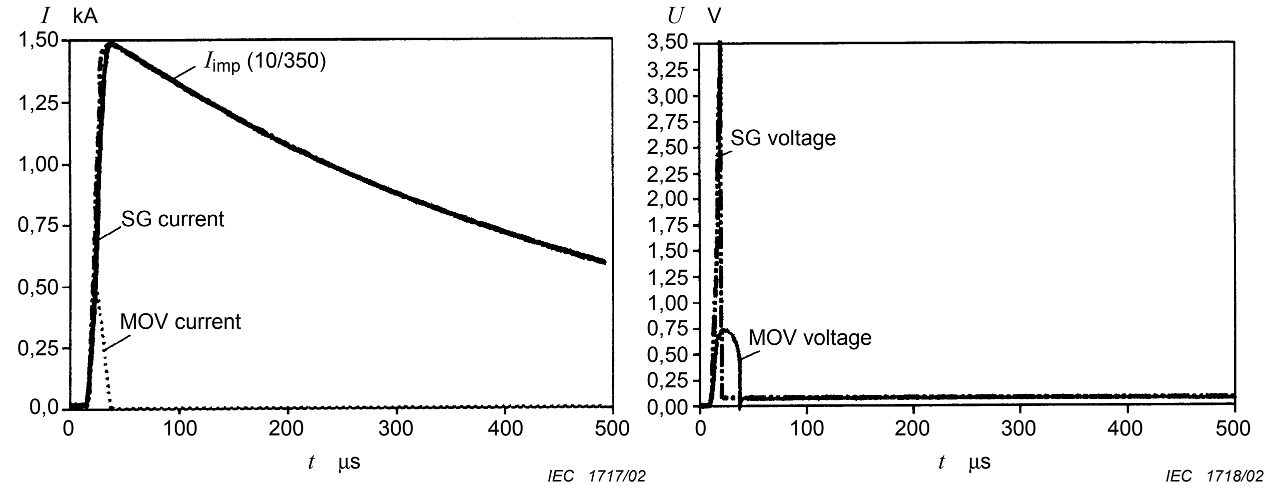


Figure E.11 – Current and voltage characteristics in the scheme of figure E.9 with sparkover

E.3.2 Determination of the necessary value of the decoupling element

As an example, figure E.12 shows a spark gap (SG) upon which a 1 kA, 10/350 µs surge is impinging, and five possibilities of downstream SPDs, cases a) through e). The most demanding case for the design of the decoupling element is given by the short-circuit case a). However, for coordination purposes, this case is not relevant. It is more realistic that the most demanding case be given by a load-side voltage or counter-voltage, case c) in the figure.

The SPDs downstream from a spark gap usually consist of single MOVs, or MOVs with series gaps. The residual voltage of such SPDs is always higher than the peak value of the nominal power supply voltage (for instance, in an a.c. system with a nominal voltage of 240 V, the peak power-frequency voltage is $\sqrt{2} \times 240$ V = 340 V, which is below the reference voltage of the installed SPD). This peak nominal power supply voltage corresponds to the lowest possible residual voltage of SPDs. Therefore, this peak voltage is to be taken as the minimum possible counter-voltage. Using the current into a short circuit, case c), instead of assuming a counter-voltage, would result in an over-dimensioning of the decoupling element. Table E.1 shows the values of inductance needed to ensure sparkover of the spark gap SG for the different downstream loads, cases a) through e) in the figure.

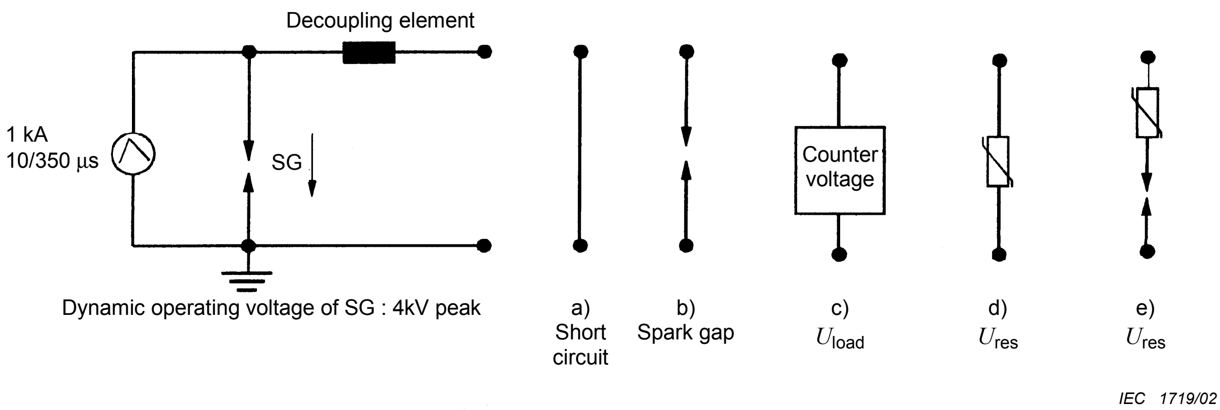


Figure E.12 – Voltage U_{SG} at spark gap depending on different loads

Table E.1 – Inductance necessary to ensure gap sparkover

Case	Decoupling inductance µH[a]	
	By computer simulation	By rough estimation[b]
a) Short circuit	30	40
b) Spark gap Arc voltage = 30 V	30	40
c) Counter-voltage $\sqrt{2} \times U_n$	24	37
d) MOV U_{res} (1 mA) = 430 V	19	32
e) MOV U_{res} (1 mA) = 180 V	22	36

[a] For a postulated surge of 1 kA, 10/350

[b] This rough estimation by using $\Delta I/\Delta T$ (10 % to 90 %) instead of maximum di/dt. See discussion in E.2.1 of the conservative results resulting from using $\Delta I/\Delta T$.

E.4 Coordination between voltage-switching type SPDs

Figure E.13 illustrates this basic coordination variant typically used in telecommunications. For the coordination of spark gaps, it is necessary to use their dynamic operating characteristics.

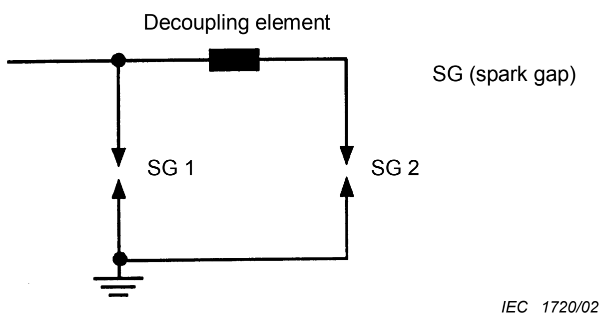


Figure E.13 – Coordination of two SPDs (voltage-switching type)

First, SG 2 will sparkover and then SG 1 will also sparkover if the coordination rules have been implemented. After sparkover of SG 2, the coordination will be realized by means of a decoupling element. To determine the necessary size of the decoupling element, SG 2 may be replaced by a short circuit. For SG 1 to spark over, the dynamic voltage drop across the decoupling element must be higher than the sparkover voltage of SG1. If inductances are used as decoupling elements, it is necessary to consider the waveshape (especially the di/dt value).

When using resistances, the surge current peak value is decisive for the necessary resistive value of the decoupling element. The voltage drops in the resistors caused by the surge current should be considered when selecting the pulse rating parameters of the device.

After sparkover of SG 1, the total energy will be subdivided according to the stationary current/voltage characteristic of the individual elements.

NOTE The case of the disturbance source being located on the load side has also to be considered.

E.5 Analytical studies, practical cases

E.5.1 Simple case of the coordination of two ZnO varistors

The following considerations apply only to one-port limiting type SPD tested to Class I and II where the curves U_{res} (I) are known for each device. These curves are measured using 8/20 µs waveshape and are given by the manufacturer in the SPD technical documentation. Class III and two-port SPDs need special attention.

This example will also enable a better understanding of the coordination issue. We will first deal with the case of the two SPDs being ZnO varistors where an analytical study is possible. Note that such an analytical study is based only on current sharing. Ensuring that the energy criterion is satisfied might require additional computations, which are generally rather complex.

If the two varistors have the same diameter (hence the same nominal discharge current I_n and the same energy withstand: same I_{max} and same I_{imp}), but have different protective levels U_{p1} and U_{p2} (defined at the same nominal discharge current), the following equations apply:

$$\begin{aligned} I_{n1} &= I_{n2} \\ I_{max1} &= I_{max2} \\ I_{imp1} &= I_{imp2} \end{aligned} \qquad \text{(E.3)}$$

Then the possible curves U_{res} (I) are illustrated in figure E.14.

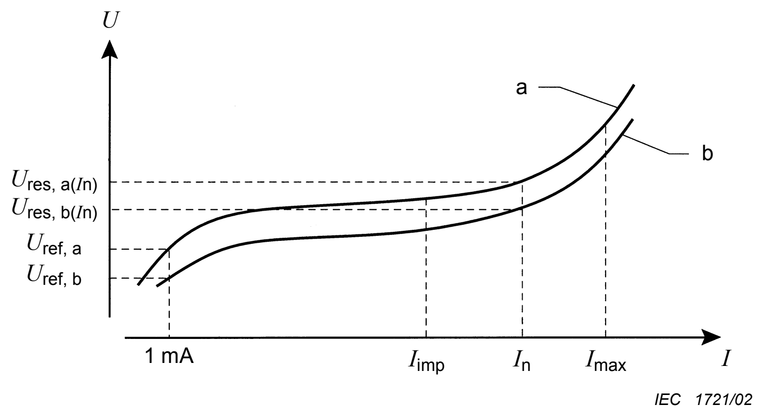


Figure E.14 – Two ZnO varistors with the same nominal discharge current

Two cases should then be considered, concerning the relative values of the protection levels of the two SPDs.

If $U_{p1} > U_{p2}$

In this case, curve a) corresponds to SPD 1 and curve b) to SPD 2. This coordination will be in general acceptable with short waveshapes if the length of cable exceeds a few metres (typically 5 m or 10 m). With long waveshapes the decoupling effect is reduced; therefore SPD 2 might have to withstand the total incoming surge, which it can, according to the postulates of this scenario where SPD 2 is capable of withstanding the total stress.

If $U_{p1} < U_{p2}$

In this case, curve a) corresponds to SPD 2 and curve b) to SPD 1. In most cases the current flowing through the second SPD is less than the impinging current.

The energy criterion is satisfied in both cases as both SPDs have the same current-carrying capability. Note that this first case was discussed just to understand the mechanism as there is no incentive in having two SPDs with the same energy withstand capability.

If the two varistors have different nominal discharge current:

For this application, a practical case is $I_{n1} > I_{n2}$ and $E_{max1} > E_{max2}$.

In addition, SPD 1 and SPD 2 can have characteristics such as U_{res1} (I_{n1}) < U_{res2} (I_{n1}).

Then the U_{res} (I) curves are illustrated in figure E.15. No impedance is involved in the characteristics shown in this figure as it is not easy to take it into account in a simplified analytical study, unless a sophisticated numerical model can be applied with reliable data on all the circuit parameters.

In this case, it can be seen from figure E.15 that with a short waveshape the coordination will be achieved as most of the current will flow through the first (upstream) SPD. But with long waveshapes the coordination could be difficult to determine. The coordination might not be achieved with a long waveshape and a magnitude of the incoming current lower than the current at the crossing point (see figure E.15) of the two curves. A greater part of the incoming current flows through SPD 2 as the U_{res2} curve becomes lower than U_{res1} at this level of current. An inductance becomes necessary between the two SPDs.

Consequently, it is necessary to compare the curves U_{res} (i) for the current I ranging from 0,1 I_{n2} up to I_{max1} to check if they cross each other, then to compare U_{res1} (I_{n1}) and U_{res2} (I_{n2}), which are given in the manufacturer technical documentation. The current value at this crossing point I_{cr} (if any) should be as low as possible.

In this case, the energy criterion has a high probability of being satisfied. The lower I_{cr}, the higher the probability of success. If there is any doubt, a computation of the energy through the second SPD is necessary taking into consideration the impedance between the SPDs and the long waveshapes. Such a computation requires a computer programme capable of simulating the non-linear behaviour of the SPDs.

If it is not possible to obtain these curves because of a lack of information or because a simple and quick result is needed, then it is necessary to compare the curves U_{res1} and U_{res2} at the same level I_{n2} (this information is given in the manufacturer specifications). In such a case, the condition for an easy and effective coordination is U_{res1} (I_{n2}) < U_{res2} (I_{n2}) as shown in figure E.15 where the lower line represents the conservative curve 1.

In this case, even if the current in the second SPD is low, the energy criterion might not be satisfied for long-duration surges. Additional computation of the energy through the second SPD might be necessary.

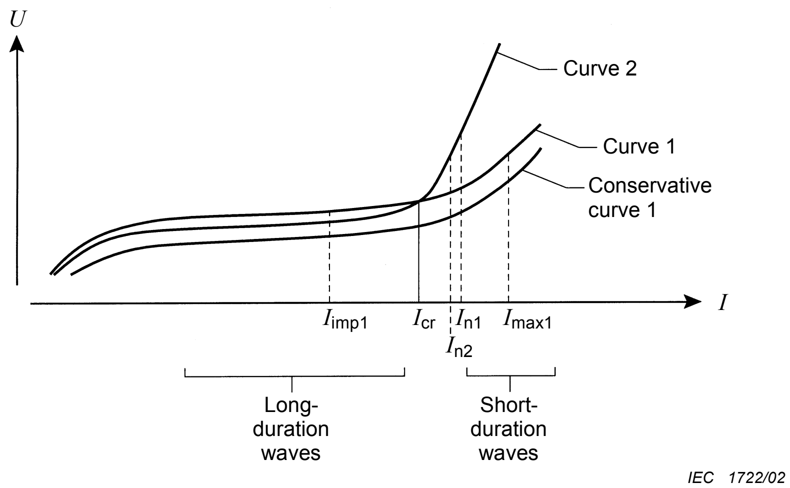


Figure E.15 – Two ZnO varistors with different nominal discharge currents

E.5.2 General conclusion concerning the ZnO varistors

In every case where two ZnO varistors need to be coordinated, the following five-step procedure should be used.

a) Identify the overvoltages expected to occur in absence of any SPD and make a distinction between long waveshapes and short waveshapes.

b) Select SPD 1 able to withstand this stress. If it is not possible to obtain information at step 1, use a sufficiently dimensioned SPD and obtain from the manufacturers the values of I_{max} and I_{imp}, and then consider these values as the given data defined in step 1.

c) SPD 2 should then be selected according to its desired protective characteristics.

d) Compare the curves U_{res} (I) with I ranging from 0,1 × I_{n2} up to I_{max1}. Then determine the crossing point I_{cr}. If this current I_{cr} is low enough (typically 0,1 × I_{n2}), then it is not necessary to calculate the energy in the second SPD. The energy criterion will be satisfied, regardless of the distance between the SPDs.

   If there is any doubt, calculate the energy through the second SPD taking into consideration the impedance between the SPDs and check the energy criterion.

   If such curves are not available, then choose SPD 2 with the following requirements

   – if SPD 2 has the same nominal discharge current: U_{res1} (I_n) < U_{res2} (I_n);

   – if SPD 2 has a smaller nominal discharge current: U_{res1} (I_{n2}) < U_{res2} (I_{n2}).

   It would then be wise to calculate the energy in SPD 2 to check the energy criterion.

e) Repeat until step c) gives a satisfactory result.

NOTE 1 The values of voltage at very low current (generally called reference voltage) are not applicable for coordination.

NOTE 2 In any case (with or without ZnO varistors), EMC considerations require that the current flowing through SPD 2 be as small as possible.

NOTE 3 The curves U_{res} (I) are maximum values. It is necessary to take into consideration the variation in characteristics due to manufacturing tolerances. The manufacturer can provide these data.

NOTE 4 The preceding studies can be generalized to more than two SPDs.

E.5.3 Analytical study: case of the gap – ZnO coordination

Another common case is the use of a gap as SPD 1 and of a ZnO varistor as SPD 2 (see figure E.9).

In this case the coordination is achieved when a sparkover occurs before SPD 2 is overstressed. Before this sparkover, we have

$$U_1 = U_{res2}\,(i) + L\ \mathrm{d}i/\mathrm{d}t \tag{E.4}$$

As soon as U_1 exceeds the dynamic sparkover voltage of the gap (U_{dyn}) the coordination is achieved as the second SPD is relieved. It depends only on the characteristics of the ZnO varistor (SPD 2), the dynamic sparkover voltage of the gap (SPD 1), the rate-of-rise and magnitude of the incoming surge i and the separation distance between the SPDs (and therefore the inductance L).

Example of calculation of the required values for a decoupling inductance between a gap and a varistor (see figure E.9).

The assumptions are:

– surge current with a 100 A/µs front (from IEC 61312-1);
– gap sparkover voltage between 3 kV and 3,5 kV. Computations made with a conservative 4 kV;
– varistor selected for limiting any overvoltage below 4 kV.

These conditions will ensure that there will not be a blind spot caused by an insufficient voltage at the gap, as this voltage is required to exceed 4 kV during the rise of the impulse. At the 4 kV level, the varistor is assumed to conduct 5 kA, with a corresponding residual voltage of 2 kV. Therefore, the inductor has to contribute an additional 2 kV, added to the residual voltage of the varistor, to obtain the required 4 kV at the gap terminals. The value of the inductance can then be computed as:

$$\begin{aligned} L &= U/(\mathrm{d}i/\mathrm{d}t) \\ &= 2\ \text{kV}/(100\ \text{A}/\mu\text{s}) \\ &= 20\ \mu\text{H} \end{aligned}$$

By applying this example, decoupling can be assured and the necessary energy rating of the varistor can be determined. The di/dt value has been selected to be the lowest rate of rise to be expected. Some 99 % of lightning events will exceed this value, and will develop higher voltages across both inductor and gap. The desired value of the inductance can also be obtained by adequate separation of the components, assuming a cable inductance of 1 µH/m.

E.5.4 General conclusion concerning the gap-MOV coordination

When the gapped SPD 1 has been selected, it is necessary to select the SPD 2 according to the following requirement, for a given incoming surge:

$$U_{dyn} < U_{res}\,(I_{peak2}) + L \times 0{,}1$$

(The term 0,1 above comes from the postulated 100 A/µs rate of rise.)

E.6 Coordination variants for protection systems

E.6.1 Basic coordination variants for protection systems

Four coordination variants may be considered for protection systems. The first three are based on current technologies for one-port SPDs. Variant IV is for two-port SPDs with integrated decoupling elements. For application of these coordination variants, it is necessary also to take into account those SPDs which may be integrated in the equipment to be protected.

Variant I (all voltage-limiting types, same residual voltage)

In this variant, all SPDs have a continuous monotonic current/voltage characteristic, such as varistors or diodes, and are selected to have the same residual voltage U_{res}.

The coordination among the SPDs and the equipment to be protected is normally achieved by making use of the inherent impedances of the connecting lines (see figure E.16).

NOTE The tolerances on SPD components can have a large influence on the result.

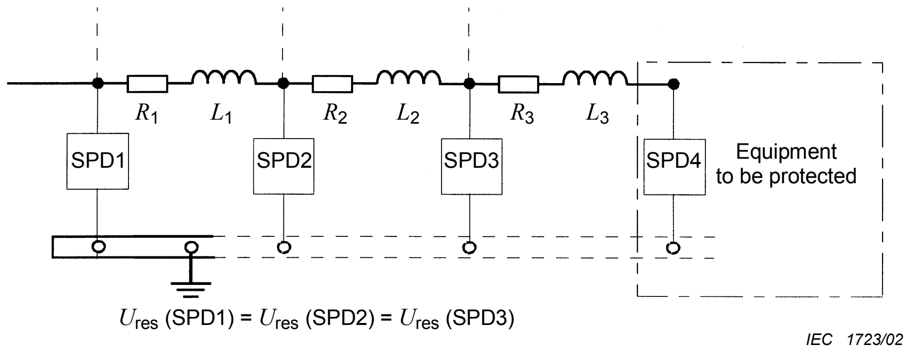


Figure E.16 – Coordination principle for variant I

Variant II (all voltage-limiting types, increasing residual voltages)

In this variant, all SPDs have a continuous monotonic current/voltage characteristic, such as varistors or diodes, and are selected to have their residual voltage U_{res} increasing by steps from the first SPD to each subsequent SPD.

This is the coordination variant for energy supply systems. The problem of this variant is that filters and SPDs that might be provided inside the equipment by the equipment manufacturer have to be included in this coordination concept (see figure E.17). This situation is very difficult because the data for these internal SPDs are usually unknown, and often these built-in SPDs have a residual voltage U_{res} selected deliberately low by the equipment manufacturer.

NOTE It is necessary that the voltage protection level of the last SPD (SPD 3 in figure E.17) be lower than the immunity level of the equipment to be protected. In other words, this variant requires that the residual voltage of the protective component which is installed in the equipment to be protected be higher than the residual voltage of that SPD which is installed directly before.

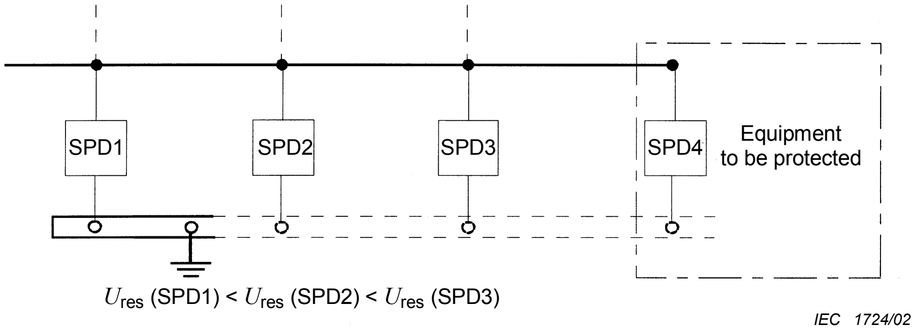


Figure E.17 – Coordination principle for variant II

Variant III (hybrid combination)

In this variant, the first (upstream) SPD (SPD 1, figure E.18) includes a component having a discontinuous current/voltage characteristic (switching type SPD, spark gap for instance). Downstream SPDs have components with continuous current/voltage characteristics (limiting type SPDs).

The characteristic of this variant is that, owing to the switching behaviour of the first SPD, a reduction of the time at half-value of the original impinging current impulse such as 10/350 µs will be achieved, which gives considerable relief to the downstream SPDs.

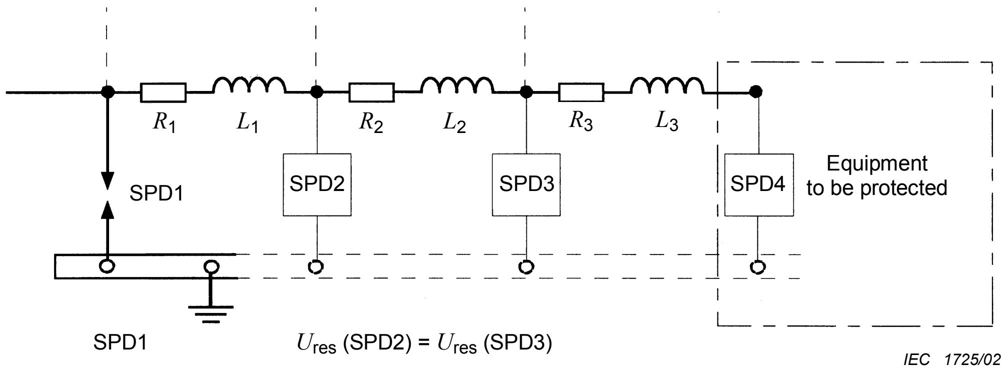


Figure E.18 – Coordination principale for variant III

Variant IV (integral decoupling element)

It is possible to construct two-port SPDs that incorporate cascaded stages of SPDs internally coordinated with series impedances or filters. The successful internal coordination means minimal energy transfer to downstream SPDs or equipment. These SPDs must be fully coordinated with other SPDs in the system in accordance to Variant I, II or III as appropriate (see figure E.19).

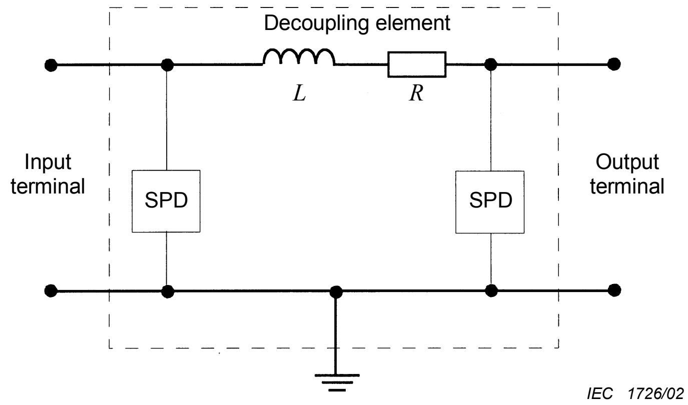


Figure E.19 – Coordination principle for variant IV

E.6.2 Let-through energy coordination method

This coordination method, with standard impulse parameters, is a procedure to select and coordinate SPDs. The main advantage of this method is the possibility to consider an SPD as a black box (see figure E.20). In this approach, for a given surge at the input port, not only is the open-circuit voltage determined, but also an output current is determined, for instance into a short circuit at the output terminals. This is the principle of let-through energy. These output characteristics are converted into an equivalent 2 Ω-combination wave-stress (open-circuit voltage of 1,2/50 μs, short-circuit current of 8/20 μs). The advantage of this method is that there is no need for special knowledge of the internal design of the SPDs [27].

NOTE This method provides satisfactory results when the characteristics of SPD 1 are so different from those of SPD 2 that the surge conditions on the SPD 2 are quasi-impressed current conditions. For instance in the case of coordination between a spark gap and an MOV, this condition is satisfied.

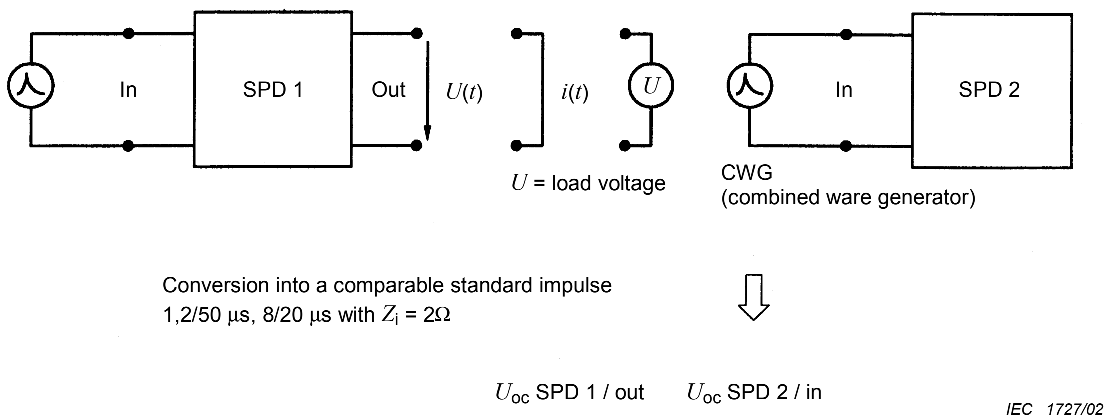


Figure E.20 – Let-through energy method with standard pulse parameters

The aim of this coordination method is to make the input values of an SPD 2 (for example, discharge current) compatible with the output values of an SPD 1 (for example, voltage protection level). For a stepped protection, the equivalent input combination wave impulse which can be discharged by the following SPD (without damage) should be equal to, or greater than, the equivalent output combination wave impulse of the preceding SPD.

For reliable coordination, the equivalent combination wave impulse must be determined for the most severe case of the stress (i_{max}, u_{max}, let-through energy). The method explained here gives in general a conservative value for the decoupling element (impedance) between the two SPDs. This means that, if such an impedance is installed between the two SPDs, the coordination will act in general better than predicted by the computation.

The basis of this method is to represent the output of each SPD as an equivalent combination wave generator (CWG), defined by an open-circuit voltage U_{oc} of 1,2/50 μs and a short-circuit current I_{sc} of 8/20 μs, the effective impedance of the generator being 2 Ω.

An SPDs tested according to Class III tests is already tested by such a CWG. In case of SPDs tested according to Class II, it is necessary to consider that $I_{sc} = I_{max}$.

The SPD at the front may be tested according to Class I tests in case of direct lightning on the structure, or according to Class II tests.

The voltage at the output of each SPD will have in general a waveshape which is not directly related to the waveshapes 1,2/50 μs and 8/20 μs. It is then necessary to normalize the actual waveshapes in order to convert them to the 1,2/50 μs and 8/20 μs waves.

This is done by calculating the following values:

– crest value of $u = \hat{u}$, $\int u \, \mathrm{d}t$ and $\sqrt{\int u^2 \, \mathrm{d}t}$;

– crest value of $i = \hat{\imath}$, $\int i \, \mathrm{d}t$ and $\sqrt{\int i^2 \, \mathrm{d}t}$.

These values are then entered in the table E.2.

Table E.2 – Normalized values

Voltage	$\hat{u}$	$\int u \, \mathrm{d}t$	$\sqrt{\int u^2 \, \mathrm{d}t}$
Current	$\hat{I}$	$\int i \, \mathrm{d}t$	$\sqrt{\int i^2 \, \mathrm{d}t}$

The same table for a CWG with an amplitude of 1 V becomes the reference table E.3.

Table E.3 – Reference table

Voltage	1	70×10^{-6}	6×10^{-3}
Current	5	12×10^{-6}	2×10^{-3}

By dividing each cell of table E.2 by the equivalent cell of the reference table E.3, table E.4 is obtained.

Table E.4 – Equivalent values

Voltage	$\hat{u}$	$\int u \, \mathrm{d}t / (70 \times 10^{-6})$	$\sqrt{\int u^2 \, \mathrm{d}t} / (6 \times 10^{-3})$
Current	$\hat{\imath}$	$\int i \, \mathrm{d}t / (12 \times 10^{-6})$	$\sqrt{\int i^2 \, \mathrm{d}t} / (2 \times 10^{-3})$

The maximum value in table E.4 gives the value $U_{oc\ equivalent}$ of the CWG. This value is equivalent to the output of the SPD.

As long as the downstream SPD has been tested according to the Class III tests with a CWG having a no-load voltage $U_{oc\ test}$ (or an equivalent CWG in case of Class II tests), it is possible to determine immediately whether the coordination is achieved or not. It is sufficient to check that $U_{oc\ test} > U_{oc\ equivalent}$.

The values at the output of the SPD, for a given stress at the entrance, have to be computed by simulation programmes. They need not be computed for each application, because they can be computed in advance by the manufacturer. For each of its products, the manufacturer can compute the output equivalent CWG for a given stress (I_{imp} for Class I tests, I_{max} for Class II tests, or $U_{oc\ max}$ of the CWG for Class III tests) taking into account both tolerances on the SPD characteristics and any blind spot (the most severe stress at the output of the SPD is not given by the maximum values: I_{imp}, I_{max} and $U_{oc\ max}$ but for lower values).

E.7 Coordination demonstration tests

The purpose of the tests defined here is to demonstrate the effectiveness of the energy coordination of multi-step cascaded SPD arrangements. Because of the different electric behaviour of the individual SPD technologies (limiting type and switching type), a common test strategy is not possible. Therefore, the following test protocols are defined, starting from basic arrangements of two cascaded SPDs, with a specified surge current impressed on the first SPD input.

NOTE If the SPDs tested according to Class I, the coordination with other SPD-classes (such as Class II or Class III), will be based on a 10/350 µs surge current waveshape. For SPDs tested according to Class II, the coordination with other SPD classes will be based on an 8/20 µs surge current waveshape. SPD arrangements with more than two SPDs to coordinate can be reduced to this basic model.

E.7.1 Coordination of cascaded voltage limiting type SPDs

The surge current is injected into the first (upstream) SPD with respect to the surge direction at the input of the cascade arrangement provided by the manufacturer. Starting from 0 kA, the surge current amplitude is raised by incremental steps of 25 % of the highest specified I_{peak} or I_{max} value of the SPD arrangement.

The test is considered as passed if the individual SPDs still meet the criteria for the individual components (no significant permanent change) in a test to be performed after the coordination demonstration test.

E.7.2 Coordination of cascaded voltage switching type SPDs

Demonstration of coordination for such an SPD cascade is carried out by means of surge voltage waveshape 1,2/50 µs. The conditions of an energy coordination are considered as satisfied if, in the relevant range of the input voltage steepness (d.c. sparkover voltage, up to some kilovolts per microsecond) for the individual SPDs, it is assured that the SPD having the highest surge-current capacity will be triggered first, before the downstream SPD having a lower surge-current capacity. If this is not achieved, the test protocol E.7.3 described below should be applied.

The test is considered as passed if the individual SPDs still meet the criteria for the individual components (no significant permanent change) in a test to be performed after the coordination demonstration test.

NOTE In this description, the term "triggered" should be understood as a generic term for the change from high to low state, characteristic of voltage-switching SPD (gap sparkover, self-triggering of a solid-state SPD).

E.7.3 Coordination of cascaded voltage-limiting type and voltage-switching type SPDs

The particular problem of this arrangement is that the voltage-switching type SPDs might have a blind spot behaviour, so that the downstream SPD has to carry the whole surge current. This worst case for the coordination can be demonstrated by the following test. A surge current of appropriate waveshape is injected into the cascade circuit arranged according to the manufacturer's instructions, by incremental steps, until the upstream SPD is triggered and passes the current. The surge current amplitude determined in this way is then reduced by decrements 5 % until the upstream SPD is no longer triggered. The complete procedure is carried out three times. The average surge current value from the three tests (when the upstream SPD just will not spark over) is defined as the blind spot value (I_{BS}). Three more shots will be applied to the cascade combination, at 75 %, 100 % and 125 % of I_{BS}.

The test is considered as passed if the individual SPDs still meet the criteria for the individual components (no significant permanent change) in a test to be performed after the coordination demonstration test.

E.7.4 Requirements for test and simulation techniques

The techniques used in demonstration tests and numerical simulations can affect the results to the point that comparisons might be difficult if care has not been exercised in defining the parameters, in particular the current waveform applied in the tests or postulated for simulations. This precaution is particularly important with regard to the rate of rise of the applied surge current. In a scheme of cascading an upstream voltage-switching SPD and a downstream voltage-limiting SPD, the intention is that triggering of the upstream SPD should occur very early in the rising portion of the surge, in a time substantially less than one microsecond. In such a case, the usual definition of front time, as given in IEC 60060 (1,25 × [time from 10 % to 90 %]) is insufficient to characterize the maximum rate of current rise, which will determine the voltage developed in the decoupling inductance of the cascade.

To obtain comparable and reasonable results, the steepness of the front of the wave has to be well defined. A steepness factor is proposed by [25] as shown in figure E.21, to provide an empirical criterion for the adequacy of the test waveform.

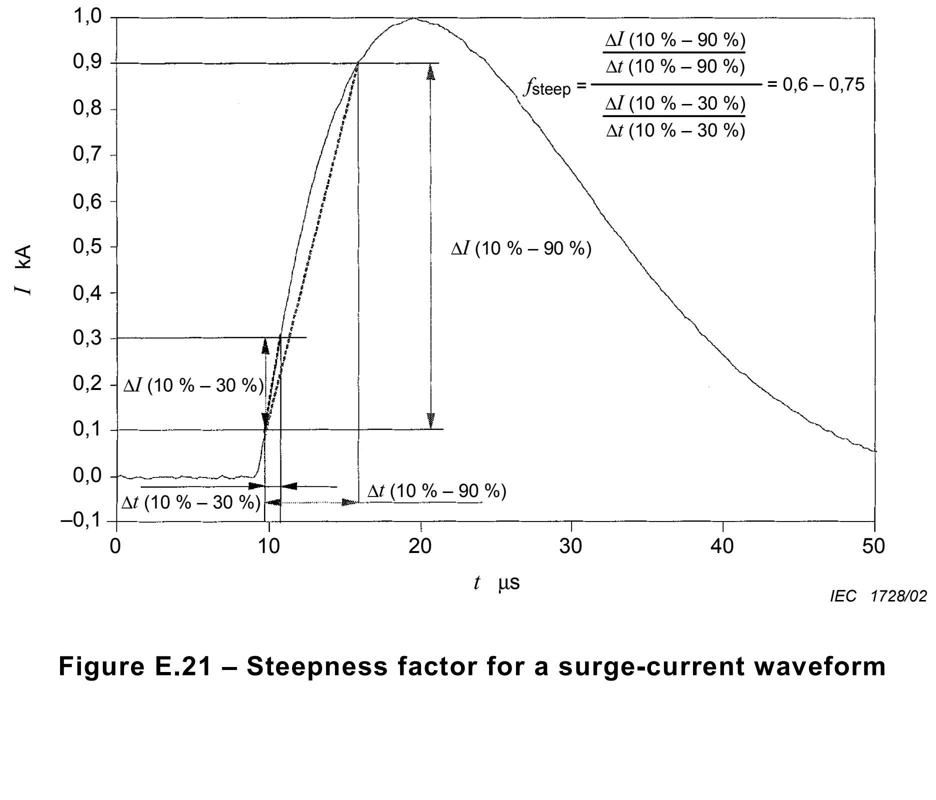


Figure E.21 – Steepness factor for a surge-current waveform

For simulations, the waveform should not have an abrupt start at time zero, but include a "gentle toe" [32]. The steepness factor, for a current impulse such as those described as double exponential or damped sine wave, is defined as the ratio of the rate of rise (di/dt), computed for the interval (10 % to 90 %), to the rate of rise computed for the interval (10 % to 30 %). Typically, a higher value of the rate of rise is found near the origin (once the "gentle toe" has been passed), i.e., in the (10 % to 30 %) interval. Thus, a "steep front" is characterized by a steepness factor smaller than unity. For the example of figure E.21, this factor is in the order of 0,7. A further criterion of a 0,1 kA/µs rate of rise for the surge current is now specified in IEC 61312-3.

E.8 Examples of coordination

Example: Coordination between two SPDs tested according to Class II tests.

The relevant parameters to characterize each of these SPDs, assuming that these SPDs are tested according to Class II tests are the following.

– U_p voltage protection level, to be selected from a list of preferred values;
– I_n peak of 8/20 current used to classify the SPD according to Class II;
– I_{max} maximum current applied for Class II test.

It is necessary to coordinate the SPD which is installed directly at the input of the equipment to be protected and the equipment itself with regard to their characteristics. This coordination requires that the withstand capability of the equipment to be protected will not be exceeded for any relevant parameter.

For any details concerning the withstand capability of the equipment terminals, refer to the relevant standards, such as IEC 61000-4-5, IEC 60664-1, ITU-TS K. 20, and ITU-TS K.21.

NOTE Equipment achieving the above standards might do so by the inclusion of internal SPDs, therefore the parameters of these devices might affect or alter the coordination principles being considered.

Table E.5 – Example of coordination between two SPDs tested according to Class II

First SPD tested according to Class II			Second SPD tested according to Class II			Minimum distance between the SPDs
U_p kV	I_{max} kA	I_n kA	I_{max} kA	I_n kA	U_p kV	m[a]
2,5	40	20	10	5	1,8	10
					1,5	15
					1,2	20
					1,0	25
	20	10	4	2	1,8	10
					1,2	15
					1,0	20
	10	5	4	2	1,5	10
2,0	40	20	10	5	1,8	5
					1,5	10
					1,2	10
					1,0	15
	20	10	4	2	1,8	5
					1,2	10
					1,0	10
1,8	40	20	10	5	1,2	5
					1,0	10
	20	10	10	5	1,5	5
			4	2	1,2	10
					1,0	10

[a] The equivalent distance is given on the basis of 1 µH/m of distance between the two SPDs. Therefore, 10 m means 10 µH and vice-versa. This distance includes margins.

Example: Coordination between a first SPD tested according to Class I of tests and a second SPD tested according to Class II tests, consisting either of a gap or of a varistor. In this case, the most severe case is to perform the computation with the SPD being replaced by a short-circuit. The results of the computation are summarized in table E.6.

Table E.6 – Example of coordination between an SPD tested according to Class I and an SPD tested according to Class II

First SPD tested according to Class I	Second SPD tested according to Class II	Minimum distance between the SPDs m[a]
Sparkover voltage 4 kV	Short circuit	40
	Spark gap	40
	Varistor (U_{ref} at 1 mA = 430 V)	32
	Varistor (U_{ref} at 1 mA = 180 V)	36

[a] The equivalent distance is given on the basis of 1 µH/m of distance between the two SPDs. Therefore, 10 m means 10 µH and vice versa. This distance includes margins.

Table E.7 – Parameters for Class I tests (IEC 61643-1)

I_{peak} kA	Q (C) within 10 ms
20	10
10	5
5	25
2	1
1	5
NOTE In case of values differing from those given in this table, the relationship between I_{peak} and Q is given by the formula Q (A.s) = 0,5 I_{peak} (kA).	

Annex F
(informative)

Avoiding overvoltages through good practice for earthing and cabling

Overvoltages can be avoided by a number of EMC measures: proper cabling, proper selection of cables for their low transfer impedance, proper routing of cables and of course by a good earthing system. Concepts to that effect are described in IEC 61000-5-2. The following clause F.1 provides illustrations of these principles of good practice for earthing and cabling.

As another example of what a good earthing system may involve, this annex also illustrates remedial measures to the problem of shifting reference potentials in information technology equipment applications. In many such applications, the earthing conductor of the power port determines the potential of the equipment chassis, which often serves as the reference potential for the signal exchanges. This illustration is given in clause F.2.

F.1 General principles

First, a clear distinction must be made between the circuits for the intended signal or power on the one hand, and the circuit through which the disturbance currents flow, as discussed in annex B of IEC 61000-5-2, on the other hand. The coupling between these circuits is described by a transfer impedance Z_t. This Z_t must be chosen in such a way that the remaining transfer of disturbances is acceptably low.

A second important concept is the parallel earthing conductor (PEC). This conductor provides a path for the disturbance currents. It may be a single lead, an intended cable shield, or even the armour of a cable which might not be intended as shield but still provides good protection when connected properly. Rules for connecting such a PEC, and for connecting cables to the PEC are given in IEC 61000-5-2.

A PEC has several advantages when installed for limiting overvoltages. First, the relation between currents and voltages is initially linear, which allows a scaling even to high-intensity disturbances, up to the range where saturation effects or intervention of SPDs begin to occur. The amount of protection can be established and tested at low-amplitude disturbances, for example, by injecting current through the PEC. Second, the protection is reciprocal. A PEC protects inside cables against outside disturbances and conversely. Third, redundancy can easily be incorporated by multiple connections between the PEC and the rest of the earthing system. Surge-protective devices, on the other hand, limit the voltage across the terminals to which they are connected by strong non-linear voltage/current characteristic. They need to be tested at the maximum expected values of surge voltage or current, and also at intermediate values to reveal possible blinds spots.

A third concept introduced in IEC 61000-5-2 is the EMC cabinet, to protect electronic equipment against a large variety of electromagnetic disturbances. An example of such cabinet is given below.

F.2 The EMC cabinet

Figure F.1 illustrates the principle of the EMC cabinet. The main action of this EMC cabinet is to provide a path for the disturbance or common-mode currents arriving at the equipment through the cables. This path should have a low transfer impedance Z_t with respect to the equipment. To this end, all cable shields are carefully and completely connected to the back panel. Power enters via a filter F also mounted at that panel; the filter should provide a path for the common-mode current to the back panel. The power-line filter used in the cabinet might also contain surge-protective devices. Other unshielded cables should also enter via appropriate and correctly mounted filters. The front of the EMC cabinet may be left open. No cable or other conductor should enter the cabinet via the front opening.

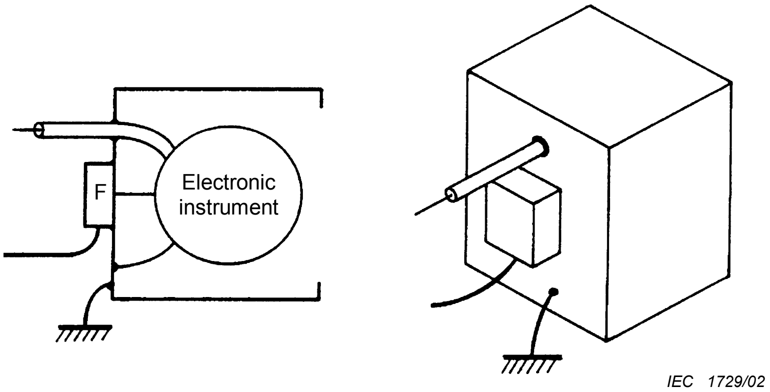


Figure F.1 – EMC cabinet protects electronic equipment against common-mode currents through cables

F.3 Example of protection provided by proper cabling

In order to demonstrate the effects of proper cabling practices in mitigating interactions, an experiment is described below, which was carried out in a high-voltage (HV) substation. Of course, the results are very general and can also be applied to many other installations where interactions between systems can occur: telecom, radio stations, computers etc. A full account of the experiment is presented in [55].

A circuit-breaker (CB in figure F.2) connects a HV transformer to the 150 kV bus bar. The first sparkover in the CB produces a steep front. Multiple reflections in the HV system distort this front into an intense high-frequency ringing wave (about 400 kHz, 250 A). The loop for the HF primary current is the HV lead, the parasitic capacitance of the transformer and its metal case; the current returns to the HV system through the earth.

Originally, a temperature sensor was mounted at the top of the transformer at A in figure F.2. Two leads carry the temperature signal to the control room. The action of the CB resulted in a common-mode voltage of several kilovolts between both leads (at D in figure F.2) and the nearby earth in the control room. This overvoltage had caused real problems in actual installations.

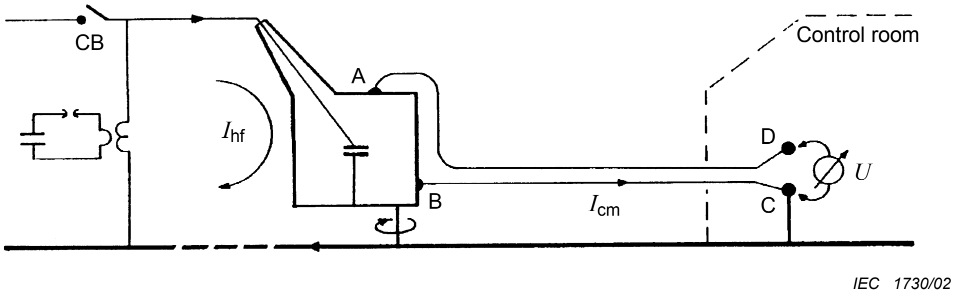


Figure F.2 – Coupling of common-mode overvoltage caused by switching surges

The closure of a circuit-breaker CB produces a steep front and ringing wave in the HV system. This wave can also be generated by a capacitor discharge. The secondary loop A-B-C-D couples with the loop for the primary current I_{hf}; a large voltage U appears between D and C in the control room. Additional conductors, earthed at A or B on the transformer, and at C in the control room strongly reduce the disturbance voltages.

In the experiment, the two leads for the temperature sensor were replaced by a cable following the same path. The cable was shorted to the top of the transformer at A in figure F.2. The primary interference current was generated by a capacitor discharge via a HF transformer into the HV lead; this source produced similar disturbances without the need of repeated CB action. With this set-up, an interference voltage of 2,3 kV was measured in the control room between D and C in figure F.2, due to the mutual induction between the primary circuit and the circuit A-D-earth at C-earth near B.

A single lead in the cable was then connected between A and C (earthed at both A and C); this resulted in a fourfold reduction of the interference voltage (see figure F.3). The coarsely woven steel armour of the cable was used as shield, and earthed at A and C of figure F.2. This arrangement lowered the interference voltage substantially again.

Finally, this cable (armour still connected at A) was routed inside a steel conduit earthed at the points B and C. The resulting interference in configuration (d) voltage was then less than 1 V, down from the initial 2,3 kV recorded for configuration (a).

In this experiment, the single lead, the armour, and the armour + conduit act as a parallel earthed conductor (PEC). In the order given, the impedance of the ground loop decreases, as is shown by the increasing current through the PEC (figure F.3). But more importantly, the transfer impedance of the PECs decreases much faster, to the point that the lowest induced voltage measured in the four cases occurred for the last case (d) involving the highest current.

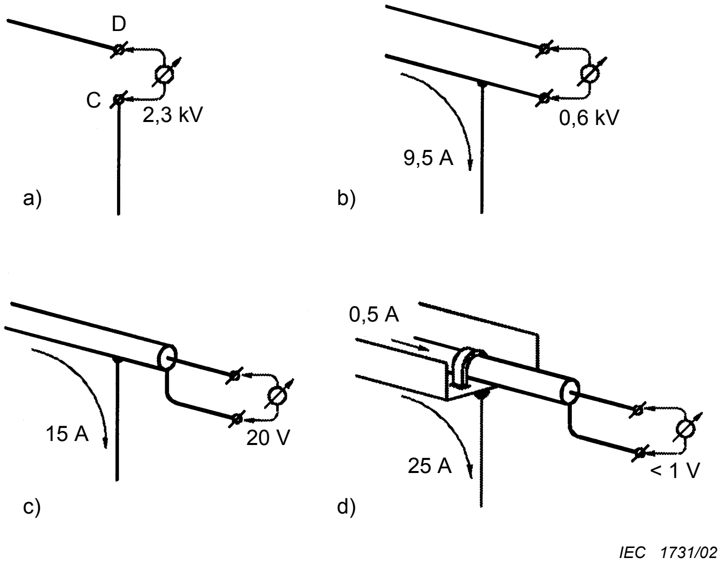


Figure F.3 – Voltages measured in the control room on a cable shorted at the other end, at the top of the transformer. The common-mode currents are indicated for the various parallel earth conductors between A and C.

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