

287

**PROTECTION OF MV AND LV
NETWORKS
AGAINST LIGHTNING**

PART 1: COMMON TOPICS

**Working Group
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Abstract

This brochure presents basic information and principles related to lightning protection of Medium Voltage (MV) and (LV) networks. The present material constitutes the first part of a 3-part guide. Parts 2 and 3, to be published later, will deal specifically with the application to MV (Part 2) and LV (Part 3) networks. This part provides first a survey of different sources of overvoltages, as well as a review of the most widely accepted and well established methods of evaluating the expected rate of direct lightning strokes and induced lightning overvoltages. The document describes in addition the characteristics of lightning overvoltages, general characteristics of surge protective devices, and earthing systems.

1. Executive Summary

Introduction

Overvoltages originated by lightning are a major cause of faults on overhead power lines. These faults may cause permanent or short interruptions, as well as voltage sags, on distribution networks. The problem of lightning protection of Medium Voltage (MV) and Low Voltage (LV) networks has been seriously reconsidered in recent years due to the proliferation of sensitive loads and the increasing demand by customers for good quality in the power supply.

Purpose of the Brochure

The goal of this brochure is to provide a survey of basic concepts and general principles applicable to the protection of the MV and LV networks.

Main Topics Covered

After an introductory part covering the classification of overvoltages and a general description of the lightning discharge phenomenon, we review the lightning discharge parameters for engineering applications. Statistical data on lightning current parameters (peak value, maximum steepness, front duration, action integral) for both first and subsequent return strokes are summarized, as well as average value for the return stroke speed.

From the point of view of the overvoltage parameters that are important for lightning protection, direct lightning overvoltages and induced overvoltages are quite different. It is therefore important to evaluate the number of events for each type of lightning (direct or indirect) that are expected to affect the distribution line. The expected number of direct and indirect lightning events depends on the exposure of the line and on the screening provided by nearby objects such as trees. A specific expression, based on the leader progression model, for the evaluation of the expected number of direct lightning is presented. This expression allows the evaluation of the expected number of direct strokes per year, per 100 km, to a distribution line as a function of the ground flash density, the average height of the line and the horizontal spacing between the outer line conductors and a parameter which takes into account the particular orography of the line. For a 10-m high line with a horizontal separation between outer conductors of 2 m located in an area with a ground flash density of 1 per km² per year, the expected number of direct strikes is 11 per year and per 100 km.

The evaluation of the expected number of induced overvoltages larger than a given value requires the application of a statistical approach and accurate modeling of the lightning induction mechanism. We describe in the document an approach based on the Monte Carlo method which consists of generating an adequate number of lightning events, each characterized by random variables such as the peak value of the lightning current, its time to peak and the position of the strike location with respect to the distribution line. We show also that the use of simplified analytical formulas based on the assumption of infinitely-long lines and perfectly-conducting ground is not adequate. In addition, the number of flashovers due to indirect strikes is strongly affected by the ground finite conductivity. For a 10-m high single-conductor line characterized by a CFO of 100 kV, the estimated number of flashovers per 100 km per year is about 3 for a perfectly-conducting ground and increases to a value of about 20 for a ground conductivity of 0.001 S/m.

Overvoltages due to direct and indirect lightning strikes are characterized by complex and very different waveshapes. Overvoltages due to a direct strike have an overall waveshape similar to that of the incident lightning current, the fast rising portion being superimposed with several spikes which are due to the insulation breakdown. Induced overvoltages are characterized by pulse widths significantly

shorter than that of the channel-base current and their waveshape is strongly affected by the ground electrical conductivity. They can feature a positive, negative, or bipolar waveshape depending on the ground conductivity, the position of the observation point along the line and the line terminal conditions.

To analyze direct lightning strikes to a line, the lightning channel is generally represented by an equivalent current source injecting the return stroke current to the line at the attachment point. In the case of an indirect lightning strike, however, the analysis is more complex and the calculation of lightning-induced voltages requires the following stages:

- a return-stroke model which specifies the spatial and temporal distribution of the lightning current along the channel during the return-stroke phase is adopted;
- then, the electromagnetic field change produced by such a current distribution, ideally including propagation effects on the field, is calculated along the line, and finally,
- induced voltages resulting from the electromagnetic interaction between the field and the line conductors are obtained by using a field-to-transmission line coupling model.

As opposed to simple analytical formulas (such as the popular formula by Rusck), which are restricted to unrealistic simple configurations, more elaborate models allow for an accurate treatment of realistic line configurations. Moreover, the presence of distribution transformers, of surge protection devices at the line terminations, as well as the presence of surge arresters and shielding wire groundings along the line, should be taken into account. The complexity of these models calls for an implementation into computer codes since, in general, they require a numerical integration of the relevant equations.

The brochure contains also a review of general characteristics of surge protective devices (SPD) used for the lightning protection of power networks and components. The operating mechanism of SPDs, their classifications and typical V-I characteristics are presented, as well as a summary of the most relevant parameters for different technologies.

The final part of this brochure is dedicated to the behavior of earthing systems for lightning frequencies (up to some MHz). Grounding impedance of typical earthing systems is constant and equal to the DC resistance, up to a characteristic frequency that depends on the grounding electrodes arrangement and length and on the ground resistivity. Typically, this characteristic frequency is some 10's to 100's of kHz. Above this characteristic frequency, the grounding behavior could be dominantly capacitive, resistive, or inductive. Resistive and capacitive behavior is advantageous since the high frequency impedance is equal or smaller than the low frequency resistance to earth. Usually, capacitive behavior is typical for electrodes with smaller dimensions and in highly resistive soils. In order to minimize the influence of inductive behavior, it is better to use smaller electrodes. However, practically this is not always possible because to fulfill requirements for low values of the resistance to earth in standards (50/60 Hz), it is necessary to use longer electrodes. The high frequency behavior of the grounding electrodes depends also on the frequency content of the lightning current pulse; that is the inductive behavior for higher frequencies is more important for faster varying current pulses (subsequent strokes). It is also shown that the use of multiple grounding rod arrangements improves the impulse efficiency of grounding systems. Horizontal rods are slightly less effective at power frequencies in comparison to vertical rods, but they have a better impulse efficiency.

2. General Introduction

Joint CIRED/CIGRE Working Group 05 "Protection of MV and LV networks against lightning"* was established in 1993 with the task to prepare an application guide for Distribution Utilities focusing on practical methods of protection against lightning of MV and LV networks, taking also into account economical aspects and quality of the supply. After an interruption in 1997, the working group resumed its activity in 2002.

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This application guide is divided into three Parts:

- Part 1: basic information common to MV and LV networks
- Part 2: application to MV networks
- Part 3: application to LV networks.

Lightning overvoltages, caused both by direct and indirect strokes may threaten MV and LV distribution networks, including the insulation of the associated equipment. Due to economical reasons, the insulation of the equipment cannot withstand lightning overvoltages that may occur. Consequently, the equipment needs protection against these overvoltages.

An appropriate lightning protection of MV and LV networks should be achieved in order to reach the best compromise between the protection costs and the benefits resulting from the relevant mitigation of the following consequences of lightning:

1 Impact on power quality, with particular reference to:

- outages of lines and substations;
- impairment of relationship between utility and customers;
- interruptions of sensitive manufacturing processes which require high quality of the supply;
- serious losses in time and money to power users and utilities;
- extra costs for restoring the service and replacing the damaged equipment.
- etc.

2 Damage to equipment or considerable reduction of the residual life of power utilities equipment, with particular reference to:

- damage to the power equipment of the utility;
- damage to electronic equipment and loss of information;
- damage to the equipment of customers;
- considerable reduction of residual life of equipment.

The objective of lightning protection of electric power systems is to ensure, as far as possible, an uninterrupted and good quality supply of power to customers. Without lightning protection such as shielding and arresters, electric power systems would be prone to unacceptably frequent service outages and damaged equipment

This guide provides first a survey of different sources of overvoltages. In order to help the Distribution engineers to improve the lightning performance of MV and LV networks, a review of the most widely accepted and well established methods of evaluating:

- the expected rate of direct lightning strokes and induced lightning overvoltages in their networks;
- the characteristics of lightning overvoltages on the networks (amplitudes, shapes, slopes, etc), as a function of the lightning stroke position, and of the current amplitude and shape are given.

3. Life of Equipment, Residual Insulation Strength

Reliability of network equipment

The ultimate goal of lightning protection is to achieve more reliable networks. Reliability of network equipment is influenced by many factors such as:

- proper design of equipment;
- quality procedures during manufacturing;
- proper installation of equipment;
- proper maintenance procedures;
- proper operation practices;
- etc.

Increasing reliability of networks will reduce outages of lines and substations and improve power quality for customers.

Life of equipment

Although all efforts are generally made to have reliable network equipment, electrical equipment have a limited life because of ageing. When approaching the end of life of equipment, the probability of outages increases rapidly.

Dielectric diagnosis

To have a better knowledge on the residual life of equipment, condition monitoring of the equipment may be performed. One can perform a dielectric diagnosis on the equipment to establish the degree of deterioration of insulating material. These techniques are beyond the purpose of this guide.

Life extension

Despite accurate monitoring, end of life of equipment is inevitable. The remaining possibility to make further use of this equipment is to extend its life. Possible measures are refurbishment, improved operation and maintenance. Part of the content of this guide may be viewed as providing some elements useful in this respect.

4. Overvoltages

Any voltage between phase conductors having a peak value exceeding the corresponding peak of the highest voltage for equipment U_m is considered an overvoltage. U_m is the highest r.m.s. value of the phase-to-phase voltage for which the equipment is designed in respect of its insulation as well as other characteristics which relate to this voltage in the relevant equipment standards.

The magnitude of overvoltages phase-to-phase is usually expressed in p.u.'s (per unit):

$$1 \text{ p.u.} = \sqrt{2} \times U_m$$

The magnitude of phase-to-earth overvoltages is usually expressed in p.u.'s (per unit):

$$1 \text{ p.u.} = \sqrt{2} \times U_m / \sqrt{3}.$$

Overvoltages in power networks resulting from the effects of lightning strokes or switching actions cannot be avoided. Several types of overvoltages are distinguished, depending on their origin.

4.1 Temporary overvoltages

Temporary overvoltages are characterized by their amplitude, shape and duration. All parameters depend on the origin and amplitudes and shapes may even vary during the overvoltage duration. For insulation co-ordination purposes the voltage shape can be considered to be equal to that of the power frequency voltage. In MV and LV networks, temporary overvoltages pose no danger to the network operation, however they are decisive for dimensioning of arresters and other equipment.

4.1.1 Single-phase earth faults

The temporary overvoltage due to earth faults is a phase-to-earth overvoltage on the two healthy phases of a three-phase system. Temporary overvoltages between phases do not arise. The overvoltage shape is a power frequency voltage.

The amplitudes depend on the system neutral earthing and the fault location. In normal system configurations the representative overvoltage amplitude is recommended to be assumed equal to its maximum value. Abnormal system configurations, e.g. system parts with unearthed neutrals in a normally earthed neutral system, should be dealt with separately, taking into account their probability of occurrence simultaneously with earth faults.

The duration of the overvoltage is equal to the time between fault and fault clearing. In earthed neutral systems it is generally less than 1 s. In resonant earthed neutral systems with automatic fault clearing it is generally less than 10 s. In systems without automatic earth fault clearing the duration may be up to 8 hours, or more.

Note: Attention is drawn to the fact that the largest voltage at power frequency, which may appear on a sound phase during a particular earth fault, does not depend only on the value of the earth fault factor, but also on the value of the phase-to-phase voltage at the time of fault occurrence. This phase-to-phase voltage will generally be taken as the highest system voltage, but, in some cases, it may be necessary to take into account the increase value of the phase-to-phase voltage.

4.1.2 Load rejection

The temporary overvoltages due to load rejection depend on the rejected load, on the system layout after disconnection and on the characteristics of the sources (short-circuit power at the station, speed and voltage regulation of the generators, etc.).

This voltage rise may be especially important in the case of load rejection at the remote end of a long line (Ferranti effect). It affects mainly the apparatus at the station connected to the line on the source side of the remote open circuit-breaker. This effect is not usual in MV and LV networks.

Note: From the point of view of overvoltages, a distinction should be made between various types of system layouts. As extreme cases, systems with relatively short lines and high values of the short-circuit power at the terminal stations, where low overvoltages occur, and systems with long lines and low values of the short-circuit power at the generating site, which are usual in an extra-high voltage system in its initial stage and where very high overvoltages may arise when a large load is suddenly disconnected, may be considered.

The overvoltage is a symmetrical three-phase power-frequency voltage. Therefore, the same relative overvoltages (i.e. the same p.u.'s amplitudes) occur phase-to-earth and phase-to-phase. The representative amplitudes are recommended to be assumed as their maximum values. As a guidance the following values apply.

- System transformers

For a full load rejection the temporary overvoltage is usually below 1.2 times the system voltage in moderately extended systems. The duration depends on the voltage control operation and may last up to several minutes. In extended systems the overvoltages may reach 1.5 times the system voltage, or even more when Ferranti or resonance effects occur. Their duration may be in the order of some seconds.

- Generator transformers

For a full load rejection the overvoltage at the transformer may reach up to 1.5 times the system voltage. The duration depends on the generator control and may be up to 3 s.

4.1.3 Ferro-resonance

Switching transients have a limited duration due to damping caused by the network. Ferro-resonance is initially a switching transient that involves magnetic saturation and the interaction between those inductive elements and capacitances strongly reduces or prevents the damping. The result is a temporary overvoltage that may have a very long duration (e.g. hours). Precautions should be taken to prevent ferro-resonance but it cannot always be avoided since it may be very sensitive to variations in parameters that are difficult to predict.

4.1.4 Resonance

Temporary overvoltages due to resonance phenomenon can reach extremely large values and should be prevented. They should not be, therefore, considered as the basis for the surge arrester selection or for the insulation design of internal insulations.

4.1.5 Combinations of different temporary overvoltages

Temporary overvoltages of different origin should be combined only after careful examination of their probability of simultaneous occurrence. Such combinations lead to high arrester ratings with the consequence of high protection and insulation levels, which are technically and economically justified, only if their probability of occurrence is sufficiently high.

- Load rejection with earth fault

The combination "load rejection and earth fault" can exist, when a large load is switched off and the temporary overvoltage due to this causes a subsequent earth fault on the remaining system. The probability of such an event, however, is small, when the overvoltages due to the change of load are themselves small and a subsequent fault may only occur in extreme conditions as in heavy pollution.

The combination can also exist, when during a fault on the line, the load side breaker opens first and the disconnected load causes a load rejection overvoltage in the still faulted part of the system until the supply side circuit breaker opens.

The combination can further occur as a result of a line fault followed by failure of a circuit breaker to open. The probability of such a combination, although small, is not negligible since these are not statistically independent events. Such an occurrence, which results in a generator connected through a transformer to a faulted long line, can result in significant overvoltage on the healthy phases. The overvoltage consists of a slow-front transient and a prolonged variable temporary overvoltage which is a function of generator characteristics, and governor-voltage regulator response.

In any case the resulting overvoltage should not be obtained by multiplying the two overvoltage factors for the single events because:

- the earth fault factor changes, when it is related to the load rejection overvoltage;
- the system configuration has changed after the load change. For example, the earth fault factor at generator transformers with earthed neutral is less than 1 after being disconnected from the system;
- for system transformers the loss of full rated load is not usual.

If such combinations are considered sufficiently probable, accurate system studies are recommended, using, for instance, EMTP-type programs.

4.1.6 Surge arresters

It is normally not possible to limit temporary overvoltages by surge arresters since the long duration of the overvoltage would cause an unreasonably high energy stress on the arrester. The arrester must withstand the expected temporary overvoltages and its rated voltage must be selected accordingly. This implies that the temporary overvoltages determine in most cases the protection level of the arrester since it is approximately proportional to the rated voltage.

An exception is given for temporary overvoltages due to some ferro-resonance cases, for which surge arresters may be applied to limit or even to prevent such overvoltages. If such protection is planned, careful studies on the thermal stresses on the surge arrester should be performed to avoid their overloading.

4.2 Slow-front overvoltages

Slow-front overvoltages have front durations of some tens to some thousands of μs and tail durations in the same order of magnitude. They generally arise from

- line energization and re-energization
- faults and fault clearing
- load rejection
- switching of capacitive or inductive currents
- distant lightning strokes to the phase conductor of overhead lines.

The representative voltage shape is characterized by its time-to-crest. For insulation co-ordination purposes it is assumed to be equal to the standard time-to-crest of 250 μs , as the insulation of the equipment is not sensitive to a deviation from this value. The peak values of slow-front overvoltages are well below 4 p.u..

4.3 Fast-front overvoltages

4.3.1 Lightning overvoltages

Lightning overvoltages are caused either by direct strokes to the phase conductors, backflashovers, or as a result of strokes to earth very close to the line which produce induced lightning surges. Induced lightning surges generally cause overvoltage below 400 kV on the overhead line and are, therefore, of importance only for systems in the lower system voltage range. Lightning discharges which produce significant overvoltages in the higher ranges are confined to direct strokes to phase conductors or strokes to towers or earth wires with subsequent backflashovers.

Lightning overvoltages reach their peak value within a few μs and subsequently decay very rapidly. The magnitude of these overvoltages in MV and LV networks can reach well over 10 p.u.. The frequency of occurrence largely depends on the lightning ground flash density in the region, on the overhead line construction and, in substations, on the construction and operating configuration of the substation itself. Generally-valid stress parameters, therefore, cannot be established. Furthermore, in the lower voltage range, surges transferred through transformers need consideration, especially at high turn ratios or when rotating machines are connected.

4.3.2 Overvoltages due to switching operations

Fast-front switching overvoltages occur, when equipment is connected to or disconnected from the system via short connections mainly within substations.

Although in general oscillatory, for insulation co-ordination purposes the representative overvoltage shape can be considered to correspond to the standard lightning impulse (1.2/50). However, special attention should be paid to equipment with windings.

The representative overvoltage amplitudes depend on type and behavior of the switching equipment. As the overvoltage amplitudes due to switching operations are usually smaller than those caused by lightning, their importance is limited to special cases. It is, therefore, technically justified to characterize the representative overvoltage amplitude by the maximum values given below.

As simultaneous occurrence of fast-front switching overvoltages on more than one phase is highly improbable, phase-to-phase overvoltage occurrences are generally considered lower than phase-to-earth ones. For the latter the following assumed maximum amplitudes can be used to check the importance of such overvoltages.

- circuit breaker switching without restrike 2 p.u.
- circuit breaker switching with restrike 3 p.u.
- disconnector switching 3 p.u.

If they determine the insulation lightning impulse withstand voltage, more careful investigations are recommended:

Note: When switching reactive loads some types of circuit breakers tend to produce multiple transient current interruptions resulting in overvoltages up to 6 p.u. unless appropriate protection measures are taken.

4.4 Very-fast-front overvoltages

Very-fast-front overvoltages originate from disconnector operations of faults within GIS due to the fast breakdown of the gas gap and the nearly undamped surge propagation within the GIS. Their amplitudes are rapidly damped on leaving the GIS, e.g. at a bushing, and their front times are usually increased into the range of those of fast-front overvoltages. Very-fast-front overvoltages may also occur at medium voltage dry-type transformers with short connections to the switchgear.

The overvoltage shape is a fast increase of the voltage nearly to its amplitude resulting in a front time below 0.1 μ s. For disconnector operations this front is typically followed by an oscillation with frequencies above 1 MHz. The duration of very-fast-front overvoltages is less than 3 ms, but may occur several times. The overvoltage amplitude depends on the disconnector construction and on the substation configuration. Maximum amplitudes of 2.5 p.u. can be assumed to be achievable. The overvoltages may, however, create high local overvoltages in directly connected transformers. Due to faults within GIS the connected equipment (e.g. transformer) are stressed by overvoltages. The shape and the amplitude of the overvoltage depend on the kind of connection of the equipment to the GIS and the location of the fault within the GIS. The overvoltages have amplitudes up to 1.6 times the breakdown voltages and frequency content up to 20 MHz within the substation.

On terminals of equipment connected with a short HV-line to the GIS (open connection) the overvoltage oscillations show frequencies in the range 0.2 - 2.0 MHz and amplitudes up to 1.5 times the flashover voltage. In this case it will be possible to protect the equipment with surge arresters. In spite of this, the frequency content of the overvoltages can cause internal high stresses in transformer windings. Alternative protection methods proved by detailed studies may be necessary.

Note: Very-fast-front overvoltages are less dangerous in medium voltage systems, due to the comparatively high withstand voltage relative to system voltage.

4.5 Conclusion

Lightning overvoltages pose the greatest threat to MV and LV networks. Overvoltage protection must be arranged in such a way as to confine the overvoltage to non-damaging values. The object of this guide is lightning overvoltage protection. Temporary overvoltages are decisive for the sizing of arresters and thus their protection level.

5. Description of Lightning Discharge Phenomena

5.1 Generalities and categorization of lightning discharges [1-3]

Lightning is a transient, high-current electric discharge whose path length is measured in kilometers. The source of lightning is the electric charge separation in thunderstorm clouds. Over half of all lightning discharges occur within the thunderstorm cloud and are called *intracloud discharges*. The usual *cloud-to-ground lightning* has been studied more extensively than other lightning forms because of its practical interest (e.g., particularly as disturbances in power and communication systems) and also, because electrical and optical measurements are much easier to perform.

Cloud-to-ground lightning has been categorized by Berger [3] in terms of the direction of development and the sign of charge of the leader that initiates the discharge (see Fig. 1). Category 1, the so-called negative cloud-to-ground lightning, is the most common cloud-to-ground lightning; it accounts for over 90% of the world-wide cloud-to-ground flashes. It is initiated by a downward leader lowering negative charge to earth.

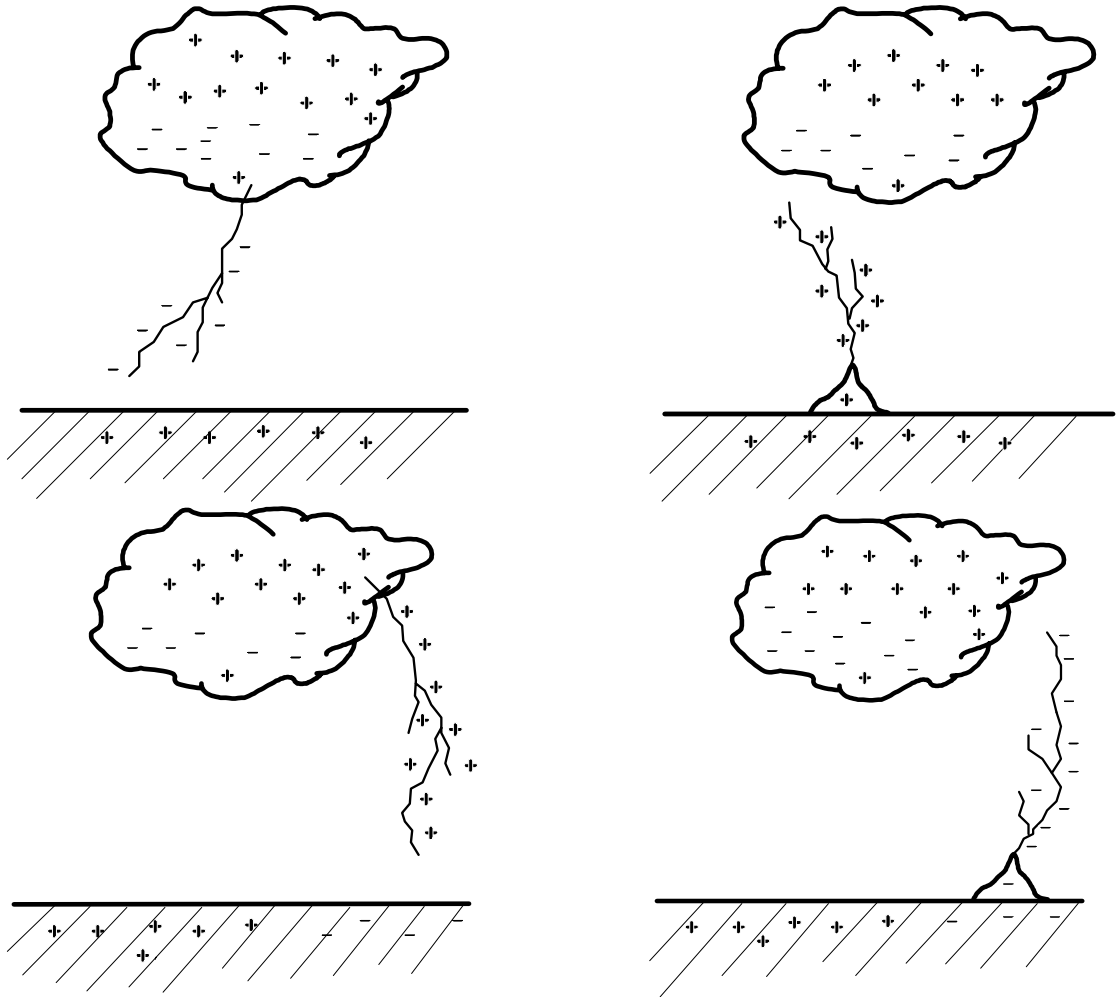


Fig. 1 - Cloud-to-ground lightning categorization according to Berger. Top left: downward negative; top right: upward positive; bottom left: downward positive; bottom right: upward negative. (Adapted from [3]).

5.2 Negative lightning return strokes: experimental observations

A description of the negative cloud-to-ground lightning flashes is given in Annex 1. In this section, we will give a brief overview experimental data on lightning current and electromagnetic fields, relevant to protection purposes.

Return stroke current. Channel-base current measurements have been performed by means of instrumented towers in some countries (e.g. Austria, Brazil, Canada, former Czechoslovakia, Germany, Japan, Italy, Russia, South Africa, Switzerland), and statistical elaboration of lightning current data has been presented in [3, 4] (see [5, 6] for a list of references). In Fig. 2, typical channel-base current wave shapes for negative first and subsequent return strokes, as reported by Berger et al. [3], are shown. The statistics of lightning current parameters which are most significant for the evaluation of overvoltages (peak value and front steepness) are shown in Table 1*

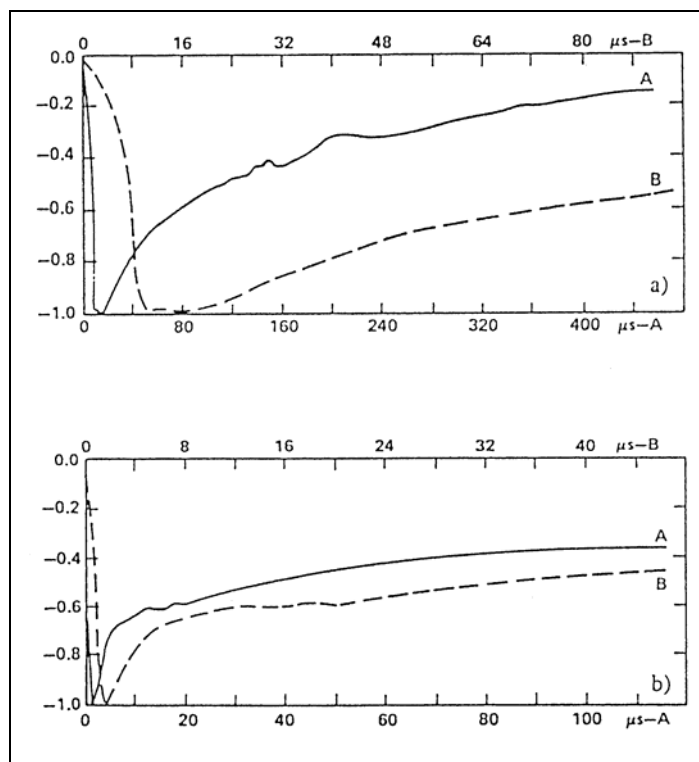


Fig. 2 - Typical normalized negative return-stroke current waveshapes: (a) First return stroke, (b) Subsequent return stroke (Adapted from [3]).

* Concerning the values of the statistical parameters reported in Table 1, it is worth observing that statistical distributions of the lightning current parameters inferred from experimental data recorded by means of tall instrumented towers are affected by the presence of the tower. Lightning current amplitudes, in particular, are 'biased' towards higher values, as the tower ability to attract lightning flashes tends to increase for flashes with larger currents. Methods to obtain the statistical distributions of lightning current parameters at ground level starting from those above mentioned have been proposed in the literature (e.g. [2], [7]). The issue is of particular concern for distribution lines, for which indirect lightning is of major importance. It is worth observing also, that the statistical distributions of current parameters are presumably affected by current reflections at both bottom and top of the instrumented tower. In principle, these reflections might alter both the front steepness and peak value of the current, depending on several factors, e.g. tower height, current wave shape and value of the reflection coefficients. To elaborate meaningful statistics on lightning current parameters, one should 'decontaminate' the measured currents also from this 'current-reflection effect' (see e.g. [8]).

Table 1 - Lightning current parameters for downward flashes. (Adapted from [3])

Parameter	Units	Sample size	Percent Exceeding Tabulated Value		
			95%	50%	5%
Peak current (minimum 2 kA)					
Negative first strokes	kA	101	14	30	80
Negative subsequent strokes	kA	135	4.6	12	30
Positive first strokes	kA	26	4.6	35	250
Charge (total charge)					
Negative first strokes	C	93	1.1	5.2	24
Negative subsequent strokes	C	122	0.2	1.4	11
Complete negative flash	C	94	1.3	7.5	40
Impulse charge					
Negative first strokes	C	90	1.1	4.5	20
Negative subsequent strokes	C	117	0.22	0.95	4.0
Positive first strokes	C	25	2.0	16	150
Front duration (2 kA to peak)					
Negative first strokes	μsec	89	1.8	5.5	18
Negative subsequent strokes	μsec	118	0.22	1.1	4.5
Positive first strokes	μsec	19	3.5	22	200
Maximum di/dt					
Negative first strokes	kA/μsec	92	5.5	12	32
Negative subsequent strokes	kA/μsec	122	12	40	120
Positive first strokes	kA/μsec	21	0.20	2.4	32
Stroke duration (2 kA to half-value)					
Negative first strokes	μsec	90	30	75	200
Negative subsequent strokes	μsec	115	6.5	32	140
Positive first strokes	μsec	16	25	230	2000
Integral ($i^2 dt$)					
Negative first strokes	A ² sec	91	6.0×10^3	5.5×10^4	5.5×10^5
Negative subsequent strokes	A ² sec	88	5.5×10^2	6.0×10^3	5.2×10^4
Positive first strokes	A ² sec	26	2.5×10^4	6.5×10^3	1.5×10^7
Time interval					
Between negative strokes	msec	133	7	33	150
Flash duration					
Negative (including single stroke flashes)	msec	94	0.15	13	1100
Negative (excluding single stroke flashes)	msec	39	31	180	900
Positive (only single flashes)	msec	24	14	85	500

An analytical expression often used to approximate lightning currents has been proposed by Heidler [9]

$$i(t) = \frac{I_0}{\eta} \frac{(t/\tau_1)^n}{1 + (t/\tau_1)^n} \exp(-t/\tau_2) \quad (1)$$

where

$$\eta = \exp \left[- \left(\frac{\tau_1}{\tau_2} \right) \left(n \frac{\tau_2}{\tau_1} \right)^{1/n} \right] \quad (2)$$

and

I_0 is the amplitude of the channel-base current

τ_1 is the front-time constant

τ_2 is the decay-time constant

η is the amplitude correction factor

n is an exponent *

This function is preferred to a double-exponential function since it exhibits, as opposed to the double-exponential function, a time-derivative equal to zero at $t=0$, consistent with measured return-stroke current wave shapes. Additionally, it allows for the adjustment of the current amplitude, maximum current derivative and charge transferred nearly independently by varying I_0 , τ_1 and τ_2 respectively.

Lightning electromagnetic fields. Typical features of electromagnetic fields of importance for the appropriate selection of the model for calculating lightning-induced voltages and for the understanding and prediction of the induced voltages waveshapes are reported in Annex 2.

Return stroke velocity. The return-stroke velocity can be an important factor in determining the radiated fields and, therefore, the induced overvoltages. The return-stroke velocity has been measured by various researchers in the past years. Mach and Rust [10] have reported two-dimensional return-stroke velocities from 88 natural strokes; the velocity measurements are divided into two groups: 'short channel' values with channel segments starting near the ground and 'long channel' values which start near the ground and exceed 500 m in length. Table 2 summarizes the values reported by [10].

Table 2 - Return-stroke velocities reported in [10] for "short-channel" and "long-channel" in negative strokes.

Type of channel	Return stroke velocity (m/s)		
	Natural first (average)	Natural Subsequent (average)	Triggered subsequent (average)
Short-channel	1.7×10^8	1.9×10^8	1.4×10^8
Standard deviation	0.7×10^8	0.7×10^8	0.4×10^8
(Number of samples)	(25)	(43)	(39)
Long-channel	1.2×10^8	1.3×10^8	1.2×10^8
Standard deviation	0.6×10^8	0.5×10^8	0.2×10^8
(Number of samples)	(25)	(54)	(40)

* It is recommended the use of $n=2$.

6. Lightning Overvoltage Generation

6.1 Lightning performance of MV and LV lines

The lightning overvoltages in MV and LV networks can be classified in two categories :

- Overvoltages due to direct lightning

Due to the relatively low levels of insulation in MV and LV networks, a lightning stroke to the phase conductor, to the neutral conductor or to the support structure causes in general insulation flashover on the line. However, the presence of surge arresters may prevent surge flashover.

- Overvoltages due to indirect lightning (induced overvoltages)

Indirect lightning, that is lightning strokes to the ground or to structures in the vicinity of a line, induces on the line overvoltages that can be larger than the insulation levels. Unlike direct strokes, the presence of neutral conductors, suspension wires etc., can have a great influence on the resulting induced lightning overvoltage amplitudes.

From the point of view of the overvoltage parameters that are important for lightning protection (e.g. amplitude, steepness, energy, etc.), direct lightning overvoltages and induced overvoltages are quite different. It is thus important to know how many events of each type are expected to affect a distribution line. The number of the expected events for each type of lightning strokes, significantly depends on the exposure of the line and on its screening by nearby objects.

When the lightning leader approaches ground, it continues its downward motion unperturbed unless critical field conditions develop so that it initiates an attachment with a nearby grounded conductor, called final jump. By assuming the leader channel perpendicular to the ground plane, it is generally accepted that the flash will strike the object if its prospective ground termination point, i.e. its strike location in absence of the object, lies within the attractive radius r . The attractive radius depends on several factors, such as the charge of the leader, its distance from the structure, the type of the structure (vertical mast or horizontal conductor), its height, the nature of the terrain (flat or hilly) and the ambient ground field due to cloud charges. Several expressions have been proposed to evaluate such a radius. Some of them are based on the electrogeometric model (e.g. [11-13]):

$$r = \sqrt{r_s^2 - (r_g - h)^2} \quad \text{for } h < r_g \quad (3a)$$

$$r = r_s \quad \text{for } h \geq r_g \quad (3b)$$

where r_s and r_g are the so-called striking distances to the structure and to the ground respectively, and where h is the height of the structure. The striking distance is related to lightning current peak I_p by means of the following expressions

$$r_s = \alpha \cdot I_p^\beta \quad r_g = k \cdot r_s \quad (4)$$

where the values of α , β and k are independent of I_p .

Other more complex and physically oriented models than the electrogeometric one have been proposed [14-17]. From such models, simple expressions of the following type have been inferred, relating the attractive radius r and the lightning current peak I_p .

$$r = c + a \cdot I_p^b \quad (5)$$

where the values of a , b and c are independent of I_p .

Tables 3 and 4 gives the values of the parameters of the models mentioned above.

Table 3 - Constants of striking distance equation (4):
values proposed by different authors

Striking distance model	α	β	K
1. Armstrong and Whitehead [12]	6.7	0.80	0.9
2. Adopted by IEEE Std. 1243 [18]	10	0.65	0.55 *
3. Adapted from Golde [11, 19]	3.3	0.78	1

* for an average conductor height larger than 40 m.

Table 4 - Constants of attractive radius equation (5):
values inferred from the models by different authors

Attractive radius model	c	a	b
4. Eriksson [14]	0	$0.84 h^{0.6}$	$0.7 h^{0.02}$
5. From Rizk [7, 20]	0	$4.27 h^{0.41}$	0.55
6. From Delleria and Garbagnati [16]	$3 h^{0.6}$	0.028 h	1

Model 2 (in Table 3) is an approximation of the formula by Love [13] using the exponential format [21], adopted by IEEE Std. 1243 [18]. Model 3 (in Table 3) is an approximation of the formula by Golde [11], proposed in [22]

The values of model 4 (Table 4, derived from the Eriksson model) are those given in [14] for masts with heights up to 100 m. As described in [7], the values relevant to model 5 (Table 4) have been inferred from the results given by Rizk in [20], which refers to the case of towers on flat terrain disregarding the ambient ground field. Concerning model 6, the values reported in Table 4 have been derived by Bernardi [23], by interpolation of plots of the lateral distance of a slim structure vs. its height (in the range 5 to 100 m), calculated using the leader progression model of Delleria-Garbagnati [16, 17].

6.1.1 Expected number of direct lightning

The expected number N_d of direct strokes per year, per 100 km, to a distribution line on a flat ground can be evaluated by means of the following formula [24], which is based on the leader progression model by Delleria and Garbagnati [16]

$$N_d = K_0 \cdot N_g \cdot (b + 10,5 \cdot H^{0.75}) / 10 \quad (6)$$

where :

- N_g is the ground flash density (number of flashes per square km per year)
- H is the average height of the line in meters
- b is the horizontal distance between the outer conductors in meters
- K_0 is the orographic coefficient

Figure 3 gives the coefficient K_o as a function of the orographic parameters defined in figure 4.

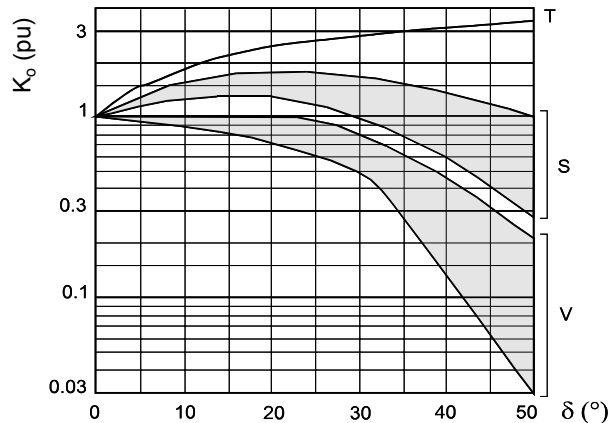


Fig. 3 - Direct strokes to a MV line. Orography correction coefficient K_o , as a function of the orography parameters defined in figure 4.

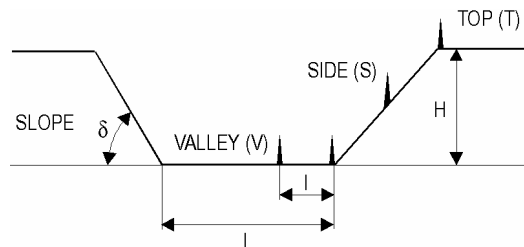


Fig. 4 - Parameters used for the evaluation of the influence of orography on the expected number of direct strokes to a MV line.

If the orographic condition is not known, $K_o = 1.8$ is suggested. This gives results in line with the CIGRE formula* developed for transmission lines [25]. As an example for a line with $H = 10$ m and $b = 2$ m in an area with $N_g = 1/\text{km}^2/\text{yr}$ and $K_o = 1.8$, the expected number of direct strokes is $N_d = 11$ per year, per 100 km.

6.1.2 Expected number of induced lightning overvoltages larger than a given value

Let us consider an equivalent single-conductor distribution line. The expected annual number of induced lightning overvoltages larger than a given value (e.g referred to a 100 km line length) gives an average indication of the indirect lightning performance. The calculation should be performed by a statistical approach. For example, by using a Monte Carlo approach, an adequate number of lightning events is generated, each characterized at least by the following random variables: the peak value of the lightning current I_p , its time to peak t_f and the position of the strike location with respect to the distribution line† [26]. For the lightning parameter values, the relevant statistical probability distributions are used, while the strike locations are considered to be uniformly distributed around the line. Other variables may be added to take into account the effects of specific line characteristics, e.g. the instantaneous value of the industrial frequency voltage, in order to simulate the surge arrester performance [27]. If the distance of the stroke location from the line is beyond the so called lateral distance d_l (see section 6.1) the event is considered an indirect flash and the maximum amplitude of the induced voltages is computed (see Section 6.3), otherwise it is considered a direct flash.

* $N_d = N_g (b + 28 \cdot H^{0.6})/10$ (line in average orographic conditions)

† When the ground is not perfectly conducting (finite conductivity), the maximum induced voltage does not necessarily occur at the point closest to the stroke location. It is therefore more suitable for the analysis to consider a matched line of finite length within an indirect stroke location area wide enough to include all the lightning events that can induce a voltage that causes an insulation flashover. Typically, for a 1-2 km long line the indirect stroke area is in the range of 4-8 km^2 . For the same reason, the induced voltages should, in general, be calculated all along the line and not only at the point of the line closest to the strike location.

The evaluation of the lightning performance of distribution systems is greatly affected by the accurate modeling of the lightning induction mechanism. For example, Fig. 5 shows the comparison between the results presented in the *IEEE Std 1410* [28], obtained by using a procedure that uses the simplified analytical formula proposed by *Rusck* [29] for the evaluation of the induced voltages, with those obtained by using the procedure described in [26, 27] that applies a more accurate model for the lightning induction mechanism, namely the LIOV (Lightning induced overvoltage) computer code*. In both cases the same expression for the lateral distance, line characteristics of the line conductor and lightning current amplitude probabilistic distribution are adopted, along with the same annual ground flash density, and it is assumed that overvoltages cause flashover when exceed a value of $1.5 \cdot \text{CFO}$ (the 1.5 factor is an approximation that accounts for the turn up in the insulation volt-time curve).

The *Rusck* formula has been derived from a more complete model of the lightning induction mechanism for very specific conditions: namely, a step waveshape of the lightning current at the channel base is assumed, the single conductor line is of infinite length, and the conductivity of the ground is infinite. The two methods predict, indeed, basically the same results when setting as inputs of the LIOV program a value of lightning current parameter t_f lower than $1 \mu\text{s}$, independently of the amplitude I_p , an infinite value for the ground conductivity and, a sufficiently large value for the line length (e.g. equal or greater than 1 km). However, Fig. 5 shows that the results significantly differ, when also the t_f lightning current parameter is considered as a random variable, taking also into account the correlation coefficient between I_p and t_f probability distributions. The results obtained by using the procedure described in [26, 27] for the case of a low ground conductivity are also presented, which show that the resistivity of the ground significantly worsens the indirect-lightning performance of the overhead line.

* The LIOV code has been developed in the framework of an international collaboration involving the University of Bologna (Department of Electrical Engineering), the Swiss Federal Institute of Technology (Power Systems Laboratory), and the University of Rome "La Sapienza" (Department of Electrical Engineering). The code is based on the field-to-transmission line coupling formulation of *Agrawal et al.* suitably adapted for the case of an overhead line illuminated by an indirect lightning electromagnetic field; the return stroke electromagnetic field is calculated by assuming the MTL engineering model by *Nucci et al.* and using the *Cooray-Rubinstein* formula for the case of lossy grounds (See Annex 3 for a brief description of the mentioned models),.

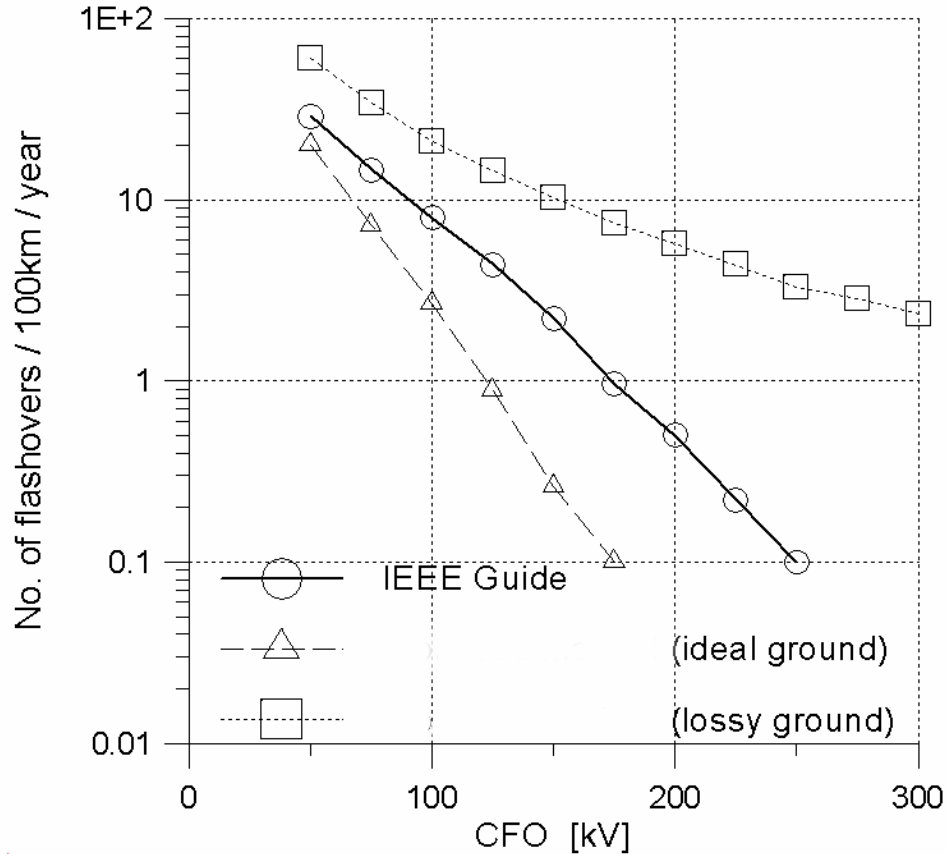


Fig. 5 - Comparison between the lightning performances of a single-conductor 10-m high distribution line evaluated by using the IEEE Std 1410 Guide procedure (solid curve) and the method proposed in [26] for two different values of ground conductivity (infinite: triangles-dashed curve, and 0.001 S/m: squares-dashed curve). I_p and t_f are lognormally distributed as proposed in [4]. The assumed annual ground flash density is 1flash/km²/year. (Figure adapted from [27]).

6.1.3 Shielding by nearby objects

Usually MV lines share, either totally or partially, the right-of-way with LV lines and even with telecommunication lines; these latter are provided with conductors that are frequently grounded (neutral conductor, suspension conductors, etc.). The coupling with these circuits, frequently not anticipated at the design stage, has a profound influence on the overvoltages induced on the line. The shielding by nearby objects having a similar height as that of the line (trees, buildings, other power lines, etc.) may be very effective in reducing the incidence of direct strikes; however, it may increase the number of induced overvoltages. Shielding by nearby objects is more usual in LV overhead lines, which generally cross areas with buildings and are often strung between buildings or even suspended along the walls of buildings.

Hereafter, the shielding effect of nearby objects is considered only by the point of view of the expected number of direct strikes. Other aspects, such as the influence on the amplitude and shape of lightning induced overvoltages and on the quality of supply are discussed in Part 2.

Quantitative evaluations of the shielding effect by structures parallel to a line can be found in [30] and [31]. These evaluations assume that a uniform row of objects of the same height is parallel to the line. The shielding effect is taken into consideration by means of a shielding factor S_f that allows to evaluate the number of direct strikes to a shielded line, N_d^s , by means of the following formula:

$$N_d^s = N_d \cdot (1 - S_f) \quad (7)$$

where N_d is evaluated through formula (4) and S_f varies between 0 and 1 (where 1 corresponds to a perfect shielding). IEC [32] gives the environmental coefficient C_e through which S_f can be evaluated ($C_e=1-S_f$).

Generally, the shielding effect of a single object on the lightning performance of the line may be disregarded while it may become important in case of lines in forested areas or parallel to other power lines. As an example, for a 10-m high line at a constant distance of 20 m from a forest where the trees are 20 m high on average, the shielding factor is evaluated as 0.75 and 0.5 by the two references [30] and [31] respectively. These values are in accordance with the environmental coefficient C_e given by [31].

6.2 Overvoltages due to direct lightning

6.2.1 Medium voltage lines

A lightning striking a phase conductor injects current waves in both directions. The corresponding voltage equals half of the current multiplied by the line characteristic impedance, which is about 400 Ω . Since more than 90% of the strokes have a peak current of at least 10 kA, the overvoltage will exceed 2000 kV for 90% of the strokes. These voltages are far above the lightning withstand voltage of the line. For this reason flashover(s) between phases and between phase and earth will normally occur.

A direct strike does not usually cause any permanent damage to a line with bare conductors if the duration of the short-circuit current is limited by a short-circuit protection device. No additional lightning protection is thus needed for the line itself.

The short-circuit (due to the insulator flashover caused by the induced voltages whose amplitude exceeds the critical flashover voltage of the line) and the subsequent fault clearance are associated with (short) voltage interruptions at the flashover location and with voltage dips at the buses of the network around it. The frequency of occurrence of these voltage disturbances is close to the frequency of occurrence of the direct strikes to the line conductors.

Lines with covered conductors represent a special problem with respect to direct lightning. A flashover between phases for such lines may cause a mechanical breakdown of the conductors. This is due to the coating which prevents the footpoint of the power frequency arcing current from moving along the line.

Special precautions should therefore be taken to limit the risk of flashover between phases for lines with covered conductors exposed to lightning. The application of arresters or spark gaps along the line is analyzed in [33]. An efficient protection requires a short distance between the protective devices (e.g. applying the devices at every pole along the line).

Components like transformers and cables are permanently damaged if they are exposed to overvoltages which cause insulation breakdown, unless protected by surge arresters. It is therefore important to analyze the lightning overvoltages at the location where an apparatus is connected.

The surge propagating from the point of strike along the line is altered by flashovers, if any, occurring between the strike location and the point of interest. Practically, all flashovers to ground occur at the poles. A flashover at a pole reduces the amplitude of the voltage wave which propagates further. If the voltage wave still exceeds the flashover voltage, new flashover will occur at the next poles further reducing the overvoltage.

Figure 6 shows, as an example, a typical overvoltage (evaluated by calculations) due to a direct lightning strike. The calculations have been performed for a single-wire line with no ground wires. The line is composed of eight spans (9 poles) of 200 m length each with a characteristic impedance of 440 Ω . Each pole, 8-m high, is modeled as a transmission line with a characteristic impedance of 300 Ω . The footing resistance was assumed to be nonlinear (current-dependent), with 30 Ω at zero current. The insulator flashover voltage was fixed at 150 kV.

The example shows the general characteristics of the direct lightning overvoltage which presents a few very short spikes, followed by an impulse voltage with a smoother shape.

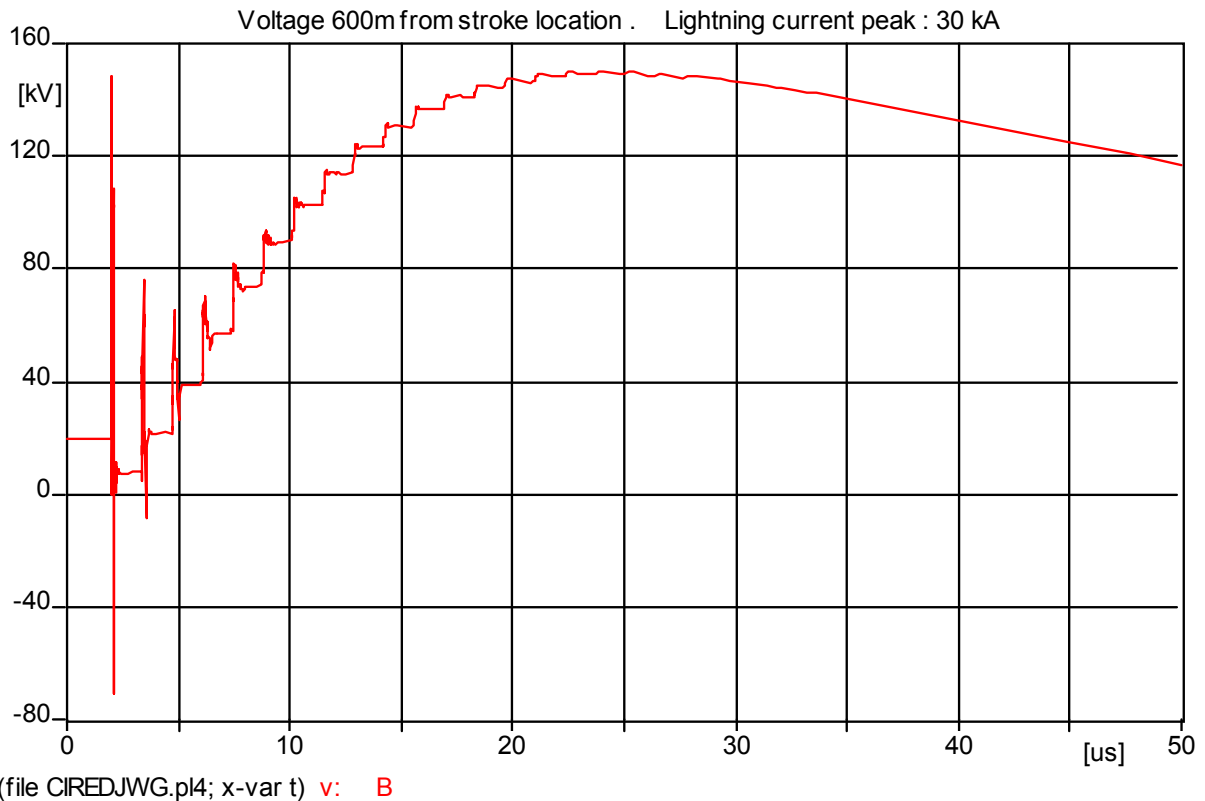


Fig. 6 - Example of a typical lightning overvoltage due to a direct strike to the MV line.

The voltage at the flashover location equals the voltage between the cross-arms and remote earth. This voltage may be higher than the flashover voltage and this causes a flashover at the next pole as the voltage wave propagates along the line.

The first spikes are very steep and are chopped due to line insulation breakdown at the first pole which the current wave meets, as well as at the following poles. The peak values of these spikes may exceed the lightning impulse withstand voltage of the line insulation due to the behaviour of air insulation at very steep front overvoltages.

The smoother impulse voltage has a shape that is similar to that of the lightning current. Its amplitude is approximately equal to the lightning impulse withstand voltage of the line insulation. For this reason it is not chopped.

Figure 6 applies to a line with earthed cross arms. The flashover voltage to ground is much larger (in the order of 2000 kV) for lines with wooden poles and no earthing of the cross arms. This implies that the initial part of the voltage in figure 6 becomes much larger for such lines.

As it may be seen from the example, the lightning overvoltage occurring at some distance from the point of strike is in general strongly dependent on the flashover voltage to earth at the poles. Other important parameters are the number of poles between the strike location and the point of interest and the grounding impedance of the poles where flashover occurs.

Furthermore the following aspects are significant:

- More flashovers occur with large lightning currents. The corresponding increase of the overvoltage at some distance from the strike location is, therefore, less than proportional to the increase of the amplitude of the current.

- The steepness of direct lightning overvoltages ranges from 100 to 2000 kV/μs.
- The lightning overvoltages propagate as traveling waves along the lines. These waves are modified due to reflections which occur at any point where the characteristic impedance is modified. Due to these reflections the shape and the amplitude of overvoltages may be significantly different from the shape shown in figure 6.
- The resulting overvoltage amplitudes are also reduced by the impulse corona effect, as they propagate along the line.

The lightning overvoltage may further be modified (limited) by surge protective devices.

6.2.2 Low voltage lines

In overhead low voltage lines the process of overvoltage propagation is somehow different from that in MV lines. More specifically, neutral conductors are often present, which may be connected to earth at regular intervals. Furthermore, the lightning impulse withstand voltage between phases and between phases and neutral are much lower than that for MV lines.

For these reasons, the phase conductors and the neutral conductors are rapidly short-circuited, so the overvoltage is dominated by the number and impedance of the earth connections. Disregarding propagation effects, the perspective overvoltage is approximately equal to the lightning current multiplied by the total impedance to ground. This means that the amplitude of overvoltages due to direct lightning is proportionally smaller in LV lines in comparison with those in MV lines.

The probability of direct lightning strikes to LV lines is generally much lower than that for MV lines due to limited extension of LV lines and to screening by houses, trees, etc.

Despite the reduced amplitude of the overvoltages in LV networks, these overvoltages are much larger than the lightning withstand voltage of the apparatus connected to the line (a few kilovolts for domestic appliances), thus many flashovers harmful for the apparatus connected to the line may occur.

Direct lightning to structures causes ground potential rise and this generally leads to a flashover between the structure and the LV supply system. This will result in overvoltages in LV system of the same nature as those caused by a direct strike to the line.

6.3 Lightning-induced overvoltages

A cloud-to-ground lightning flash generates a transient electromagnetic field which can induce overvoltages of significant magnitudes on overhead power lines situated in the vicinity. The return stroke phase of the lightning discharge is considered to be the major responsible for the induced voltages, because the most intense electromagnetic radiation occurs during this phase. To analyze direct lightning strikes to a line, the lightning channel is generally represented by an equivalent current source injecting the return stroke current to the line at the attachment point. In the case of an indirect lightning strike, however, the analysis is more complex and the calculation of lightning-induced voltages requires the following stages:

- a return-stroke model which specifies the spatial and temporal distribution of the lightning current along the channel during the return-stroke phase is adopted;
- then, the electromagnetic field change produced by such a current distribution, ideally including propagation effects on the field, is calculated along the line, and finally,
- induced voltages resulting from the electromagnetic interaction between the field and the line conductors are obtained by using a field-to-transmission line coupling model.

As opposed to simple analytical formulas (such as the popular formula by Rusck [29]), which are restricted to unrealistic simple configurations, more elaborate models (e.g. [5, 6, 34-36]) allow for an accurate treatment of realistic line configurations. Moreover, the presence of distribution transformers, of surge protection devices at the line terminations, as well as the presence of surge arresters and shielding wire groundings along the line, should be taken into account.

The complexity of these models calls for an implementation into computer codes since, in general, they require a numerical integration of the relevant equations. Annex 3 presents a summary of return

stroke models and field-to-transmission line coupling models and a sensitivity analysis of lightning-induced overvoltages as a function of different parameters. The computed results are obtained by using the LIOV computer code [34-37], developed in the framework of an international collaboration involving the University of Bologna (Department of Electrical Engineering), the Swiss Federal Institute of Technology (Power Systems Laboratory), and the University of Rome "La Sapienza" (Department of Electrical Engineering).

7. Characteristics of Surge Protective Devices

7.1 Definitions

According to IEC* a Surge Protective Device (SPD) is a device that is intended to limit transient overvoltages and divert surge currents. It contains at least one nonlinear component. It can be used for the protection of alternating current power circuits at different voltage levels and also for the protection of equipment or telecommunication circuits.

When reference is made to MV networks ($U_n > 1$ kV) the name **Surge Arresters** or **Lightning Arresters**† is generally preferred to that of **Surge Protective Device** which usually deals with low voltage protections.

The following definition is given by IEC 99-1 for Surge Arrester: "A device designed to protect electrical apparatus from high transient voltage and to limit the duration and frequently the amplitude of follow-current."

Note - Surge arresters are usually connected between the electrical conductors of a network and earth

although they may sometimes be connected across the windings of apparatus or between electrical conductors".

As there is no fundamental distinction between both definitions (SPD and Surge Arrester) we will use in the following the most general concept of SPD for all what concerns the common working mechanisms. For low voltage application a distinction is sometimes made between One-Port SPD and Two-Port SPD. Both devices have protective components connected in shunt with the circuit to be protected and both devices may have separate input and output terminals; however in a two-port SPD a specific series impedance is inserted between these terminals. This means practically that a Two-Port SPD is nothing other than two one-Port SPDs installed in the same case in coordination with each other.

In this situation the first SPD has a high energy handling capability and mainly the part of diverting the surge current, while the second SPD, with a faster time response than the first one and a lower energy handling capability, has the part of limiting the amplitude of transient overvoltage.

When both devices are not installed in the same case the first one is sometimes called "**(Lightning) Arrester**" and the second one "**Overvoltage Arrester**" or "**Suppressor**" in order to highlight their specific functionalities and capabilities.

Such a distinction is also made by IEC according to the type of tests to be applied on the SPDs. In this sense most "**Arresters**" will be "**type I**" components and most "**Suppressors**" will be "**type II**" components.

7.2 Operating mechanisms

Basically two kinds of components can be considered in order to classify the different existing devices:

- a) *Voltage switching components*
- b) *Voltage limiting components*

Voltage switching SPDs are components that have a very high impedance when no surge is present, but that have a sudden change in impedance to a low value in response to a voltage surge.

* SC37A/31/CDV

† Or even "Surge diverter" in some countries

Common examples are: spark gaps, gas tubes, thyristors (S.C.R.s), triacs, breakover diodes.

Voltage limiting SPDs are components that have a quite high impedance when no surge is present, but will reduce it continuously with increased surge current and voltage. Common examples are: non linear resistors such as varistors (VDRs) and suppressor diodes (avalanche diodes, zener diodes).

The main advantage of voltage switching devices is their relative high current handling capability compared to voltage limiting SPDs; their main drawback, however, is the state of quasi short-circuit which is created in operating mode and which frequently involves a high follow current in power systems.

Some devices are (series or shunt) combination of voltage switching components and voltage limiting components. The most classical example is that of the “non linear resistor type gapped surge arresters” used in some AC systems. It concerns arresters having a single or a multiple spark-gap connected in series with one or more non linear resistors.

7.3 SPD Classification

7.3.1 (Air) spark gap arresters (sga)

A spark gap arrester is nothing other than a set of two (or three) spaced electrodes having between each other an intentional air gap. Such a device operates on the gas-physical principle of the arcs discharge and acts as a voltage-dependent switch.

As soon as the voltage applied to the SGA exceeds the spark-over voltage (some kilovolts per mm depending on the shape of the electrodes, the pressure and the humidity), an arc is formed and the voltage collapses to some tens of volts.

When the discharge has died down the SGA extinguishes and the internal resistance immediately returns to a very high value (several 100 M Ω)

Thanks to the low value of the arc voltages the surge current handling capability is very high (low energy dissipation).

On the other hand the very high impedance (as well resistive as capacitive) of the device in normal conditions combines with its high robustness and low cost has made this type of arrester very popular for the protection of MV networks.

Unfortunately the existence of a follow current constitutes a severe drawback limiting the use of this kind of component (at least in MV networks). Indeed, after the passage of the discharge current, if the spark gap is installed on a power source, the arc will not be extinguished and a power fault will occur. For that reason, and taking into account the existence of other components with better performance (metal oxide varistors), spark gaps are to a large extent replaced by metal oxide varistors in new MV installations.

7.3.2 Gas arresters

Gas arresters are components based on the same principle as spark gaps but using a hermetically sealed envelope filled with a special gas enabling a better control of the spark-over voltage.

Depending on the spacing of the electrodes, their shape and coating, the type of gas and its pressure, DC spark overvoltages ranging from a few tens of Volts up to several kVolts can be achieved.

The operating mode of a gas arrester can be compared with a symmetrical switch of low capacitance. The resistance may jump from $> 10 \text{ G}\Omega$ during normal operation to values lower than $0,1 \Omega$ after ignition due to surge voltage.

At that time, the voltage drops to the glow voltage level (about 100 V) if the current is limited to a few hundreds of mA. With a further increase in current, an arc mode occurs with an arc voltage of typically 10 to 20 V which is virtually independent of the current.

With decreasing overvoltage, the current decreases accordingly until it drops below the minimum value (type-dependent from some 10 mA to some 100 mA) necessary to maintain the arc mode.

The arrester returns then automatically to its original high-impedance state after the influence has died down.

Figure 7 shows the voltage behavior and the current versus time when limiting a sinusoidal overvoltage.

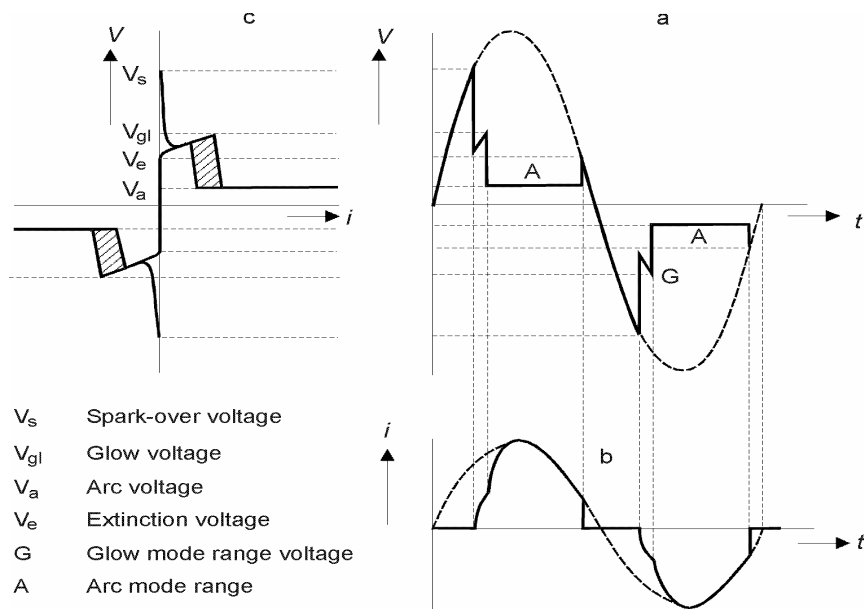


Fig. 7 - U/I characteristics and U/t behaviour of gas arresters (Courtesy Siemens).

One important feature of gas arresters is their dynamic behaviour when subject to voltage waves with high steepness. Above a steepness of about $1 \text{ V}/\mu\text{s}$ the spark overvoltage starts to increase as a consequence of the time necessary for ionization of the gas.

Typical impulse spark-over voltages range from 500 to 1000 V at $1 \text{ kV}/\mu\text{s}$; they are relatively independent of the static threshold.

7.3.3 Special technology gaps

New technologies involving the use of insulation material between the electrodes or allowing the arc due to the follow current to be automatically blown (Slide discharge arrester, Spark creepage gap, Arc chopping ...) have been developed during the last decade or so. Those new devices have usually a very high energy handling capability without presenting the same drawbacks as gas arresters (follow current).

However their protection level is generally quite high; hence they can only be used as lightning arresters.

7.3.4 Varistors

A varistor or Voltage Dependent Resistor (VDR) is a non linear resistor of which the resistance depends on the applied voltage. The value decreases with increasing voltage, thus "short-circuiting" a further rise in overvoltage. The U/I characteristics of a varistor can be approached by an exponential function

$$I = K V^{\alpha} U \quad (8)$$

where K is a constant depending on the geometry and α is the exponent of non linearity depending on the material (and partially on the current)

The higher the value of α , the better the performance of the varistor. Two types of varistors are in use:

- silicon carbide (SiC)
- metal-oxide (MOV)

Silicon Carbide

SiC varistors are the most ancient components. They are constructed from SiC crystals which are ground into powder form and then are mixed and pressed together with insulating material, forming a block. In this way a SiC particle partially touches other particles and partially is insulated by the insulating material. The nonlinear characteristics are due to the resistance vs temperature properties of the junction between the SiC crystals. Due to the relative low value of α ($\alpha < 5$), SiC varistors can seldom be used alone in power circuits because the leakage current involved is too high.

Metal-Oxide

A metal oxide varistor is formed from a variety of materials via a manufacturing process which provides the desired electrical properties to the varistor. The typical structure of a metal-oxide varistor consists of highly conductive tiny particles of metal oxide (usually zinc oxide, ZnO) suspended in a semiconducting material. The metal-oxide particles do not touch each other but are separated by the semiconductor material.

The voltage current characteristic of MOA is much better than that of SiC varistors (Figure 8).

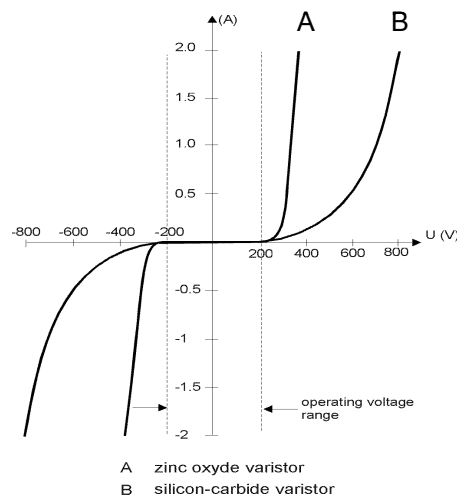


Fig. 8 - Comparison of the characteristics of a MOA and a SiC varistor.

The non-linearity coefficient α usually exceeds 30. This property, however, is only valid in the nominal part of the U/I characteristic (Figure 9)

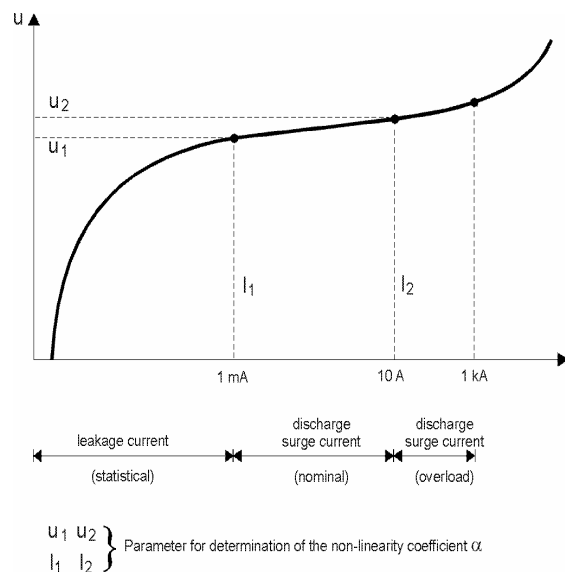


Fig. 9 - Actual U/I characteristic of a metal oxide Varistor.

The maximum temperature of the varistor is a critical parameter. The varistor exhibits power losses for any voltage and they are very high when the arrester limits a lightning overvoltage. The corresponding energy must be kept below a specified value.

This is normally not a problem due to the very short duration of the prospective lightning overvoltage.

A temporary overvoltage has on the other hand a very long duration and the arrester current must be low in order to keep the temperature within an acceptable limit. The arrester voltage characteristic as shown in Fig. 9 is practically proportional to the rated voltage and it must be selected sufficiently high to assure that the arrester withstands the expected temporary overvoltages. Increasing the rated voltage gives an additional margin regarding stresses due to temporary overvoltages, but it increases the protection voltage as well. This gives a less efficient lightning protection. The rated voltage should therefore be selected as low as possible taking the expected temporary overvoltage into account.

Another feature of varistors is the fact that they always exhibit a high capacitance (in parallel with the non linear resistance), which at high frequencies can affect the performance of the circuit to protect.

This capacitance increases with decreasing nominal voltage (decreasing thickness of the component) and increasing energy dissipation capability (increasing diameter of the component). It can be a severe limitation in the use of low voltage varistors for the protection of electronic circuit.

7.3.5 Gapped Surge Arresters

In the past, when only the SiC technology was applied in the manufacturing of varistors it was a necessity in power systems to isolate the current limiting block of the surge arrester from the power frequency voltage under normal operating conditions. This was achieved by connecting in series plate spark-gaps with blocks of SiC varistors.

The (air) gap was necessary because the current limiting block would fail thermally if subjected to the continuous normal power frequency voltage.

Gapped surge arresters are a significant improvement with respect to simple spark gaps in that the serial resistor limits the power follow current and prevents a new spark-over after the voltage has reached the zero crossing. It is worth mentioning that also MOV varistors are sometimes combined with spark-gaps (in series or in parallel with one MOV block).

7.3.6 Suppressor diodes

Suppressor diodes are rapid-response Zener or avalanche diodes able to bear important surge currents*. Thanks to their extremely fast response time (in the order of picoseconds) and very high α coefficient, suppresser diodes are very well suited for the secondary protection of semiconductor components.

Unlike most other overvoltage devices, suppressor diodes exhibit asymmetric U/I characteristics. However most manufacturers propose serial back to back combinations with symmetrical characteristics.

7.3.7 Breakover diodes

A breakover diode (BOD) is a kind of avalanche diode also known for other purposes as "DIAC". However, unlike a zener diode, where a transient is absorbed at a specific clamping voltage which increases with the current value, a breakover diode, like a spark gap, absorbs a transient at a much lower voltage (a few volts), allowing the device to exhibit a high peak current-handling capability.

As for suppressor diodes, the U/I characteristic of BODs can be symmetrical or asymmetrical (Figure 10)

Contrary to spark gaps, the breakover voltage is well defined even for fast transients, and unlike VDRs there is no deterioration of performances over the operating life.

* They are sometimes known under the name of TRANSZORB or TRANSIL which are registered trademarks.

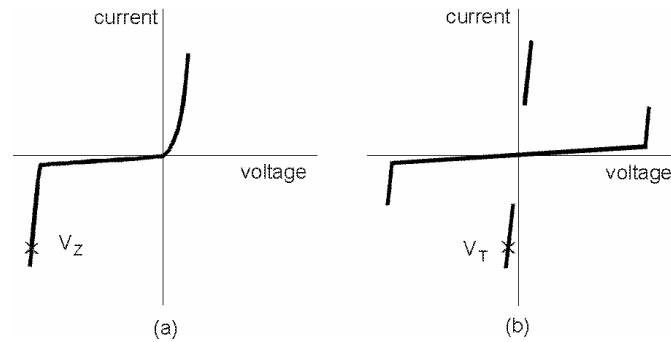


Fig. 10 - Characteristics of a breakover diodes (doc Philips):
 (a) asymmetrical, (b) symmetrical.

7.4 Summary of the most relevant parameters

7.4.1 High voltage devices

a) Spark gaps

Spark gaps are the simplest surge protective devices used in MV networks. Their main characteristics are the arcing distance and the shape of the electrodes. The arcing distance is chosen in order to obtain the required flashover voltage. The shape of the electrodes is designed to elongate and cool the arc, in order to facilitate its extinction. A third electrode (at floating potential) is frequently put between the two main electrodes to avoid flashovers due to the accidental interposition of objects. Criteria to design spark gaps will be given in Part 2.

When using spark gaps, it is important to verify their capability to extinguish the arc across the electrodes in a time sufficiently short to avoid the operation of the protection system and the opening of the line circuit breaker (to avoid short time interruptions). A spark gap is able to extinguish the arc, without the opening of the circuit breaker, provided that the arc current is sufficiently low (lower than a few hundreds of amperes). For this reason, spark gaps are applicable only in MV networks with isolated neutral, or where the single phase-to-ground current is limited by resistors or where the neutral is connected to ground with a tuned impedance (arc suppression coil).

b) Metal Oxide Arrester

In medium voltage (MV) networks mainly two types of arresters are used: Respectively with nominal discharge currents of 5 kA and 10 kA (see Table 5).

Table 5 – Two types of arresters used on MV networks.

Nominal discharge current (8/20 μ s wave)	5 kA	10 kA
High current impulse (4/10 μ s wave)	65 kA	100 kA
Long duration current impulse : duration	1000 μ s	2000 μ s
peak current	75 A	300 ... 400 A
Energy input capacity relative to U_c	ca. 0.4 kJ/kV	ca. 3 kJ/kV
Protection level at nominal discharge current relative to U_c	ca. 4	ca. 3.2
Protection level in p.u. of system voltage for systems with :		
insulated neutral ($U_c = U_m$)	4.9 p.u.	3.9 p.u.
earthed neutral ($U_c = U_m / \sqrt{3}$)	2.8 p.u.	2.3 p.u.

7.4.2 Low voltage devices

Table 6 below summarizes typical characteristics associated with most usual low voltages SPDs.

Table 6 - Typical characteristics of most usual low voltage S.P.Ds.

	8/20 μ s discharge surge current (kA)	Max 10/350 μ s discharge surge current (A)	Max response time (ns)	Max energy absorbing capacity (J)	Max permanent dissipation (W)	Capacitance (pF)	Max leakage current (μ A)	Follow current
Gas discharge tube	2 - 65	1-5000	100	Not applicable	Not applicable	1 – 2.5	<1	yes
Spark gap	> 100	10-100'000	100	Not applicable	Not applicable	10-1'000	<1	Yes/no, it depends on type and application
MOV	0.1 – 40	100-1'500	25	<550	2	100-2'000	<500	no
Sup-pressor diode	0.01 - 1	1-200	10	Not applicable	5	300 – 5'000	<5	no
Break-over diode	0.01-0.2	1-50	500	Not applicable	2	50-500	<5	yes

8. Earthing Systems

The purpose of grounding for protection against lightning is to bypass the energy of the lightning discharge safely to the ground [39].

This Section aims at giving some theoretical and practical information regarding the influence of earthing systems implementation on conducted overvoltages due to lightning. However, it does not provide information about specific parameters such as :

- soil resistivity,
- design calculation,
- nature, section of conductors and connection techniques,
- burying techniques, and,
- measurement practices.

For these subjects, published Standards give practical information.

8.1 Frequency dependent behaviour of earth electrodes

The potential rise of the earthing systems of transformers, poles or lightning protective devices under the influence of a lightning return stroke is one of the main sources of overvoltages on the MV and LV installations.

For that reason it is important to know how far the surge impedance of the different types of earth electrodes deviates from their low frequency value, i.e. from their power frequency resistance.

Many theoretical and experimental studies have shown that it is possible to model single conductor earth electrodes by a series - parallel equivalent circuit similar to that of a transmission line (figure 11)

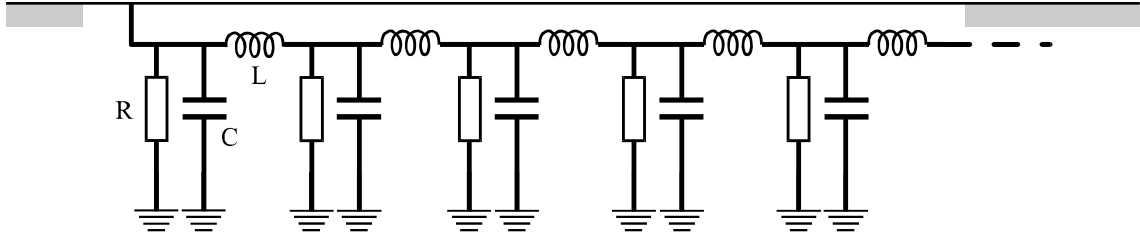


Fig. 11 - Circuit theory model of an earth electrode.

To take into account soil ionization the non-linear resistance might be included in the model instead of the linear one in Fig. 11 [40]. It has been shown however that soil ionization is not instantaneous: soil resistivity decreases with a time constant of about 2 μ s. This value is rather large compared with the time constants associated with most negative subsequent strokes. Moreover if soil ionization occurs, it will always have as consequence a reduction of the ground potential rise. So ignoring this phenomenon always gives conservative results.

For these reasons we will consider here only the linear components of the impedance. Although different authors diverge in determining the per-unit-length values of R, L and C, the discrepancies obtained remain usually small with respect to the approximations introduced for seasonal variations of soil resistivity or lack of soil homogeneity.

The classical expressions of R, L, C for a vertical rod are [41]:

$$R = \frac{\rho}{2\pi} A_1; \quad L = \frac{\mu_0}{2\pi} A_1; \quad C = \frac{2\pi\epsilon}{A_1} \quad (9a)$$

$$A_1 = \ln \frac{4l}{a} - 1, \quad (l \gg a)$$

and for a horizontal rod:

$$R = \frac{\rho}{\pi} A_2; \quad L = \frac{\mu_0}{2\pi} A_2; \quad C = \frac{\pi\epsilon}{A_2} \quad (9b)$$

$$A_2 = \ln \frac{2l}{\sqrt{a2d}} - 1, \quad (l \gg a, d \ll l)$$

In these expressions:

- ℓ is the rod length in m
- a is the equivalent mean geometric radius of the rod in m
- ρ is the soil resistivity (supposed to be homogeneous) in Ω m
- $\mu_0 = 4 \pi 10^{-7}$ H/m
- ϵ is the soil permittivity (typical value : $\epsilon = 10 \epsilon_0$ with $\epsilon_0 = 8.85 \times 10^{-12}$ F/m)
- d the depth of burial in m

If the transmission line in Fig. 11 is energized at one end and the other end is considered open, the harmonic impedance to earth $Z(j\omega)$ can be simply computed as [42]:

$$Z(j\omega) = Z_C \coth \gamma \ell \quad (10a)$$

where Z_C is the characteristic impedance and γ is the propagation constant. Equations (9a) and (9b) can be combined for vertical rod [43]:

$$Z_C = \frac{A_1}{2\pi} \sqrt{\frac{j\omega\mu_0\rho}{(1+j\omega\epsilon\rho)}}, \quad \text{and} \quad \gamma = \sqrt{j\omega\mu_0(1/\rho + j\omega\epsilon)} \quad (10b)$$

and for horizontal rod:

$$Z_c = \frac{A_2}{\pi} \sqrt{\frac{j\omega\mu_0\rho}{2(1+j\omega\varepsilon\rho)}}, \text{ and } \gamma = \sqrt{j\omega\mu_0(1/\rho + j\omega\varepsilon)/2} \quad (10c)$$

Therefore, in comparison to 50 / 60 Hz case, where resistance to earth can be simply computed for vertical and horizontal rod as:

$$R_g = \frac{\rho}{2\pi\ell} A_1, \text{ and } R_g = \frac{\rho}{\pi\ell} A_2, \quad (11)$$

respectively, impedance to earth (10a) is complex and frequency dependent.

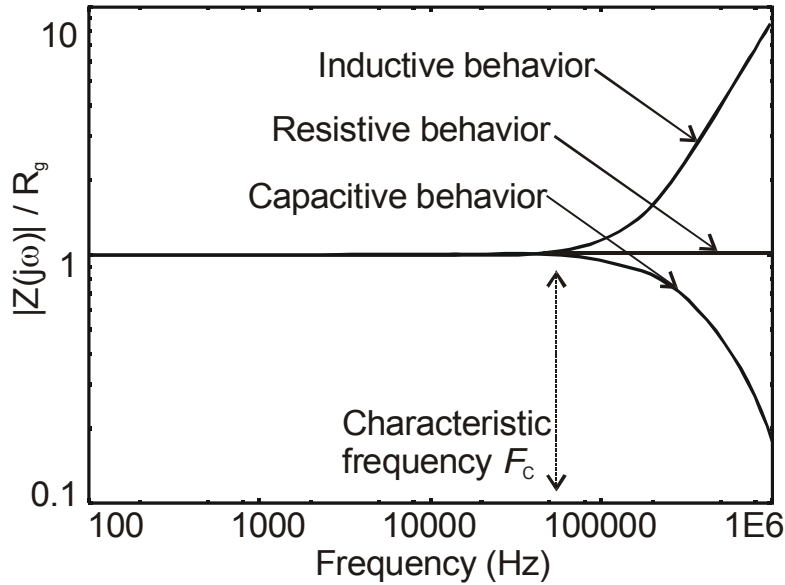


Fig. 12 - Frequency dependence of the impedance to earth.

Fig. 12 shows typical frequency dependence of the impedance to earth. Figure shows the ratio of the impedance modulus $|Z(j\omega)|$ and the low frequency resistance to earth R_g . Speaking in circuit terms, the grounding behavior may be considered as dominantly capacitive ($|Z(j\omega)|/R_g < 1$), resistive ($|Z(j\omega)|/R_g = 1$) or inductive ($|Z(j\omega)|/R_g > 1$). Two frequency ranges may be distinguished: low frequency (LF) range, where the impedance is nearly constant, that is, frequency independent, and high frequency (HF) range, where impedance is changing with frequency. The limiting frequency is some characteristic frequency F_c [44], which is larger for smaller dimensions of the electrode and more resistive earth and for central discharge point.

Resistive and capacitive behavior is advantageous since the HF impedance is equal or smaller than the LF resistance to earth. Usually capacitive behavior is typical for electrodes with smaller dimensions and in highly resistive soils, and in the other cases the grounding electrode behavior is mostly inductive. Fig. 13 gives the regions of inductive and capacitive behavior of vertical and horizontal rods depending on the length, earth resistivity and discharge point [45, 46].

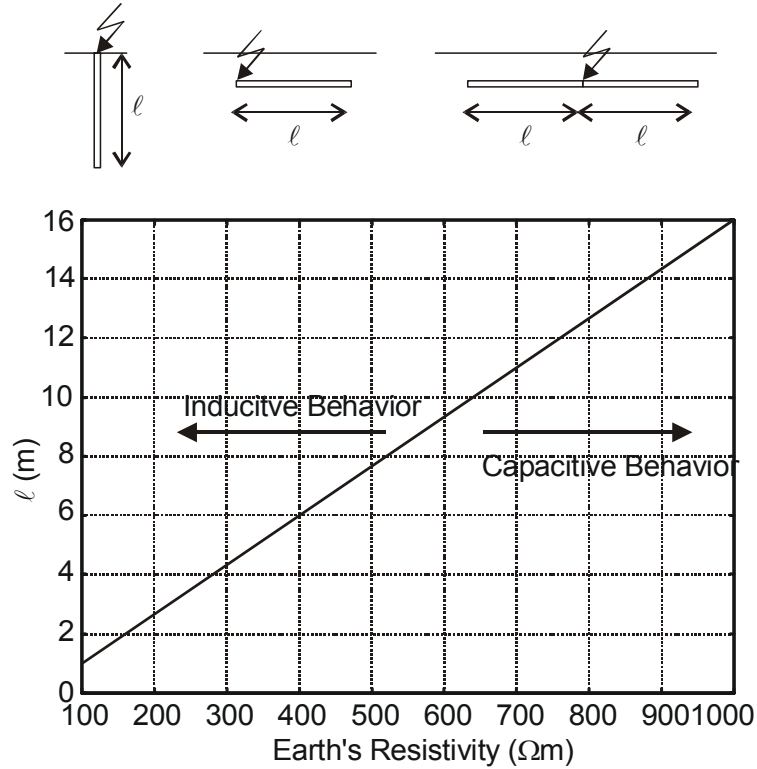


Fig. 13 - Regions of inductive and capacitive behavior of grounding electrodes

It is clear that in order to minimize the influence of the inductive behavior, it is better to use smaller electrodes. However, practically this is not always possible since to fulfill requirements for low values of the resistance to earth in standards (at 50/60 Hz) it is necessary to use longer electrodes. On the other hand, what is important is the dynamic behavior of the grounding electrodes subjected to lightning-related current impulses. The importance of the high frequency behavior of the grounding electrodes depends on the frequency content of the lightning current pulses, that is, the inductive behavior for higher frequencies is more important for faster varying current pulses.

8.2 Dynamic behaviour of earth electrodes

When harmonic impedance $Z(j\omega)$ (10a) is determined, then the time function of the voltage to earth (transient voltage) at the feeding point $v(t)$ as a response to injected lightning current pulse $i(t)$ can be evaluated by:

$$v(t) = \mathbf{L}^{-1}\{Z(j\omega) \cdot \mathbf{L}[i(t)]\} \quad (12)$$

where $i(t)$ is the lightning current pulse, and \mathbf{L} and \mathbf{L}^{-1} are Laplace (or Fourier) and inverse Laplace (or inverse Fourier) transforms, respectively.

Several parameters are used to characterize dynamic behavior of earth electrodes. One is impulse (transient) impedance $z_0(t)$, defined as the ratio between the instantaneous values of the voltage to earth at the feeding point and of the current injected in the electrode [47]:

$$z_0(t) = \frac{v(t)}{i(t)} \quad (13)$$

Most usually the conventional impedance Z is used, which is defined as the ratio between the maximum value of $v(t)$ and the peak value of the current pulse $i(t)$:

$$Z = \frac{\max[v(t)]}{\max[i(t)]} = \frac{V_{\max}}{I_{\max}} \quad (14)$$

Important parameter is the impulse efficiency defined as the ratio between the conventional impedance and the resistance at low frequency, Z / R_g . It is worth noting that a lower value of the impulse efficiency means better impulse performance.

Figures 14 and 15 show one example of the frequency and time characteristics of a ground electrode¹⁴. Fig. 14 shows harmonic impedance of a 12-m long vertical rod constructed of copper with radius 0.7 cm in earth with resistivity 100 Ωm and relative permittivity 10.

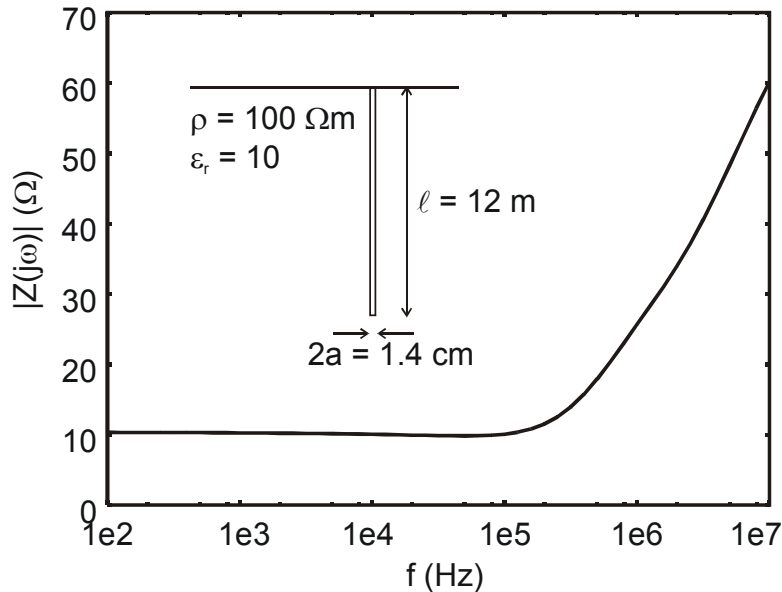


Fig. 14 – Modulus of the harmonic impedance to ground of a 12-m vertical rod

It can be seen that harmonic impedance is frequency independent and equal to the low frequency resistance to ground $R_g = 10.3 \Omega$ up to the characteristic frequency $F_C \approx 100 \text{ kHz}$. For higher frequencies, it exhibits inductive behavior and its value becomes larger than R_g . The influence of such larger values of $Z(j\omega)$ on the transient response depends on the frequency content of the excitation lightning current impulse.

Figure 15 shows transient impedance and voltage at the feeding point for injected lightning current pulse typical for the first stroke, given in Fig. A3.2. Since such impulse does not have significant frequency content above the characteristic frequency $F_C \approx 100 \text{ kHz}$ (in Fig. 14), the voltage response is not substantially influenced by the inductive part of the harmonic impedance. The response is mostly determined by the frequency independent part, that is, the pure resistive part of the harmonic impedance, below F_C . Although the transient impedance $z_0(t)$ starts from some high value it quickly settles to the low frequency resistance value even during the rise of the current. The transient impedance determines the duration of the transient period; here after 4 μs transient period is finished and afterwards quasi-static analysis might be applied. The transient voltage has similar wave shape as the exciting current pulse, and their maximums occur at the same time. The impulse efficiency is excellent, equal to 1, that is, the conventional impedance is equal to the low frequency resistance $Z = R_g$.

¹⁴ Presented results in this section are by the electromagnetic model [48], [49] which is more appropriate for modeling multiple ground rods arrangements and analysis at higher frequencies and earlier times than circuit models.

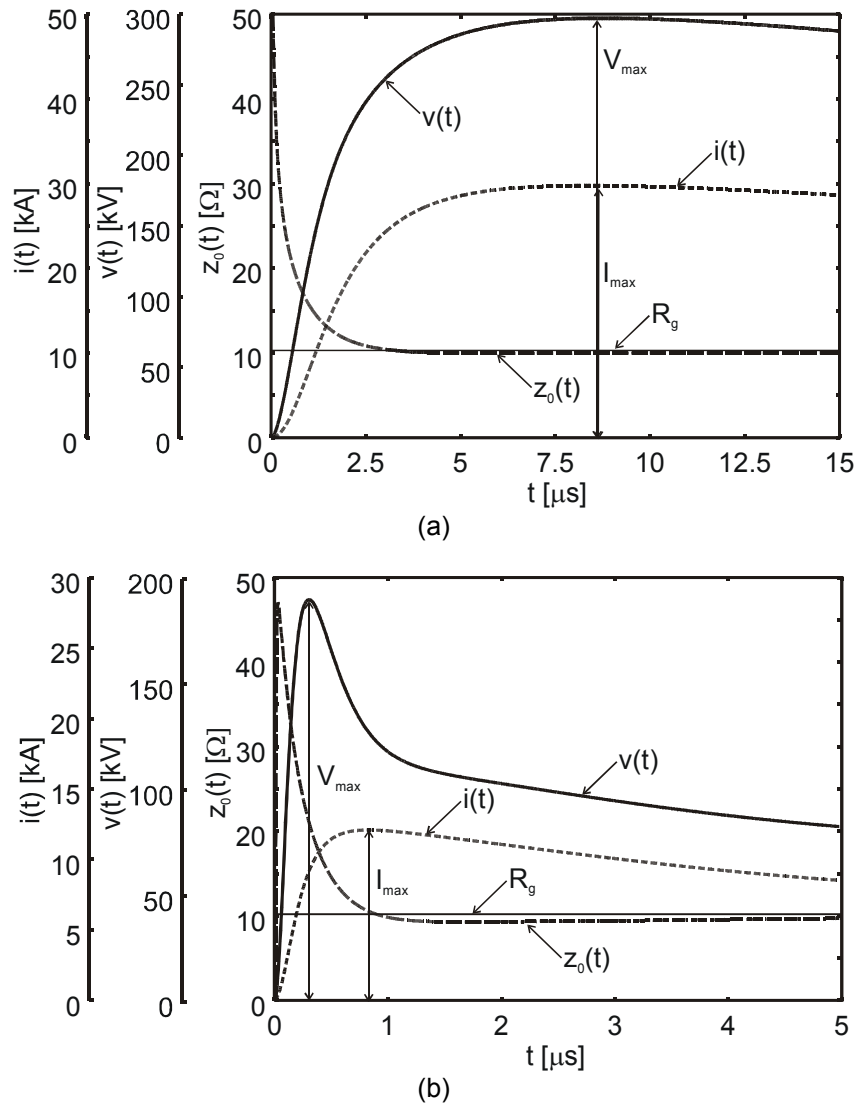


Fig. 15 – Transient voltage at feeding point and impedance to ground of 12-m ground rod (given in Fig. 14). (a) Response to typical first stroke current pulse. (b) Response to typical subsequent stroke current pulse (given in Fig. A3.2).

For the subsequent stroke current pulse in Fig. 15b the situation is different. The corresponding current pulse has significant frequency content above the characteristic frequency $F_C \approx 100$ kHz (in Fig. 14), and consequently the response is influenced by the inductive part of the $Z(j\omega)$. The transient impedance $z_0(t)$ starts from high values and settles to values near the low frequency value (R_g) after the occurrence of the peak of the current. However, during the rise of the current the transient voltage has a large peak V_{max} . Also, typically for inductive behavior, the voltage pulse precedes the current pulse. This causes larger conventional impedance $Z = 15.7 \Omega$, than the low frequency resistance ($R_g = 10.3 \Omega$) and impulse efficiency equal to 1.5.

From Fig. 15 it can be concluded that voltage peaks might occur during the rise of the current pulse in case when the ground electrode exhibits inductive behavior at high frequencies and the current pulse has enough high frequency content to be influenced by such inductive behavior. However, after few μs transient processes are finished and transient impedance is settled to the value of the power frequency resistance.

Figure 16 shows the impulse efficiency of vertical ground rods dependent of rods' length and earth's resistivity for the first and subsequent stroke current pulses defined in Fig. A3.2 [50].

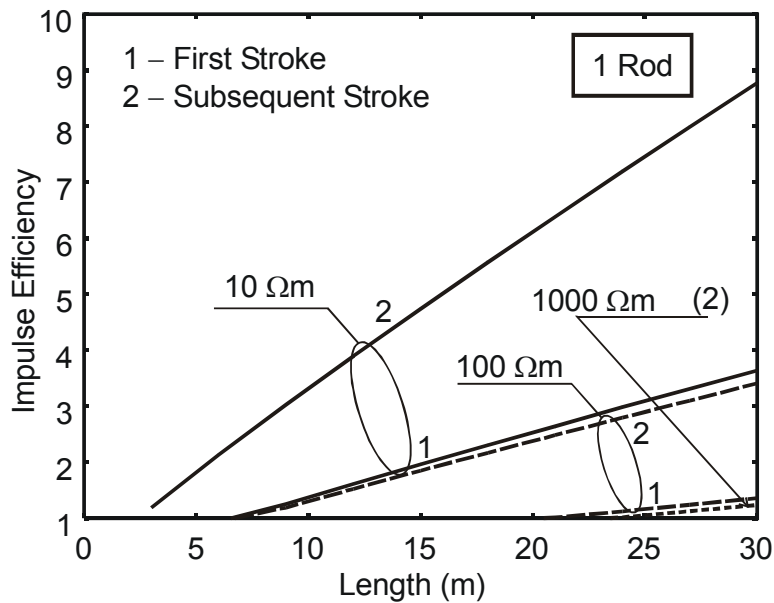


Fig. 16 – Impulse efficiency of a single vertical rod (adapted from [50])

It can be concluded that impulse performance is worse for longer rods in better conductive earth and for faster varying pulses, such as subsequent strokes. This effect is less important in less conductive soil and for not so fast varying pulses, such as first strokes.

Fig. 15 might be used for a first estimate of impulse efficiency of some other ground rod arrangements. Table 7 gives the extent of the reduction of the impulse efficiency of the single vertical rod, given in Fig. 15, for other multiple or horizontal ground rod arrangements.

Table 7 – Impulse efficiency of several ground rod arrangements (adapted from [50])

Ground rod arrangement						
Percentage of values in Fig. 15	100	95	85	85	80	70

Use of multiple ground rod arrangements improves the impulse efficiency. Horizontal rods are slightly less effective at power frequency in comparison to vertical rods, but have better impulse efficiency.

8.3 Complex grounding systems

Often grounding systems are more complex, especially if other more extended ground electrodes are connected such as for example metallic shields of power cables. It has been concluded in experimental [51] and simulation [52] studies that most of the lightning current is carried away by the extended parts of the grounding system except in the first moments of the stroke when the most of the current is discharged in the part of the grounding system near the discharge point.

8.4 Earthing systems and impulse withstand voltage - General considerations

Other aspects have to be taken into consideration when analyzing the influence of lightning on earthing systems:

Existence of different earthing systems on the same site

Different earthing systems, used in distribution networks, telecoms networks, public lighting utility services, lightning protective systems, can be located on a same site (or can extend on the same site). From a protection point of view, all these different earthing systems should be connected together. If, for security reasons, they cannot be connected together, a minimum distance must be kept between them to limit the transfer of potentials in case of a lightning strike. The existing methods which are used to separate different earthing systems at 50 Hz can be used in a conservative way.

Level of insulation of equipment

If an equipment installed in a location protected by a dedicated earthing network (e.g. MV/LV substation...) is connected to an installation or a circuit referring to another earthing system (e.g. LV network, telecommunication network), it can happen, in case of direct or nearby lightning strike, that the equipment insulation be overstressed. Part of the earth potential rise can also be transferred by capacitive coupling (e.g. between the windings of a transformer) to the other system.

In order to avoid this, it is necessary either to ensure that the insulation level of the equipment is appropriate, or to install external barriers of potential based, for example, on the use of isolation transformers (up to some tens of kV surges) or fiber optic (for higher potential rises).

Appendix 1: Negative Cloud-to-Ground Lightning [1, 2]

A typical negative cloud-to-ground discharge brings to earth tens of Coulombs of negative cloud charge. The total discharge is called a *flash* and has a time duration of about half a second. A flash is made up of various discharge components, among which are typically a few high-current pulses called *return strokes*. Each return stroke lasts about a millisecond, the separation time between strokes being typically several tens of milliseconds. A negative cloud-to-ground lightning flash is illustrated in Fig. A1.1. The *stepped leader* initiates the first return stroke by propagating from cloud to ground in a series of discrete steps. The stepped leader is itself initiated by a *preliminary breakdown* within the cloud. Leader steps are typically 1 μsec in duration and tens of meters in length, with a pause time between steps of about 50 μsec . A fully developed stepped leader lowers up to 10 or more Coulombs of negative charge toward ground in tens of milliseconds with an average downward speed of about 2×10^5 m/sec. The average leader current is in the 100-1000 A range. The steps have pulse currents of at least 1 kA. As the leader tip approaches ground, the electric field at sharp objects on the ground or at irregularities of the ground itself exceeds the breakdown value of the air and one or more upward-moving discharges are initiated from these points, thus beginning the *attachment process*. When one of the upward-moving discharges from the ground contacts the downward-moving stepped leader some tens of meters above ground, the leader tip is connected to ground potential. The leader channel is then discharged when a ground potential wave, the first return stroke, propagates up the previously ionized and charged leader path with a typical speed of 1 to 2 times 10^8 m/sec. The total transit time from ground to the top of the channel is typically about 100 μsec . The first return stroke produces a peak current near ground of typically 30 kA, with a time from zero to peak of a few microseconds. After the return stroke current has ceased to flow, the flash may end. The lightning is then called a *single-stroke flash*. If additional charge is made available to the top of the channel, a continuous dart leader may propagate down the residual first return stroke channel at a speed of about 3×10^6 m/sec which initiates the second or any subsequent return stroke. Dart leaders and return strokes subsequent to the first are usually not branched. Subsequent return stroke currents have faster zero-to-peak rise times than do first return stroke currents. There may be even ten or more subsequent strokes in a flash. The time between successive return strokes in a flash is usually several tens of milliseconds, but can be tenths of a second if a *continuing current* (not illustrated in Fig. A1.1) flows in the channel after a return stroke. Continuing current magnitudes are of the order of 100 A and represent a direct transfer of charge from cloud to ground. It is worth noting that more than a half of multiple-stroke flashes have multiple ground terminations.

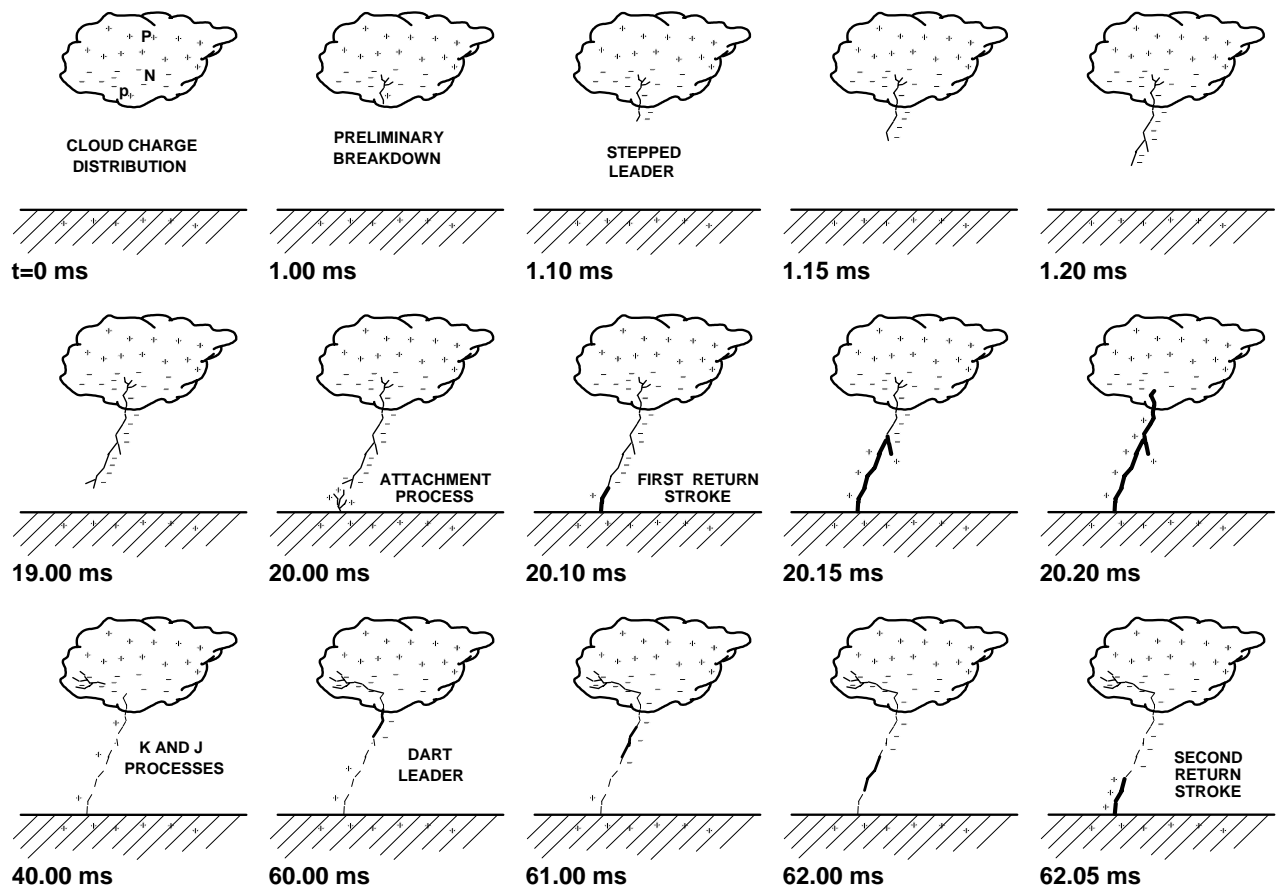


Fig. A1.1 - Illustration of various processes comprising a negative cloud-to-ground lightning flash (Adapted from [53]).

Appendix 2: Lightning Electromagnetic Fields

Vertical electric field and horizontal magnetic field [5]. Measurements of electromagnetic fields from natural lightning have been performed by several authors. In Fig. A2.1, typical wave shapes of vertical electric and horizontal (transverse) magnetic fields for first and subsequent negative return stroke as a function of distance from the lightning channel, as reported in [54], are shown. Fields at all ranges shown in Fig. A2.1 exhibit an initial peak that reduces approximately inversely with distance. The close electric field (range=1-10 km) exhibits a ramp, and the close magnetic field exhibits a hump at tens of microseconds. The electric and magnetic field waveshapes are nearly identical beyond 100 km where they are bipolar with a zero crossing in the tens of microsecond range; the field wave shape around the time of the initial peak exhibits some subsidiary peaks following the main peak. At very close distance ranges (below 1 km), some data have been obtained by means of the 'triggered lightning' technique* and are reported in [55, 56].

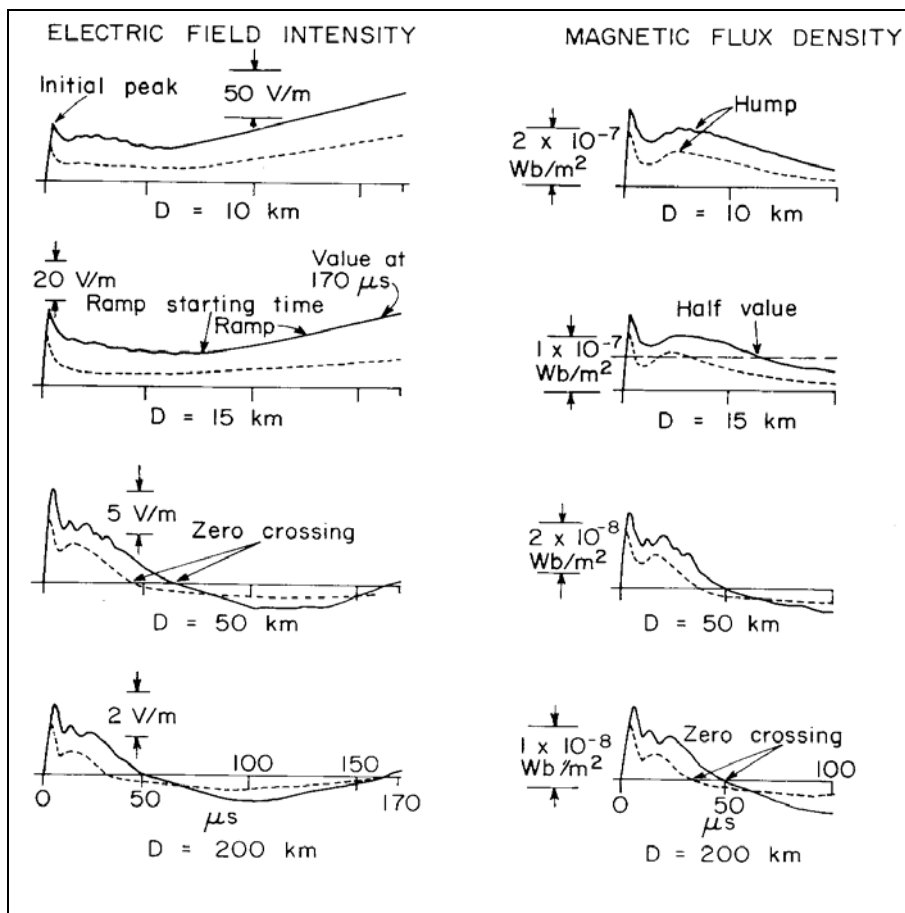


Fig. A2.1 - Vertical electric field intensity and horizontal magnetic flux density for first (solid line) and subsequent (dashed line) return strokes at distances of 10, 15, 50, and 200 Km (Adapted from [54]).

Horizontal electric field. Wideband measurements of the horizontal component of the electric field E_h , about 1 m above ground level from lightning return strokes at distances beyond some kilometers have been reported in [57, 58]. However, a complete characterization of the horizontal electric field similar to that performed for the vertical electric and transverse magnetic fields, is not yet available. Contrarily to the vertical electric and transverse magnetic fields, the horizontal electric field is significantly affected by the ground conductivity [5].

* According to this technique, lightning is artificially initiated firing small rockets trailing grounded wires upward a few hundred meters under thunderstorms. In spite of differences in the formation mechanism of triggered and natural lightning processes, it is generally accepted that, as far as subsequent return strokes are concerned, natural and triggered lightning are similar.

Appendix 3: Lightning-Induced Voltages: Computational Models and Sensitivity Analysis

A fast time-varying electromagnetic field (such as the field radiated by a lightning discharge) illuminating a transmission line induces on that line overvoltages and overcurrents. The problem has been studied since the beginning of the last century (see [6] for a historical review).

In parallel with the theoretical studies, many tests with voltages induced on experimental lines [6] have been performed. The collected data result in a better comprehension of the phenomena involved, although some controversy about their interpretation still seems to exist.

The evaluation of induced overvoltages is generally performed in the following way:

- the lightning return-stroke electromagnetic field change is calculated at a number of points along the line employing a lightning return-stroke current model, that is a model which specifies the form of the return stroke current as a function of height and time along the channel;
- the computed electromagnetic field is then used to calculate the induced overvoltages making use of a coupling model which describes the interaction between the field and the line conductors.

Lightning return-stroke current models.

Fig. A3.1 shows the geometry for the calculation of the lightning return-stroke electromagnetic fields, as generally adopted. The lightning channel is assumed to be a straight vertical uni-dimensional antenna, perpendicular to the conducting ground plane. In all the models to be considered the current at the channel base $i(0, t)$ can be specified along with other model parameters to allow a determination of the current as a function of height and time along the return stroke channel $i(z', t)$. Then, introducing the expression $i(z', t)$ in the electromagnetic field equations, one can calculate the electric and magnetic field change at a general point in space.

A number of lightning return-stroke current models have been proposed in the last years (see [5] for a survey). However, only those return-stroke models in which the return stroke current $i(z', t)$ can be simply related to the specified channel-base current $i(0, t)$ are of interest from an engineering point of view, since it is only the channel-base current that can be measured directly and for which experimental data are available*.

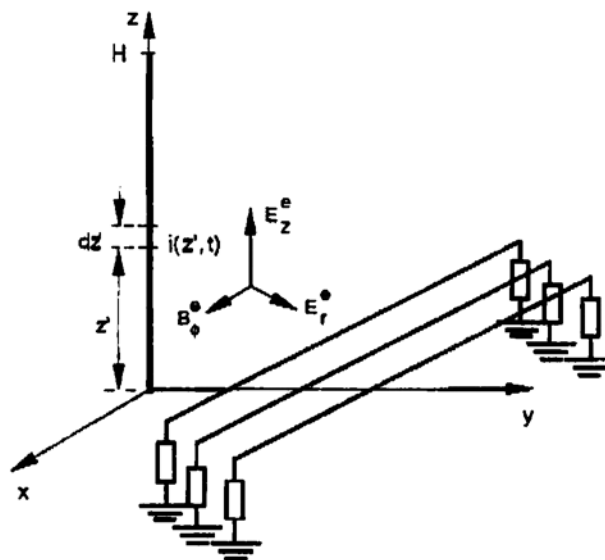


Fig. A3.1 – Geometry for the calculation of lightning-induced voltages on overhead power lines.

* Note that in the return-stroke models described here, the channel-base current is to be viewed as the result of the flowing towards ground of charges contained in the leader channel and in the corona sheath around the channel during the return-stroke phase. These models have been conceived to describe the field *change* due to the return stroke phase, the total return-stroke field being the sum of the return-stroke field change plus the final value of the field produced by the preceding leader phase.

The validation of the various return-stroke models is not straightforward since, for natural lightning, no experimental set of simultaneously-measured currents and fields is available. Thus, although a direct comparison is possible for artificially-initiated lightning^{*}, only a qualitative comparison is possible for natural lightning. The most important factors for the calculation of lightning-induced overvoltages are the peak fields and the peak field derivatives. Thus, a return stroke model is to be considered adequate if it yields simultaneously a good approximation to the observed current at the channel base, to the observed electric and magnetic fields at various distances (with particular reference to the peak fields and peak derivatives), and to the observed return stroke wave front speed.

In [5], three of the most commonly adopted return-stroke models, namely the

- the Traveling Current Source (TCS) model [59];
- the Modified Transmission Line (MTL) model [60, 61];
- the Diendorfer-Uman (DU) model [62].

have been compared and discussed assuming the same current at the channel base for each.

In [5], it is concluded that although some models are thought to produce more accurate results and are more physically reasonable (but are mathematically more complex), for most engineering coupling calculations any one of the mentioned models is adequate in that they all produce fields which are reasonable approximations to available measured fields from natural lightning and are within a factor of 2 or so of each other[†].

If one model has to be selected as the one representing the best compromise between mathematical simplicity and accuracy in field reproduction, this is probably the MTL model, as supported by comparisons reported in [38].

Coupling models.

Fig. A3.1 shows the geometry of the problem. Three coupling models are commonly adopted in the power literature to describe the coupling between lightning return-stroke fields and overhead lines:

- the model by Rusck [29];
- the model by Chowdhuri and Gross [65] (henceforth called the Chowdhuri model),
- the model by Agrawal, Price and Gurbaxani [66] (henceforth called the Agrawal model).

It is shown that only the Agrawal model is rigorous within the limits of the adopted hypothesis (transmission line approximations) [5]. The two other models can be utilized only in some particular cases.

The transmission line 'coupling' equations of the Agrawal model can be represented by means of an equivalent coupling circuit. Note that the forcing functions which explicitly appear in the equations are the horizontal component of the incident electric field along the line and the vertical component of the incident electric field at the vertical line terminations. These forcing functions are represented by distributed voltage sources along the line (horizontal electric field) and by the two voltage sources at the line terminations (the so-called 'risers'), respectively.

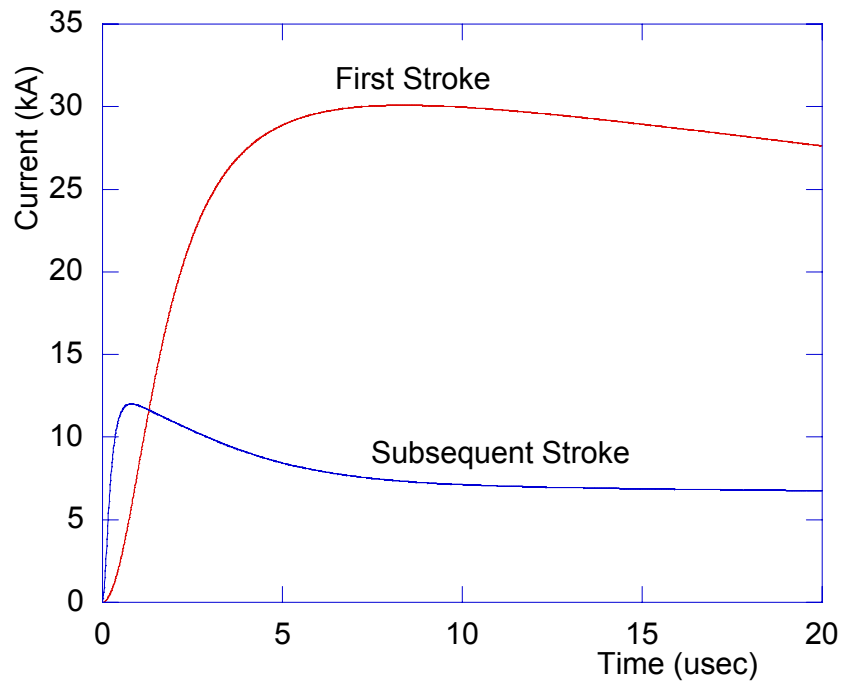
The Agrawal model is the only one that has been thoughtfully tested in the sense already specified in the Introduction: starting from measured fields, overvoltages were calculated and compared with those measured and induced by the same input fields. Although some of the first tests did not provide satisfactory agreement between theory and measurements, in subsequent experiments the agreement was largely improved (see [5, 67]).

Field tests, however, are affected by many uncertainties: calibration errors, imperfect knowledge of the causative fields (measured in general only in one or two points, and not all along the line as the coupling models would require) and, in some cases, of the ground conductivity, are factors that suggest to carry out further experiments in more controlled conditions. Recently, some tests of the Agrawal model have been performed making use of Nuclear Electromagnetic Pulse (NEMP) simulators [6] and the obtained results have shown a good agreement between measurements and theory. Other equivalent formulations of Agrawal model which are in terms of different electromagnetic field components are also presented in literature [6].

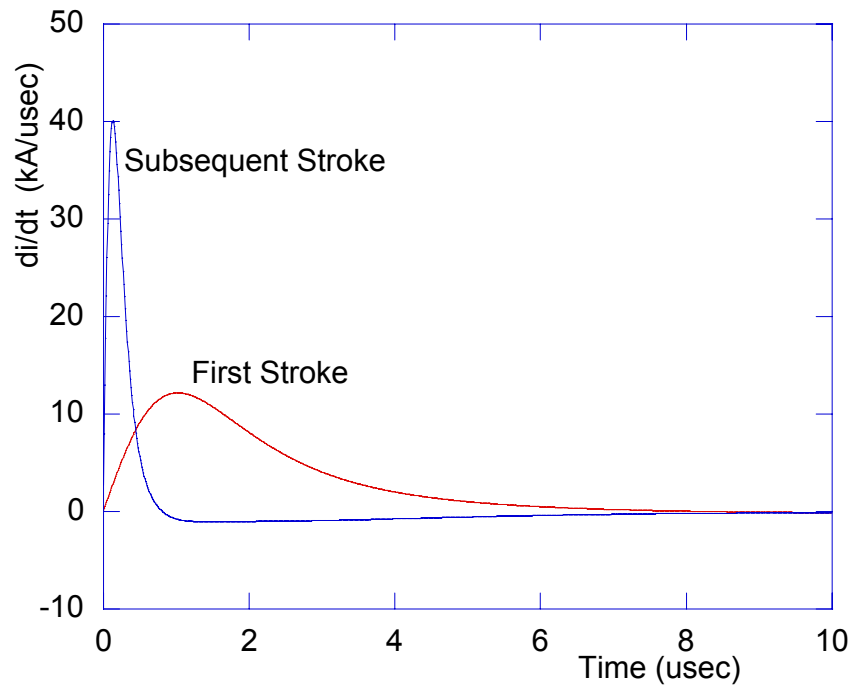
* Simultaneous measurements of lightning currents and fields have been obtained by means of the already mentioned "triggered lightning" technique.

† Similar conclusions can be found in a recent paper by Thottapillil and Uman [38] in which the same three models above mentioned, together with the Transmission Line model [63] and the Modified DU (MDU) models [64], are compared on the basis of simultaneously measured channel base currents, return stroke speeds, and electric fields at about 5 km from triggered lightning in Florida.

Sensitivity analysis of the induced voltages. Lightning channel-base current for typical first and subsequent return strokes are presented in Fig. A3.2. The parameters of function (1) used to reproduce the current are presented in Table A.1.



(a)



(b)

Fig. A3.2– First and subsequent return stroke current waveforms (a) and their derivatives (b).

Table A.1 – Parameters of the two Heidler's functions used to reproduce the channel-base current waveshape.

	I_{o1} (kA)	τ_{11} (μ s)	τ_{21} (μ s)	N_1	I_{o2} (kA)	τ_{12} (μ s)	τ_{22} (μ s)	N_2
First Stroke	28	1.8	95	2	-	-	-	-
Subsequent Stroke	10.7	0.25	2.5	2	6.5	2	230	2

First and subsequent return stroke, stroke location

In Fig. A3.3 we present, for a stroke location at 50 m from the line center and equidistant to the line terminations (stroke location A), the overvoltages calculated assuming the two channel-base currents of first and subsequent return-strokes. It is interesting to observe that although the amplitude of the first return-stroke current is about three times that of the subsequent one, the peak value of the two induced voltages (relevant to the first and to the subsequent strokes) is practically the same.

Similar results are shown in Fig. A3.4 concerning stroke location B). The above result can be explained by virtue of the lower frequency content of the electromagnetic field produced by the first return stroke. Indeed the maximum time-derivative of the first return-stroke current is lower than the subsequent one. However, beyond a certain value of time-derivative of the current, it is the amplitude of the current that plays a dominant role in the determination of the induced voltages amplitude. Table A.2 presents the parameters of voltages induced by typical first and subsequent return strokes for close and distant stroke location.

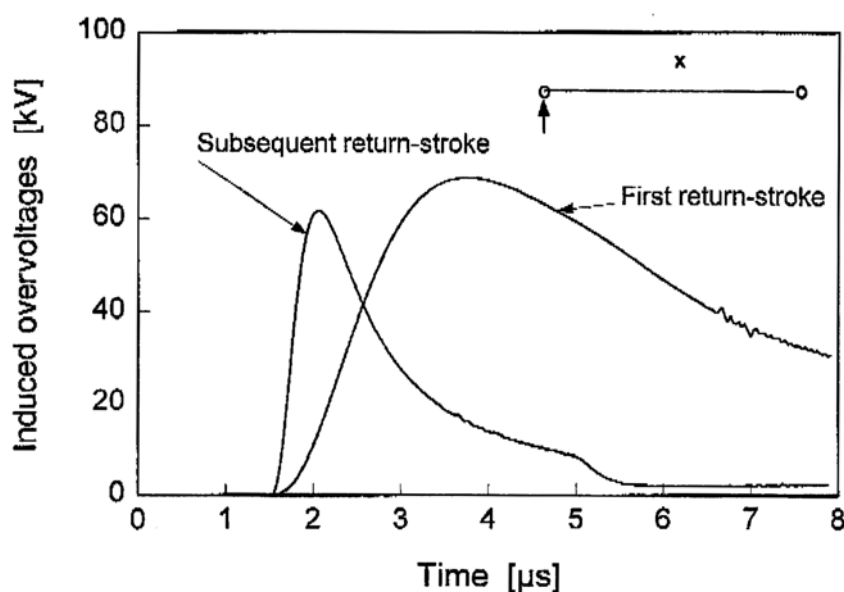


Fig. A3.3 – Overvoltages induced by typical first and subsequent return strokes. Stroke location: 50 m from the line center and equidistant to the line terminations (case A). Observation point indicated by arrow.

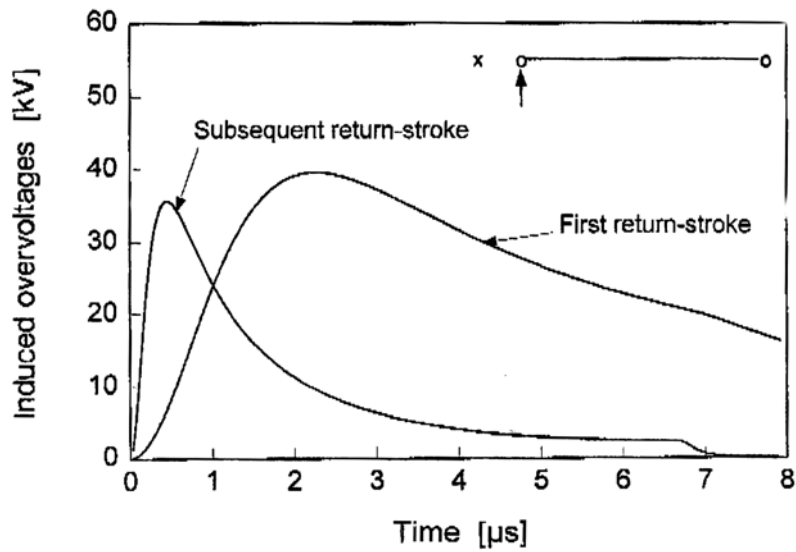


Fig. A3.4— Overvoltages induced by typical first and subsequent return strokes. Stroke location: 50 m from one of the line extremities along the line prolongation (case B). Observation point indicated by arrow.

Channel-base current peak value and maximum time-derivative

In Fig. A3.5, we report the variation of the induced voltage as a function on the peak value of the channel-base current (keeping constant the maximum time derivative of the current at 40 kA/ μs); in Fig. A3.6, we show the influence of the maximum time-derivative of the channel-base current, keeping constant the peak value at 12 kA. For an increase of a factor 10 in the examined range, the maximum front steepness of the induced voltage (time-derivative) increases by a factor of 4, whereas the peak voltage increases only by a factor of about 1.4. (see also Table A.3 for numerical values).

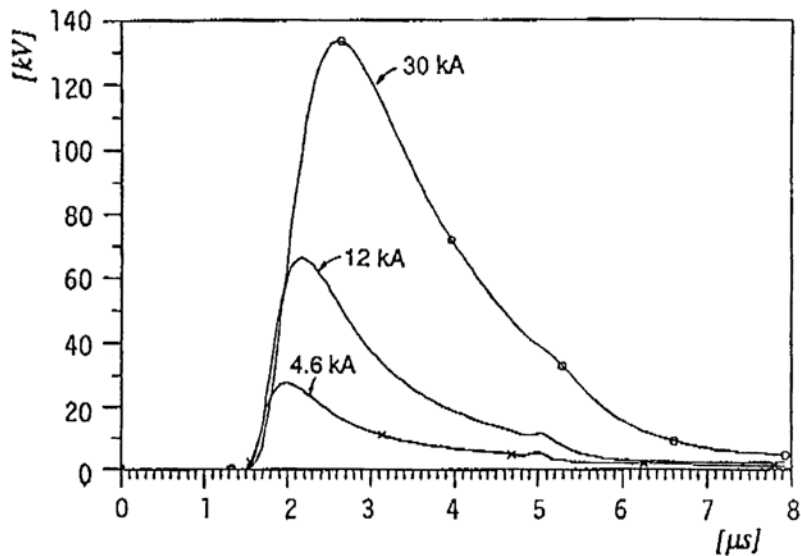


Fig. A3.5 — Influence of the peak value of the channel-base current on the induced overvoltage. Maximum front steepness of the channel-base current $(di/dt)_{max}=40 \text{ kA}/\mu\text{s}$. Stroke location: A. Observation point: line terminations.

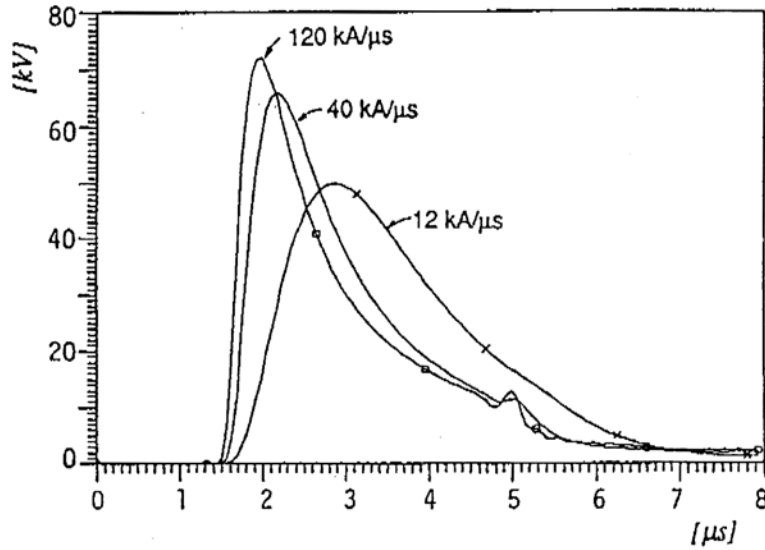


Fig. A3.6 – Influence of the maximum time derivative of the channel-base current on the induced overvoltage. Peak value of the channel-base current $I_p=12$ kA. Stroke location: A. Observation point: line terminations.

Table A.2 – Parameters of the voltages induced by typical first and subsequent return strokes. The ‘close’ observation point refers to case A. The ‘distant’ observation point is at 1 km of the line center and symmetrical to the line terminations.

	Close strike location		Distant strike location	
	First	Subsequent	First	Subsequent
U_p (kV)	74	53	4	2.2
$(dU/dt)_{max}$ (kV/ μ s)	52	153	1.3	3.8
zero-to-peak time (μ s)	2.8	0.8	4	3.3
Time-to-half $t_{50\%}$ (μ s)	5.8	1.7	11	3.1

Table A.3 – Influence of lightning discharge parameters on the peak value U_p , maximum time derivative $(dU/dt)_{max}$ and time-to-half value $t_{50\%}$ of the induced voltages. Calculations performed using the MTL return stroke model.

Case	U_p (kV)	$(dU/dt)_{max}$ (kV/ μ s)	$t_{50\%}$ (μ s)
BASE ($I_p=12$ kA, $(di/dt)_{max}=40$ kA/ μ s, $v=1.3 \times 10^8$ m/s)	66	190	1.4
$I_p=4.6$ kA	28	105	1.1
$I_p=30$ kA	133	225	2.1
$(di/dt)_{max}=12$ kA/ μ s	50	65	2.2
$(di/dt)_{max}=120$ kA/ μ s	72	290	1.1

Return stroke velocity

Concerning the influence of the return-stroke velocity, we here vary this parameter keeping constant the intensity of the current, even though correlation between velocity and return stroke currents have been considered by other authors. Three different values for a constant return-stroke velocity along the channel, namely: 0.6×10^8 , 1.3×10^8 , and 2×10^8 m/s, have been chosen, and calculations are presented in Fig. A3.7. It can be seen that, for the given configuration, an increase in the return stroke velocity results in a marked increase of the induced voltage front steepness but does not affect very much the peak value. This result can be explained, considering the contribution of the different field terms to the total electric field and hence on the induced voltage. At close distances from the lightning channel, the radiation term is responsible only for the fast-rising part of the field. During this early

period, this term increases nearly proportionally to the return-stroke velocity; soon after the electrostatic term, the amplitude of which decreases slightly with the velocity, becomes predominant. Since experimental data on lightning seem to show a decrease of velocity with height for a kilometer scale [3a], a velocity decreasing along the channel has been considered. However, no significant variation in voltages have been found using an exponentially decreasing velocity $v = v_0 \exp(-z/g)$, with g varying from 0.5 km to infinity.

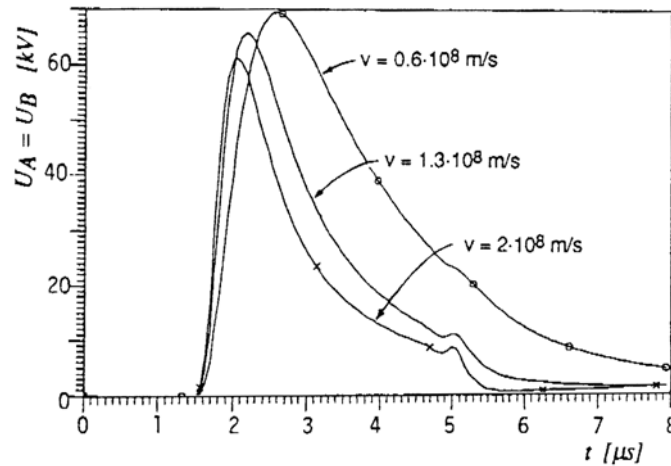


Fig. A3.7 – Influence of the return stroke velocity on the induced overvoltage. Peak value of the channel-base current $I_p=12$ kA. Maximum front steepness of the channel-base current $(di/dt)_{max}=40$ kA/ μs . Stroke location: A. Observation point: line terminations.

Ground conductivity

Figures A3.8 and A3.9 present the influence of the finite ground conductivity on lightning induced voltages, for two different stroke locations. It can be seen that this parameter can significantly affect the induced voltage amplitude, polarity and waveshape [34].

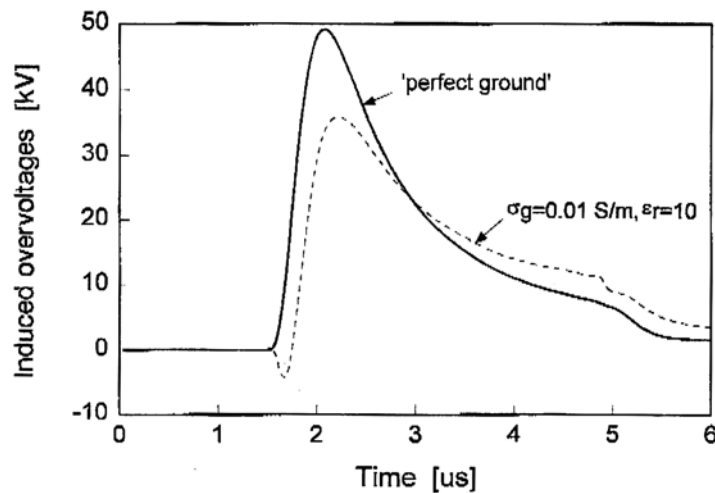


Fig. A3.8 – Influence of the ground conductivity on the induced overvoltage. Peak value of the channel-base current $I_p=12$ kA. Maximum front steepness of the channel-base current $(di/dt)_{max}=40$ kA/ μs . Stroke location: A as defined in Fig. A3.3. Observation point: line terminations.

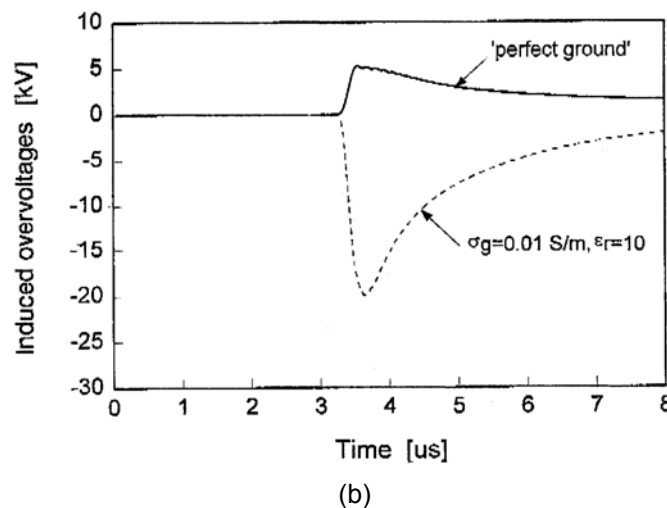
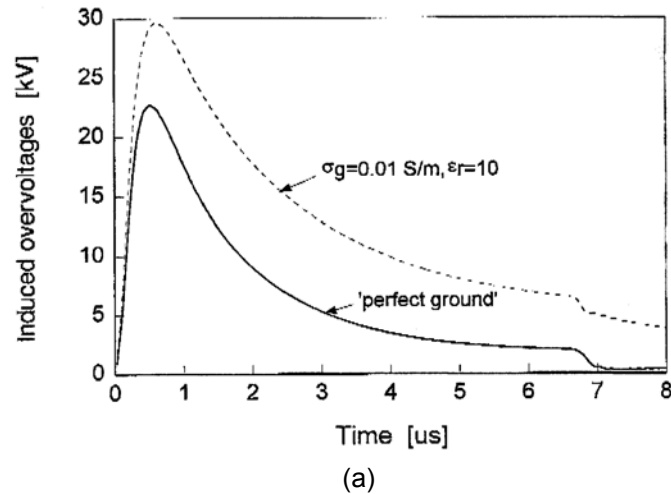


Fig. A3.9– Influence of the ground conductivity on the induced overvoltage. Peak value of the channel-base current $I_p=12$ kA. Maximum front steepness of the channel-base current $(di/dt)_{max}=40$ kA/ μ s. Stroke location: B as defined in Fig. A3.4. Observation point: line terminations. (a) near-end terminal, (b) far-end terminal.

Multiconductor lines

Using two three-phase line configurations shown in Figure A3.10, the shielding effect of conductors in a multiconductor overhead line as well as that of the ground wire is quantified [68]. It can be seen that

- the induced voltage on one conductor of a multiconductor loaded line is affected by the presence of other conductors. For the examined cases, the voltages induced on each of the line conductors are generally 15 to 25% lower than those corresponding to a single conductor located at the same location (Table A.4).
- the presence of ground wires results in a significant shielding effect. It allows a reduction of about 25% (vertical configuration with 1 grounding wire) to 35% (horizontal configuration with 2 grounding wires) of the peak values of the induced voltage (see Table A.5).

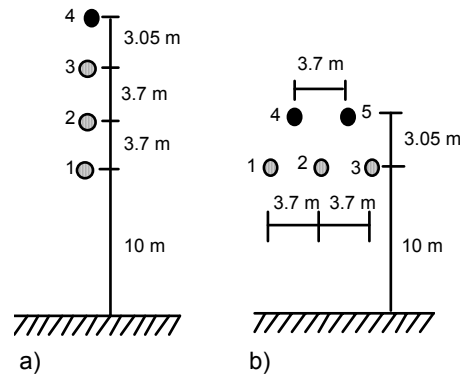


Fig. A3.10 – Two considered power line configurations for the analysis. (a) vertical, (b) horizontal. Conductors numbered 1, 2 and 3 refer to phase conductors and conductors 4 and 5 to ground wires.

Table A.4 – Ratio between peak values of the induced voltages on a line conductor V_i and those corresponding to a single-conductor line of the same height $V(h_i)$. (Adapted from [68])

Voltage Ratio	Vertical Configuration	Horizontal Configuration
$V_1/V(h_1)$	0.75	0.85
$V_2/V(h_2)$	0.79	0.81
$V_3/V(h_3)$	0.89	0.85

Table A.5 – Protection coefficient PR_i associated with ground wires. (Adapted from [68])

wire	Protective Ratio	Vertical Config.	Horizontal Config.
1	PR_1	0.81	0.67
2	PR_2	0.78	0.60
3	PR_3	0.72	0.67

From the above we can conclude that, contrary to direct-lightning induced-voltages, lightning-induced voltages exhibit short duration (time-to-half value of the order of some microseconds). The peak value of the induced voltages depends strongly on the distance from the line and on the peak value of the lightning current. However, simulations performed with the LIOV code show that the peak value does not exceed a few hundreds of kV, a value that is confirmed by the existing experimental data.

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