

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

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# National foreword

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The British Standards which implement international publications referred to in this document may be found in the *BSI Catalogue* under the section entitled “International Standards Correspondence Index”, or by using the “Search” facility of the *BSI Electronic Catalogue* or of British Standards Online.

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# TECHNICAL REPORT

# IEC TR 62066

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

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



Reference number  
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## INTERNATIONAL ELECTROTECHNICAL COMMISSION

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

## FOREWORD

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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- withdrawn;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  $2\ \Omega$ ; 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 disconnecter**

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

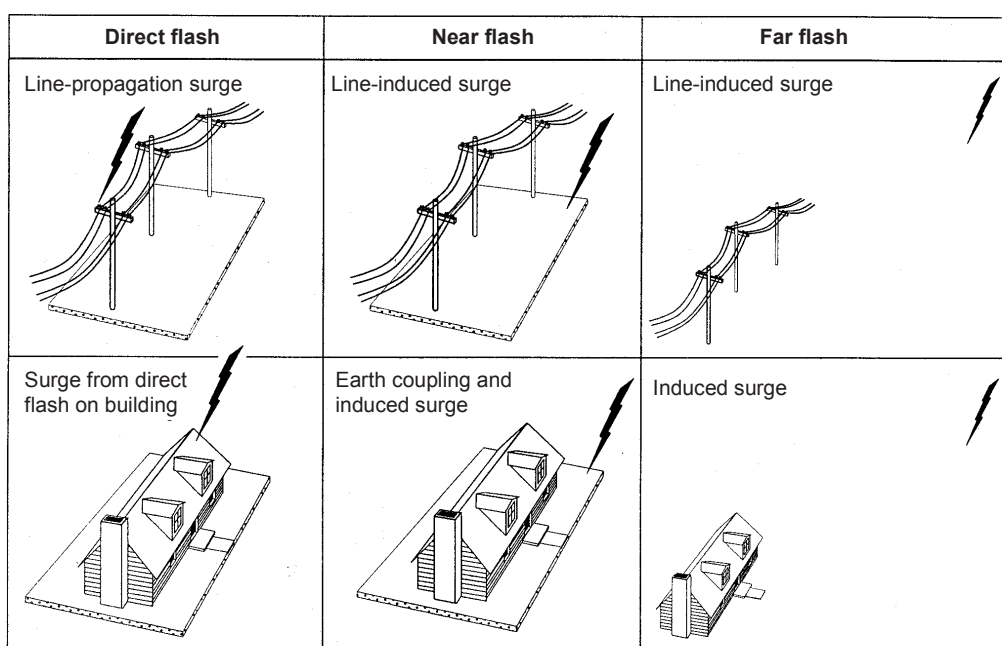
Overvoltages can occur between different systems, such as power and communications, during the flow of surge currents in one of the systems. These are briefly described in clause 8.

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.



IEC 1636/02

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) |

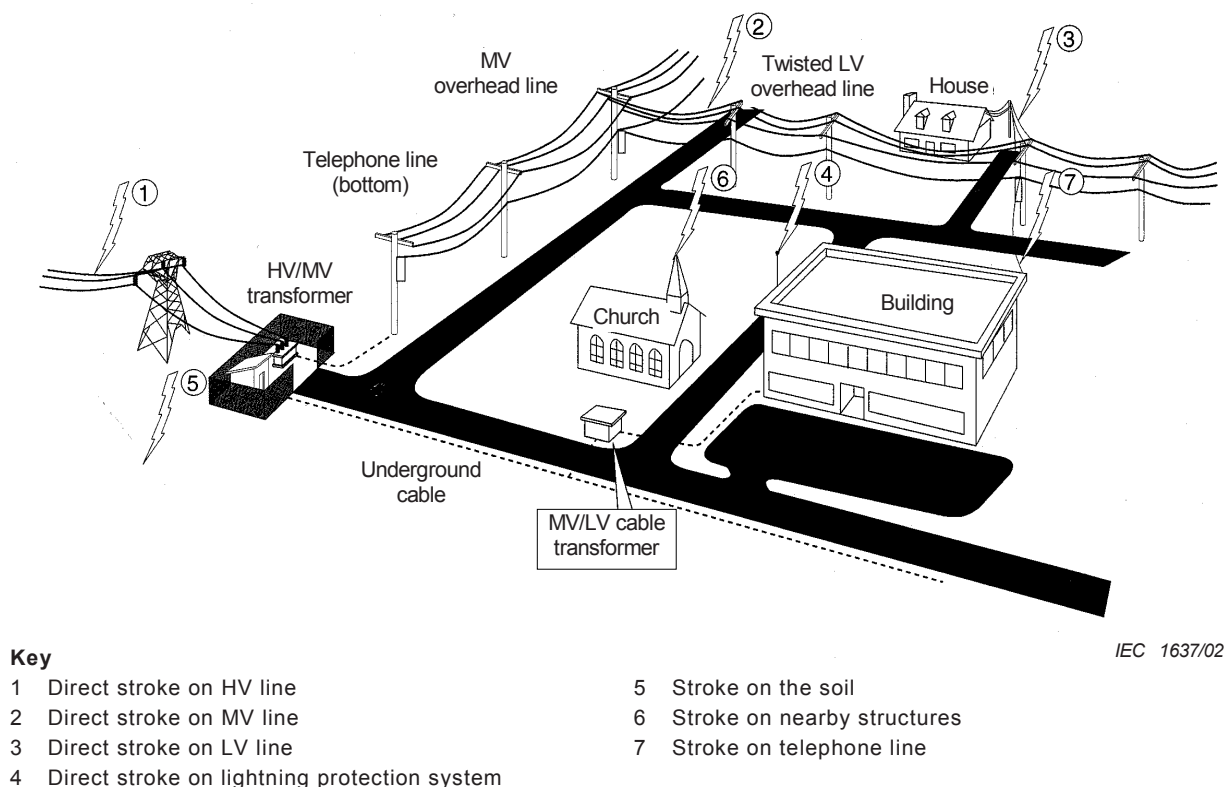


**Figure 2 – Examples of lightning flashes to a complex electrical system**

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.

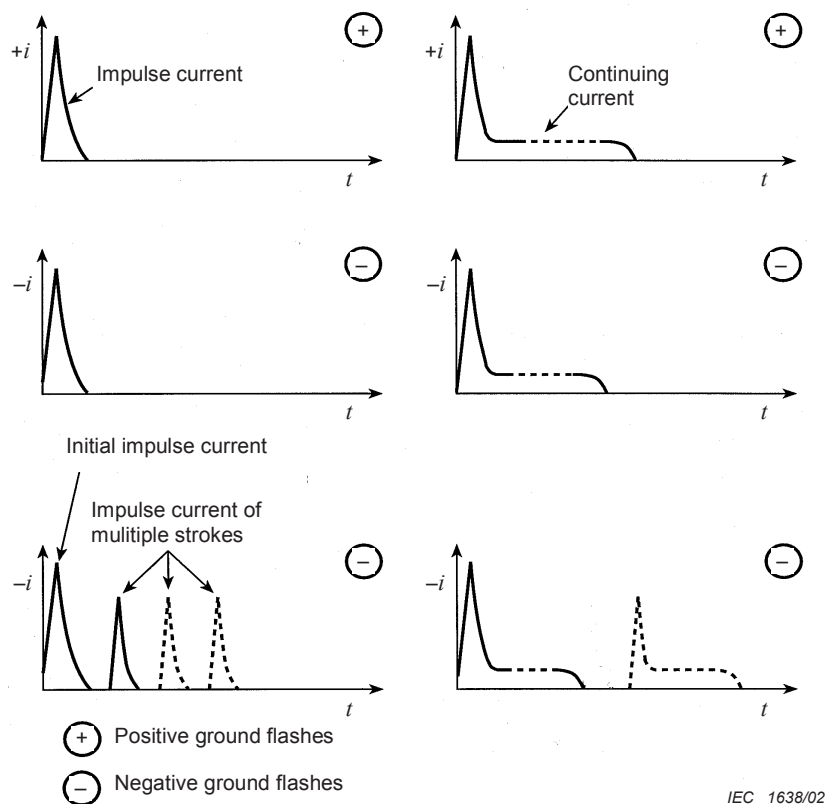
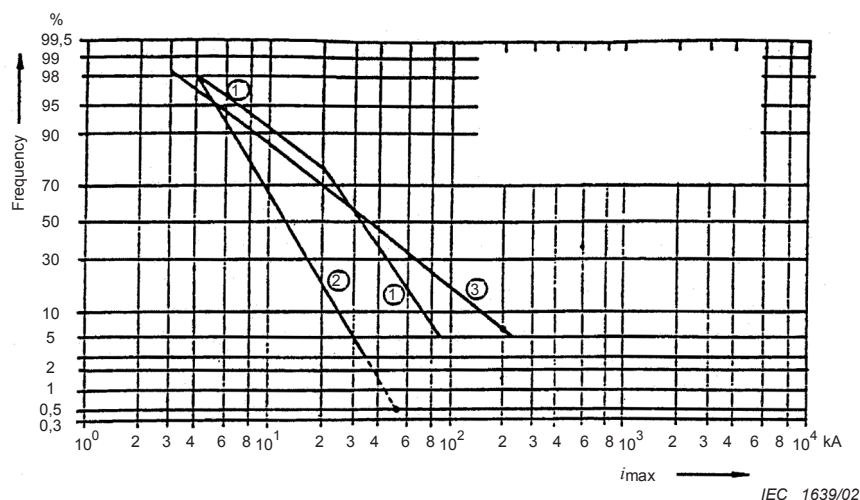


**Figure 3 – Possible waveforms of lightning current striking ground-based objects**

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.

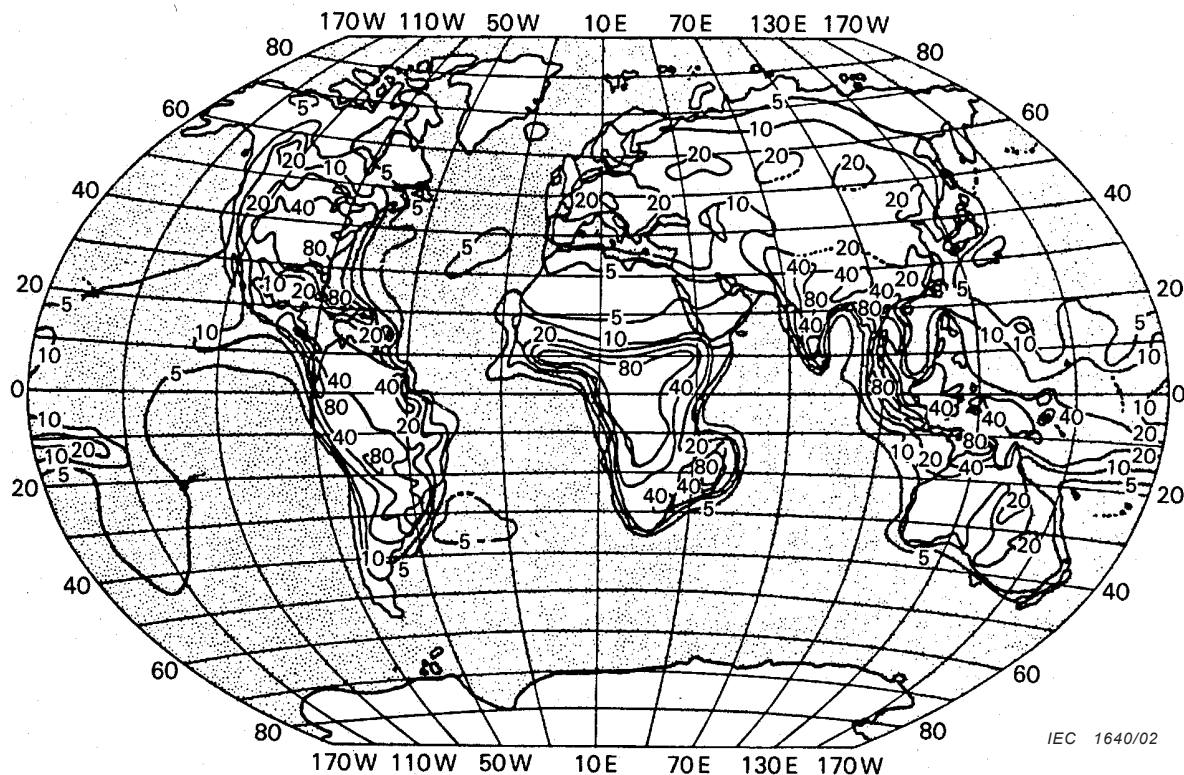


Figure 5 – Map of annual thunderstorm days [7] <sup>1)</sup>

## 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  $\Omega$  to 500  $\Omega$  for one conductor. As shown in figure 6, the current ( $I$ ) is initially divided in two parts, one in each direction.

<sup>1)</sup> Figures in square brackets refer to the bibliography.

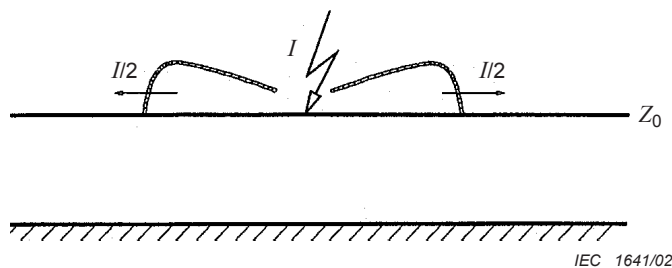


**Figure 6 – Direct flash to an overhead line**

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

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

where

$U$  is the voltage surge (kV);

$Z_0$  is the surge impedance ( $\Omega$ );

$I$  is the lightning current (kA).

For a moderate current of 20 kA and a surge impedance of 400  $\Omega$ , the prospective voltage surge at the point of attachment of the stroke is 4 000 kV. On medium-voltage (MV)<sup>1)</sup> 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  $\Omega$ , 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:

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

where

$A$  is the effective area;

$H$  is the height;

$L$  is the line length

<sup>1)</sup> 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 ( $\text{m}^2$ );

$N_g$  is the local flash density per  $\text{km}^2$  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  $10 \Omega$  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.

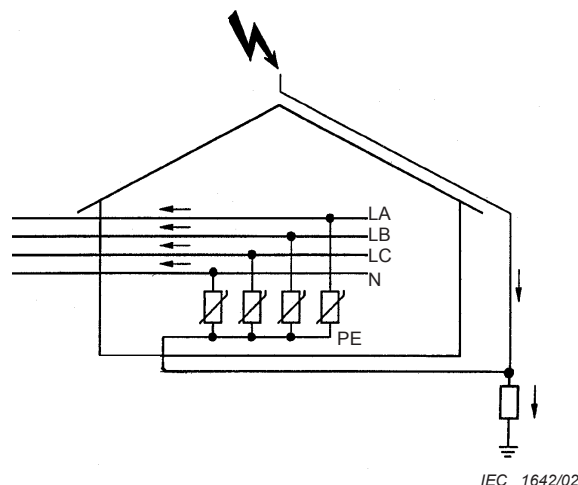


Figure 7 – Example of resistive coupling from lightning protection system

### 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.

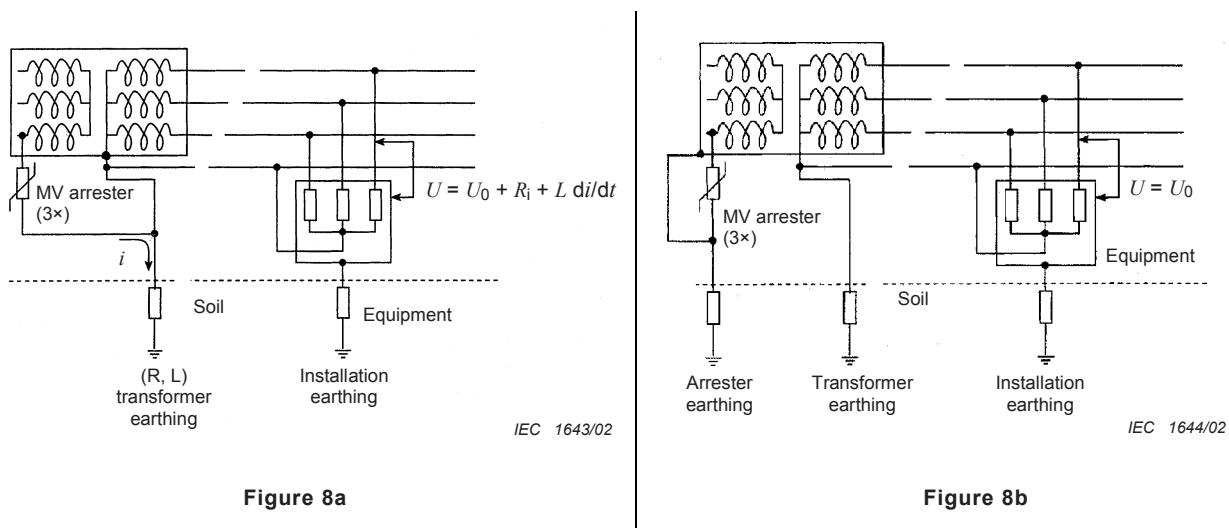


**Figure 8 – Typical earth coupling mechanisms**

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.

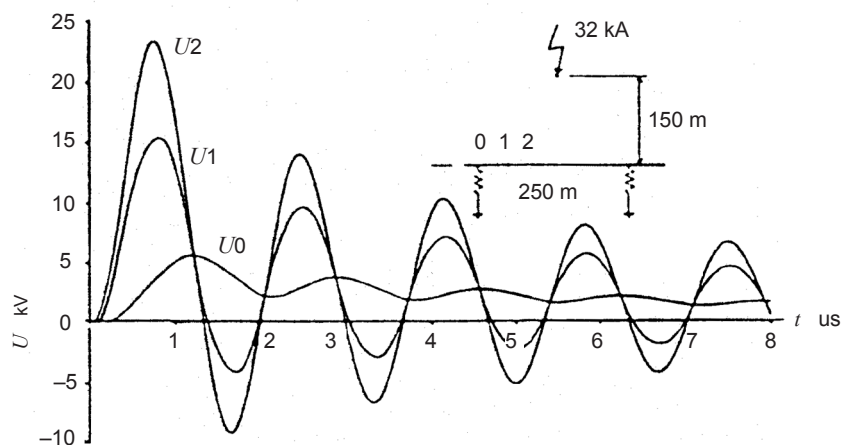
#### **5.5 Lightning surges induced into LV systems**

##### **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.



IEC 1645/02

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<sup>2</sup> 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:

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

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.

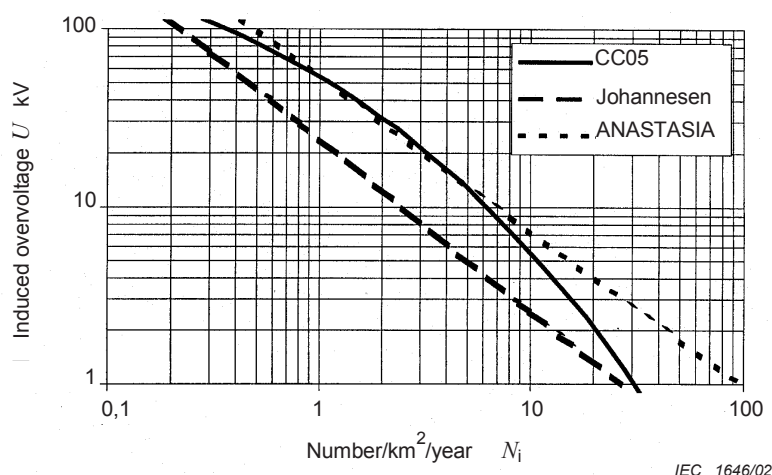


**Figure 10 – Example of estimated frequency of occurrence of prospective induced lightning overvoltages on LV overhead lines**

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

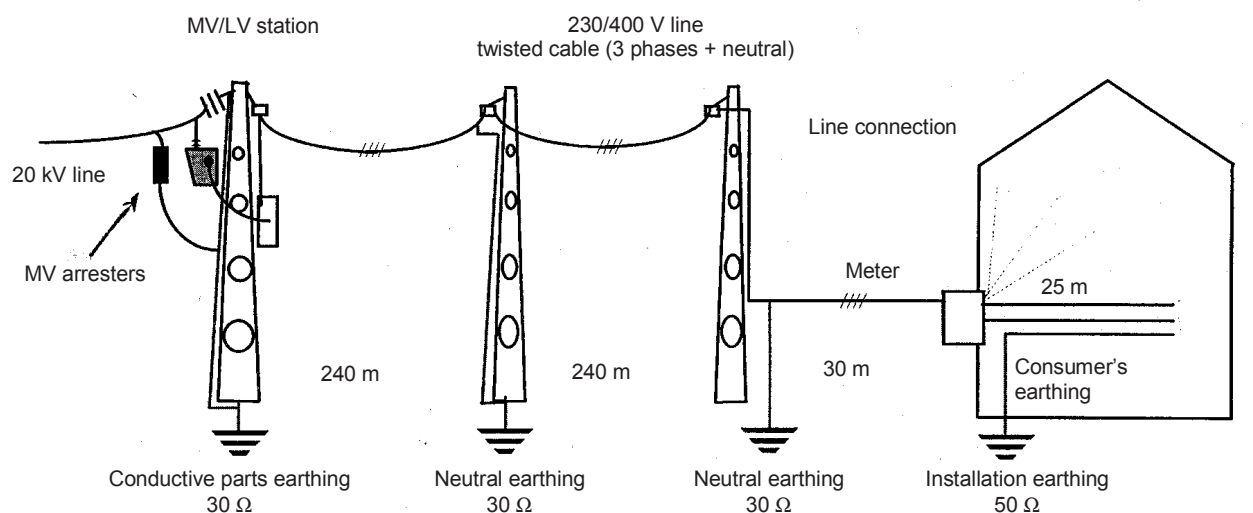
As an example of prospective overvoltages that might be expected, a simulation with Monte-Carlo statistics was performed on a model of a LV distribution system shown in figure 11. The ground flash density was assumed to be 2,2 flashes per km<sup>2</sup> per year, and all loads were simply modelled by 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.



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*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<sup>2</sup>, 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<sup>2</sup>/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<sup>1)</sup> 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  $i_{\text{imp}}$  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):

$$i_m/i_e = R_e/R_m \quad (6)$$

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  $\Omega$  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].

<sup>1)</sup> 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.

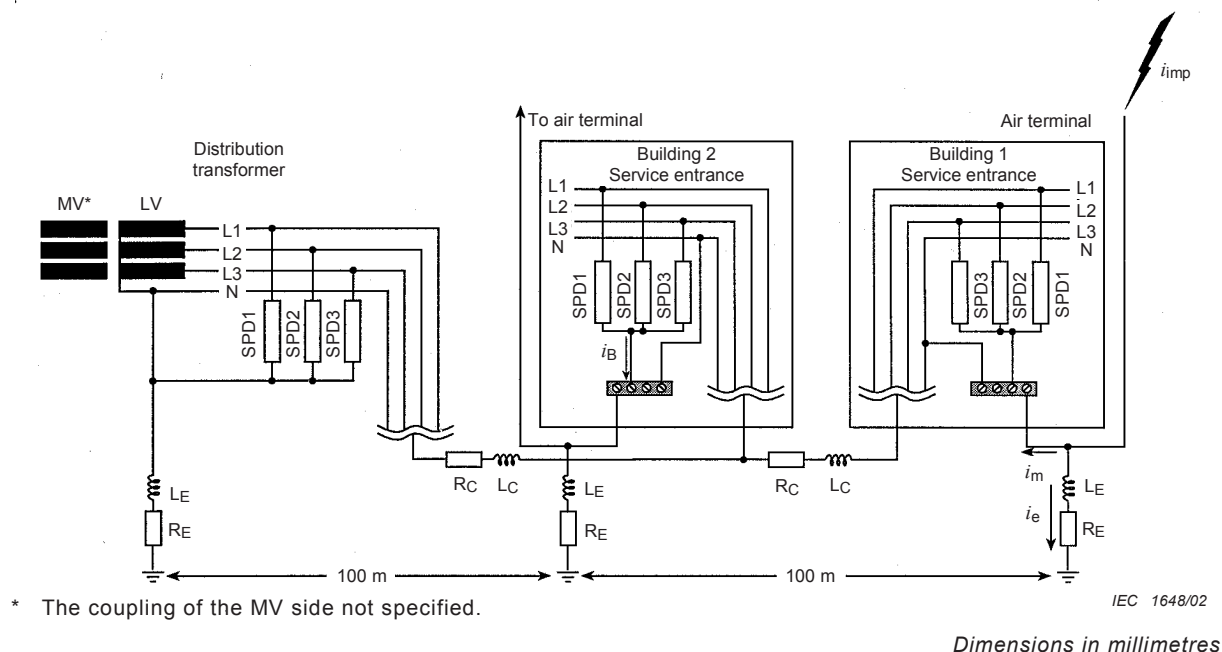


**Figure 12 – Model for computing dispersion of lightning current among parallel buildings in an example of TN-C system**

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  $\mu$ s, 100 kA)**

| Available path to earth                                                     | Approximate current amplitude, (beyond initial stage)<br>kA | Approximate charge<br>C |
|-----------------------------------------------------------------------------|-------------------------------------------------------------|-------------------------|
| Earthing electrode(s) of building 1 ( $i_{\text{Earthing}}$ )               | 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<sup>2</sup> per year) by the effective collection area of the structure  $A_e$  (km<sup>2</sup>) as follows:

$$N_d = N_g \times A_e \quad (7)$$

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:

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

where

$A$  is the horizontal area of the structure in m<sup>2</sup>;

$h$  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<sup>-2</sup> to 10<sup>-3</sup> 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.)

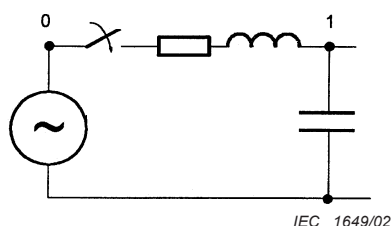


Figure 13 – Generation of overvoltage by switching an RLC circuit

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<sup>1)</sup>, 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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<sup>1)</sup> 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].

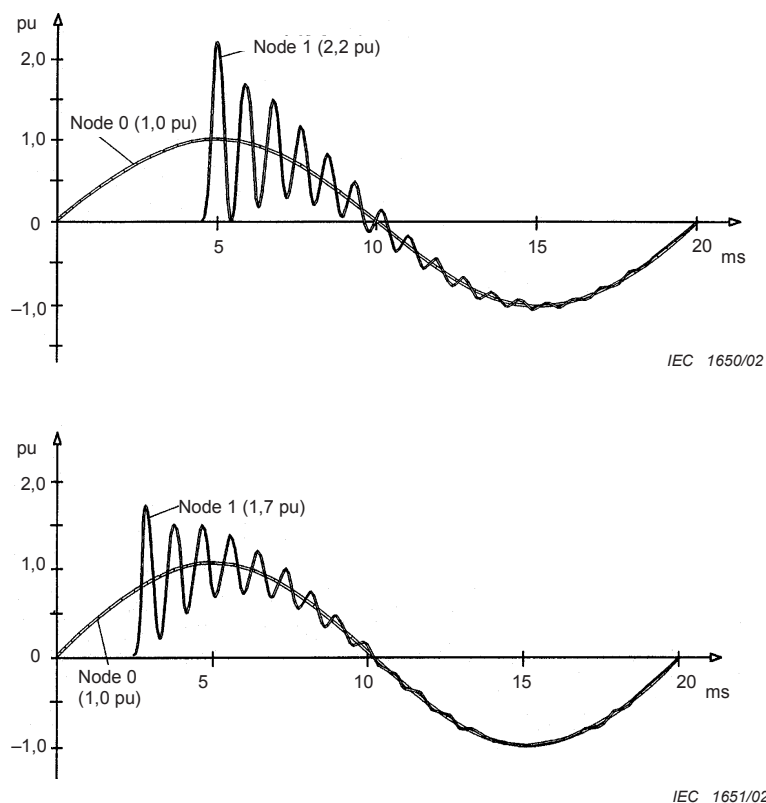


**Figure 14 – Typical switching overvoltages**

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.

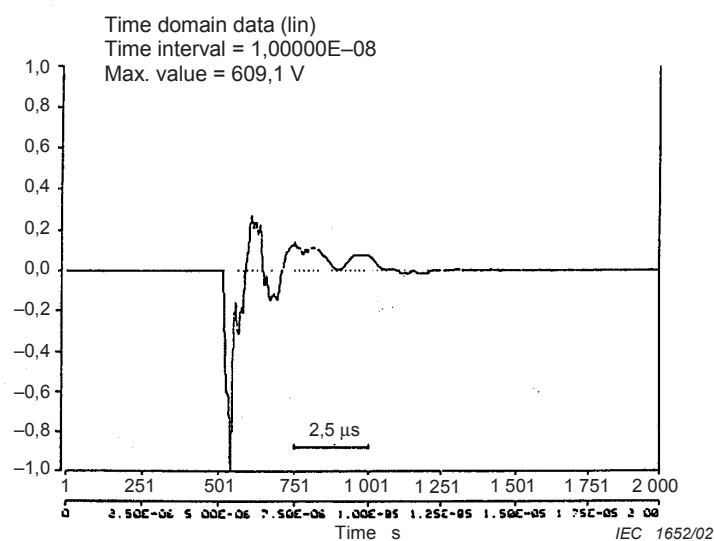


**Figure 15 – Example of a high-frequency switching surge**

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

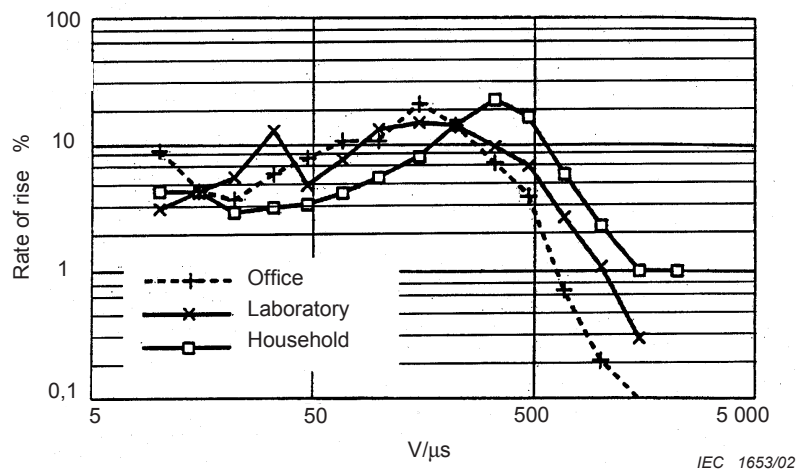


**Figure 16 – Distribution of the rate of rise of switching surges at different locations**

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  $\mu\text{s}$  to 2  $\mu\text{s}$ . 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  $\mu\text{s}$  impulse or the 0,5  $\mu\text{s}$  - 100 kHz ring wave. The correspondence with the 1,2/50  $\mu\text{s}$  impulse is shown in figure 18 for rather low amplitudes.

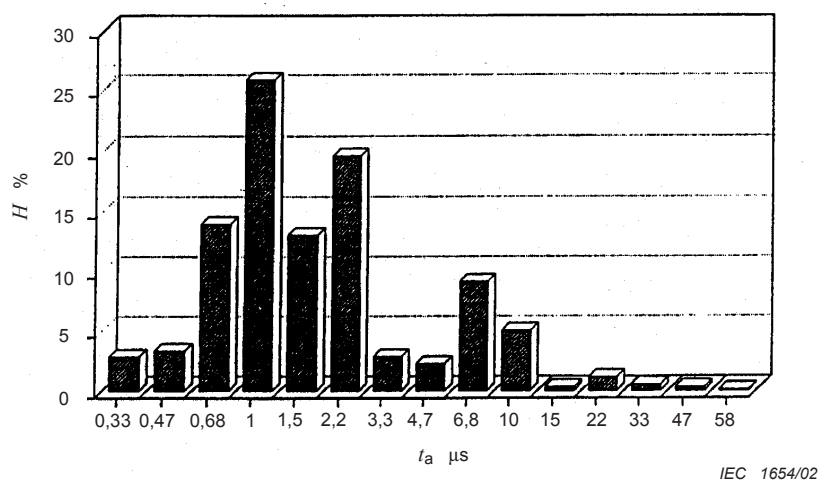


**Figure 17 – Distribution of the rise time of switching surges**

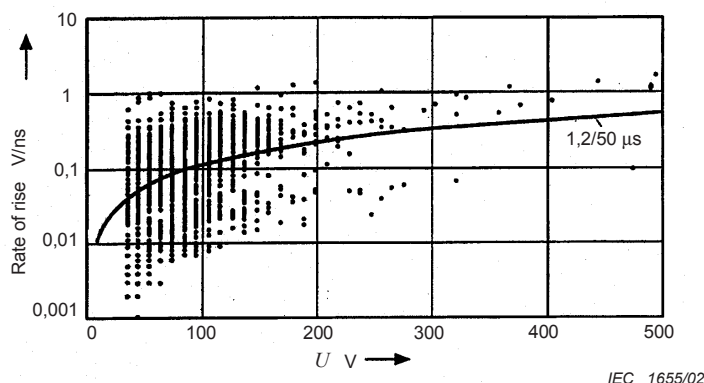


Figure 18 – Rate of rise of the switching surges and their crest values

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  $\mu\text{s}$  to 50  $\mu\text{s}$ , which is shown in figure 19.

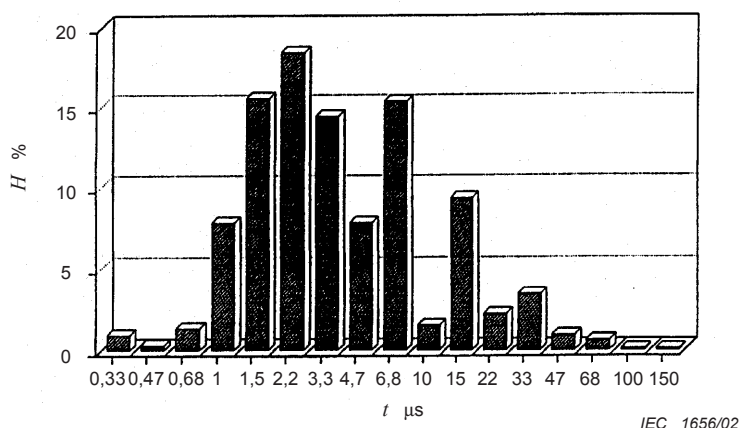


Figure 19 – Distribution of the duration of the switching surges

## 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.

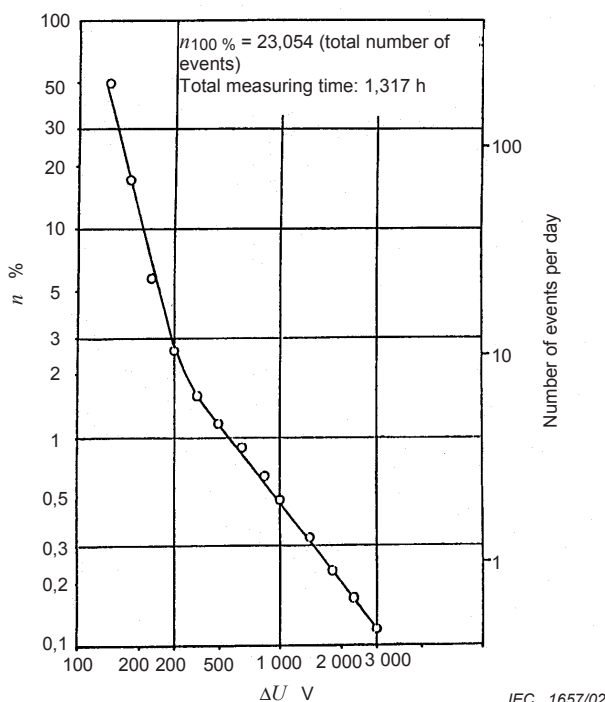


**Figure 20 – Example of distribution of switching surge amplitudes measured in industrial distribution systems rated 230/400 V**

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<br>A | Time to half value<br>μs |
|------------------|--------------------------|
| 1                | 8                        |
| 1                | 24                       |
| 1,6              | 36                       |
| 10               | 64                       |

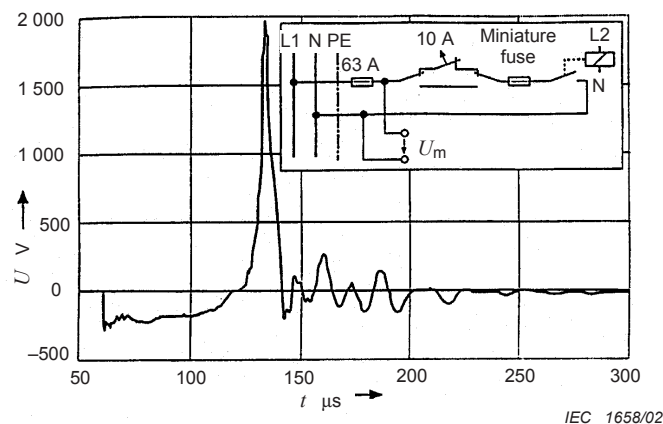


**Figure 21 – Switching surge during interruption by a miniature fuse [48]**

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

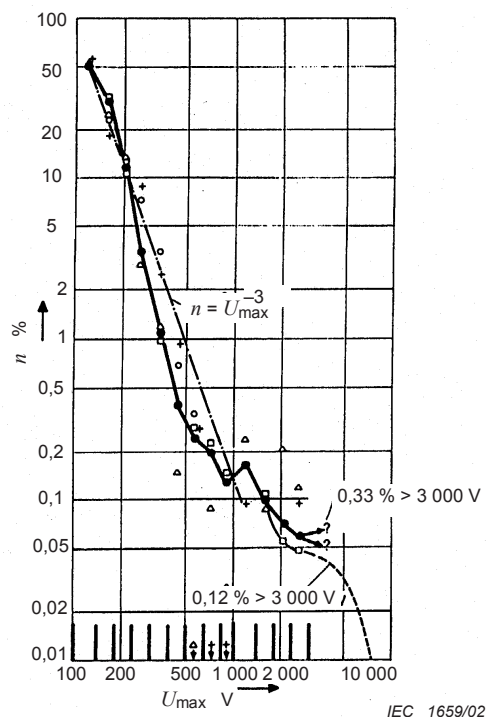
Both the relative values of the probability of occurrence of switching surges and the absolute values may be evaluated. The first method, relative values, is more appropriate if different measurements and/or locations have to be compared.

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
- 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.