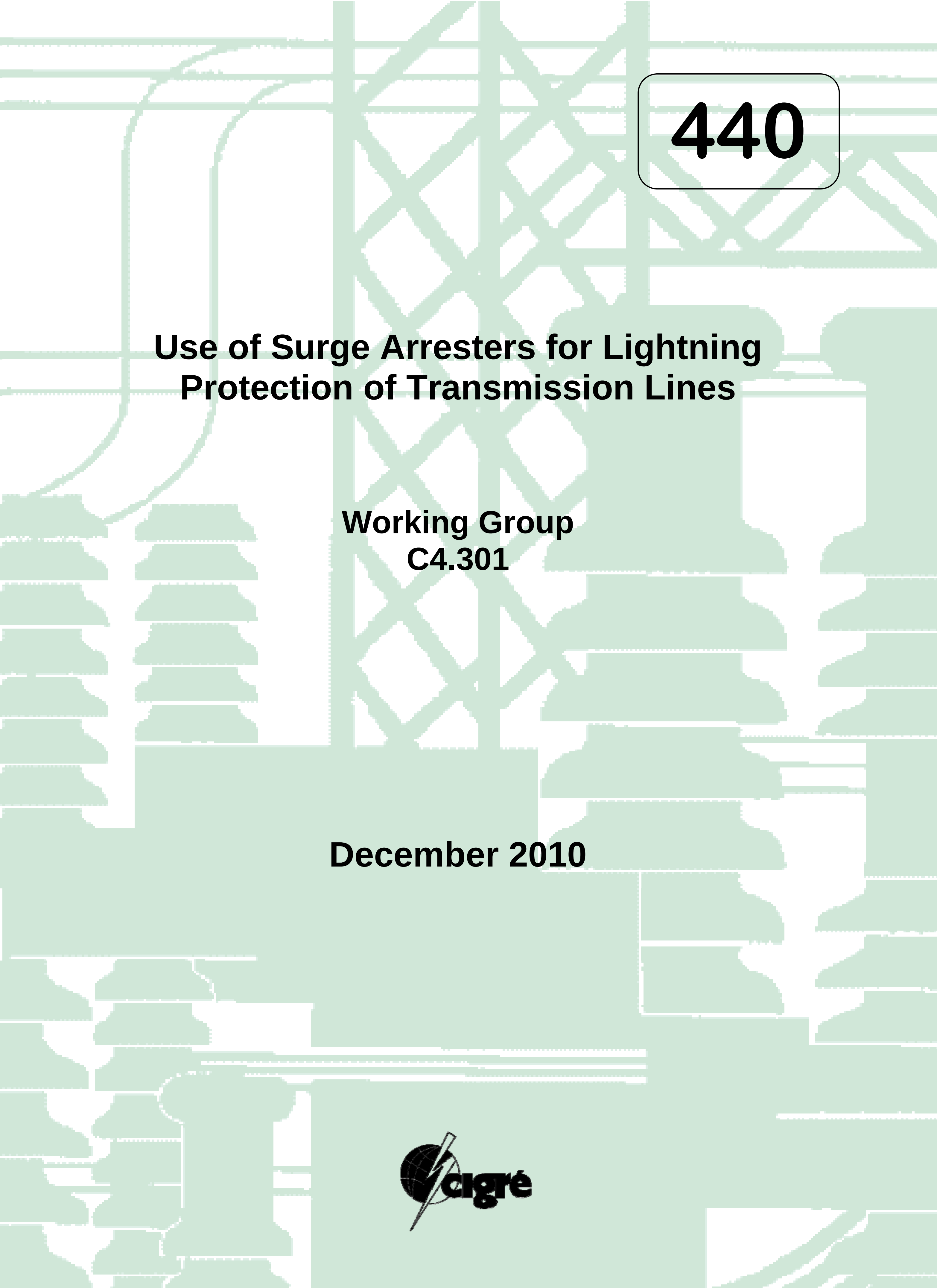

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Use of Surge Arresters for Lightning Protection of Transmission Lines

Working Group
C4.301

December 2010

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ISBN: 978-2-85873-128-2

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1 Introduction

This guide discusses the application of arresters on transmission lines to improve lightning flashover rate. A lightning flashover on a transmission line requires breakers operation to eliminate the resulting short-circuit resulting in a voltage interruption. This voltage interruption can be a short duration one if the line has a fast reclosing sequence. Even if it is of short duration, the momentary voltage dip represents a major concern for customers as equipment or process are nowadays more sensitive than in the past to short interruptions. If flashover occurs on both circuits of a double circuit transmission line, the impact can be very detrimental. Utilities are well aware of the problem and are looking to all possible solutions to improve the situation.

Metal Oxide (MO) arresters are voltage limiting devices that appeared on the market at the end of the 1970s [1][2]. Since then, they have been widely used on power systems and proved their increased robustness, energy absorption capacity and reliability compared to Silicon Carbide (SiC) gapped arresters used in the past on distribution lines [3][4][5]. The performance of MO arresters and the necessity to reduce lightning flashovers convinced electric utilities to try them on transmission lines. Hundreds thousands of units have been installed, during the last ten years, on utilities transmission lines worldwide. Installations were done on lines of different voltage level and configurations [6]. Field performance of the installed line arresters has been very good for the most part [7][8][9][10][11] although mechanical failure rates in some regions are high [12]. The guide presents in §3 the main reasons for line arresters installation.

The arresters installed in parallel with the insulator strings are of two different types [13], as it is presented in §4. One type, called “gapless”, Non Gapped Line Arrester (NGLA), has a normal rating for the service voltage level and its design is similar to the substation arrester. It is equipped with a special disconnector to allow line reclosing and power supply availability in case of arrester failure. The other type, called “gapped”, Externally Gapped Line Arrester

(EGLA), is equipped with an external series air gap that sparks over only when a lightning overvoltage of sufficient magnitude occurs on the line. The gap eliminates flexible connections to ground, and allows the rating of the arrester to be reduced. In case of an arrester failure line reclosing should be successful as the air gap is designed to withstand the resulting switching overvoltages. Each type of arresters has advantages and inconveniences that will be described later in this guide.

The guide proposes also a method to calculate lightning performance of different types of transmission lines (see §5.2) and evaluate improvement resulting from the addition of arresters on selected phases of the lines. The impact of tower grounding resistance is also considered. The last part of the guide is devoted to the presentation of different case studies illustrating the main application of line surge arresters.

2 Generalities

2.1 Some preliminary consideration on line lightning incidence and relevant protection using surge arresters

2.1.1 What is a surge arrester

A surge arrester is a protective device that limits overvoltages on a power system to protect equipment by discharging or bypassing surge current. Its protective level may be selected to limit only lightning overvoltages, in the case of a typical line surge arrester, or it may also conduct during switching surges or temporary overvoltages.

NGLA limits the power frequency flow current to less than a few mA under normal service voltage after any overvoltage. It is able to repeat the overvoltage protection function many times. It has a non linear voltage-current characteristic, typically varying as $V=kI^{1/\alpha}$ with α between 5 and 50, permitting to discharge high magnitude surge currents while limiting voltage to a safe value. The arrester conducts a negligible current at power frequency voltage, even under adverse weather conditions including pollution, wetting, ice or snow, to limit internal power dissipation. A typical characteristic corresponding to an arrester used on a 220 kV system is presented in Figure 1.

EGLA having a series air gap do not conduct power frequency current but provides the same voltage limiting characteristic after flashover of the air gap.

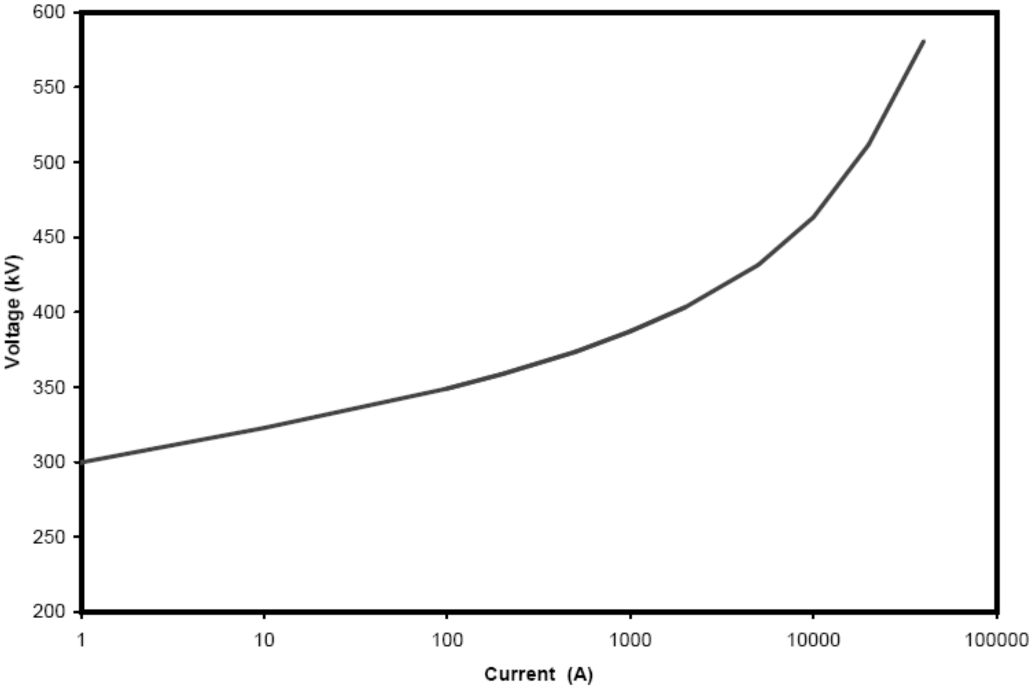


Figure 1: Voltage-Current characteristic of a NGLA.

When surge arresters are installed in parallel with insulator strings (see Figure 2) the arresters are selected to limit the voltage along the insulator strings below their flashover voltage. This avoids flashover of the protected insulator and the air gaps between the protected conductors and the tower. The current conducted by the arrester during this protection function raises the voltage of the protected phase conductor, and a fraction of this voltage is coupled by mutual surge impedance to nearby unprotected phases. The improved coupling, achieved by adding an additional overhead groundwire in parallel with those already existing, affords an additional benefit in reducing the back flashover rate of the unprotected phases, as it will be discussed later in next paragraph.

The next paragraph will give some basic insight on lightning overvoltages occurring on overhead lines and the different possible methods to limit the number of lightning flashovers on overhead transmission lines.

Figure 2: Left picture: RTE employees (France) installing line surge arresters on a 90 kV tower (extracted from [20]); Right Picture: Line surge arresters are installed on a high alpine 110 kV line by a KELAG service team (courtesy KELAG, Austria).

2.1.2 Lightning stroke impacts on a phase conductor, a tower, or a shield wire

Flashovers due to shielding failure

Even if a line is protected by shield wires, it is still possible that a lightning stroke of low current magnitude terminates on a phase conductor. This mostly happens if the so-called protection angle exceeds a given value [14][15] or if the first lightning stroke current has a low amplitude. This phenomenon, called shielding failure, could be a direct root cause of flashover of insulator strings. Shielding failures may result or not in flashover, depending on the amplitude of the lightning current and on the LIFV. Further, one needs to take into account that a large percentage of first strokes are followed by subsequent flashes with a current sufficient to cause flashover, which may result in flashover of an unprotected insulator. For this reason shielding failure is considered to be a problem. The rapid decay of voltage (chop) at the time of flashover is at the origin of severe overvoltage stresses at line terminals.

Figure 3 represents the typical shape of a lightning current. In case of shielding failure, the crest value of the lightning current is equal to a few kA only. Lightning currents of higher magnitude will generally be intercepted by the shield wires as illustrated by electrogeometric models.

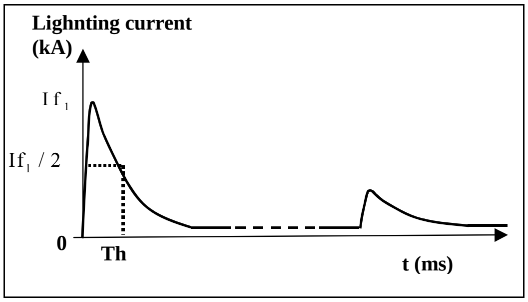


Figure 3: Representation of the lightning current including a first stroke (higher magnitude) and a subsequent stroke.

If lightning terminates on a phase conductor of surge impedance Z_c, which includes corona effects, a voltage travelling wave propagates towards both terminals of the line. Its amplitude, if we assume that that the channel impedance is much greater than the line surge impedance, and denoting with *I*(t) the lightning current, is given by:

$$V(t) = Z_c \frac{I(t)}{2}$$ **Equation 1**

When, at a given tower, the magnitude of the traveling wave overvoltage is higher than the lightning flashover voltage of the insulator string, a flashover occurs. One way to avoid the local flashover is to install a line arrester in parallel with the insulator string. The LSA has to have a lightning protection level lower than the Lightning Impulse Flashover Voltage (LIFV) of the insulator string. However, this may simply transfer the location of the flashover to an adjacent, unprotected insulator, requiring LSA to be installed on adjacent towers where the overvoltages can still exceed insulator LIFV.

The back flashover

When lightning terminates on a tower or a shield wire connected to it, the lightning current circulating through the tower and the grounding electrode will produce a voltage at the top of the tower. In a first approximation, the voltage at the top of the tower can be expressed by:

$$V(t) = L\frac{dI_{tw}(t)}{dt} + RI(t)$$ **Equation 2**

Where :

- R is the resistance of the grounding electrode;
- L is the equivalent inductance of the tower;
- $I_{tw}(t)$ is the current circulating in the tower.

A fraction of the tower-top voltage will appear on every insulated phase conductor, based on the coupling coefficient C_n established by mutual surge impedances between the nth phase conductor and the shield wires. The voltage appearing across the insulator string will be approximately $V(t)\,(1-C_n)$.

If the voltage appearing along the insulator string is higher than its LIFV , a back flashover occurs.

The number of back flashovers can be reduced by:

- lowering the grounding electrode resistance *R*;
- installing line arresters in parallel with insulator strings;
- increasing the lightning withstand voltage of the insulator strings;

- adding shield wires to raise the coupling coefficient C_n;
- adding guy wires to the tower to lower L.

Line surge arresters (LSA) are installed in parallel with line insulators in order to prevent flashovers by limiting the overvoltage. The LSA provides several additional benefits:

- it diverts a fraction of the lightning current in the phase conductor, reducing by this way the current flowing to the tower footing resistance;
- the current circulating in the phase conductors reduces the overvoltage between the terminals of the insulator strings not protected by LSAs;
- the prevention of flashovers reduces the stresses on circuit breakers and terminal equipment, increasing equipment life and allowing longer maintenance intervals.

The characteristics of the arresters are normally chosen to maintain the overvoltage below the LIFV of the insulator strings or air gaps, except in very severe cases.

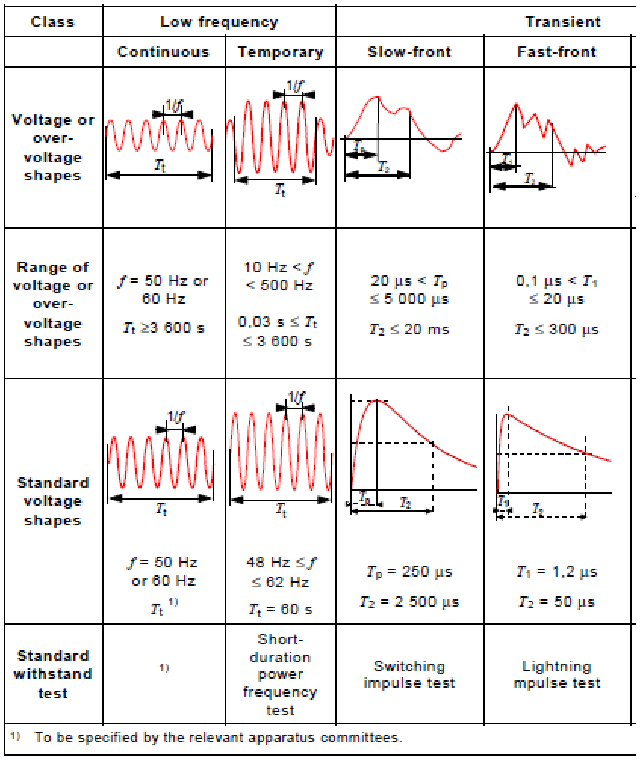
For unshielded line applications, the arrester protective level for high discharge currents may be selected to flash over the insulator for very severe currents. This type of coordination would raise the critical current needed to produce a flashover to a higher level and thus eliminate most but not all back flashovers on the protected phases.

2.2 Notations and acronyms

AC: Alternative Current
BFOR: Back flashover Rate
CLAH: Current-Limiting Arcing Horn
EGLA: Externally Gapped Line Arrester
FOR: Flashover Rate
FFO: Fast Front Overvoltage
LIFV: Lightning Impulse Flashover Voltage
LIWV: Lightning Impulse Withstand Voltage
LSA: Line Surge Arrester
MOR: Metal Oxide Resistor .
MOV: Metal Oxide Varistor
NGLA: Non Gapped Line Arrester
p.u.: per unit
SFIFV: Slow Front Impulse Flashover Voltage
SFO: Slow Front Overvoltage
SFR: Shielding Failure Rate
SFFOR: Shielding Failure Flashover Rate
TFOR: Total Flashover Rate
TOV: Temporary Overvoltage

2.3 Definitions

The Figure 4 below presents the different classes of overvoltages and the corresponding standard voltage shapes specified by IEC.



Class	Low frequency		Transient	
	Continuous	Temporary	Slow-front	Fast-front
Voltage or over-voltage shapes	$1/f$ T_t	$1/f$ T_t	T_p T_2	T_1 T_2
Range of voltage or over-voltage shapes	f = 50 Hz or 60 Hz $T_t \geq 3\,600$ s	10 Hz < f < 500 Hz $0{,}03 \text{ s} \leq T_t \leq 3\,600$ s	$20\ \mu\text{s} < T_p \leq 5\,000\ \mu\text{s}$ $T_2 \leq 20$ ms	$0{,}1\ \mu\text{s} < T_1 \leq 20\ \mu\text{s}$ $T_2 \leq 300\ \mu\text{s}$
Standard voltage shapes	$1/f$ T_t f = 50 Hz or 60 Hz T_t [1]	$1/f$ T_t $48 \text{ Hz} \leq f \leq 62$ Hz T_t = 60 s	T_p T_2 $T_p = 250\ \mu\text{s}$ $T_2 = 2\,500\ \mu\text{s}$	T_1 T_2 $T_1 = 1{,}2\ \mu\text{s}$ $T_2 = 50\ \mu\text{s}$
Standard withstand test	[1]	Short-duration power frequency test	Switching impulse test	Lightning mpulse test

[1] To be specified by the relevant apparatus committees.

Figure 4: The Classes and shapes of overvoltage are shown in Table 1 [IEC 60071-4, 2004].

3 Main reasons for line surge arrester installation

3.1 *Lightning performance improvement*

On transmission lines in the range 60 to 300 kV, generally, more than half of line outages are caused by lightning overvoltages. Line outages on transmission systems have a significant impact on many customers' equipment or processes. In some cases, the automatic and momentary opening and reclosing sequences used to restore service can also increase damage to customer equipment, compared to longer duration interruptions. LSA can be very helpful to reduce the number of disturbances to customers and to improve power supply availability.
The occurrence of double circuit outages on a transmission lines often leads to especially severe power interruption problems. For the reduction of this type of outage, line surge arresters or differential insulation may be considered.
The principle of differential insulation is based on the use of a higher insulation level on one circuit than on the other. The number of double circuit flashovers and the number of flashovers on the highest insulated circuit are reduced. Generally, performance of differential insulation schemes has been highly variable because of variations in tower-to-tower footing resistance, and it is not recommended as a reliable solution for improving double-circuit outage rates. Another disadvantage of this solution is that it does not reduce the total outage rate of the line.
The use of LSA is a better solution than differential insulation. By default, using LSAs on all conductors of one circuit completely eliminates flashovers on that circuit, thus eliminating

double-circuit tripouts. This configuration will also reduce the number of flashovers on the other circuit, as it both reduces the tower-top voltage and increases the coupling of this reduced potential to any phases not protected by LSA, reducing their overvoltage magnitudes and leading to a total line lightning performance improvement.

Double circuit flashovers can also be reduced, but at a lesser degree, using arrester installation configurations that do not protect every phase of one circuit, or every tower. The reduction in double circuit outage rate depends on the arrester installation configuration and on the tower footing resistance, and some of the same problems that affect differential insulation influence the effectiveness.

3.2 Extended protection of substations

By locating arresters on towers in the vicinity of a substation it is possible to eliminate the risk of flashover near or in the substation. This leads to a reduction of the stress on substation equipment due to incoming travelling waves. In some cases the need for additional expensive metal enclosed arresters can be reduced. However the protective performance of line arresters such as residual voltage needs to be evaluated properly, as it may not be equivalent to that of substation arresters. Detailed modelling of incoming surges suggests that LSA tend to reduce the steepness of incoming waves.

3.3 Switching surge control

NGLA may be applied to reduce adequately slow front overvoltages (SFO) such as switching surges [16], as an alternative to breakers closing resistors or point on wave control. This application calls for evaluation of the energy duty.

Reference [17] presents a case of 765 kV overhead line on which line arresters are used to keep the magnitude of the fast front surge below the line insulation Slow Front Flashover Voltage (SFIFV). However, the issue of arrester failure due to excess energy absorption needs to be considered carefully. Transient simulations should be performed in order to determine the amount of energy absorbed by the arresters.

EGLA cannot be used to limit SFO because the external gap is selected to withstand these transients.

3.4 Compact lines

Due to the development of the composite line post insulators, compact line designs could be a very realistic alternative to the standard line designs [18]. Polymer housing surge arresters can be easily installed in parallel with a stack of two or more line post insulators, so that one or more of the line posts forms a natural and fixed series air gap. These devices are controlling overvoltage stresses on the line insulation. With proper selection and insulation coordination, both lightning and switching surge flashover rates can be reduced substantially by the use of NGLA.

3.5 Line voltage uprating

When uprating a line several issues have to be considered : choice of conductors, corona effect, electromagnetic compatibility and clearances. In many cases, it is possible to reduce the phase to phase clearances and the length of the insulator strings of an overhead line by using SFO controls such as closing resistors, point-on-wave switching or surge arresters located at line entrance and if necessary all along the line. A reduction of SFO may also be obtained by using line arresters at specific towers along the line [19]. However, if arresters are not installed on every tower, the flashover rate might be higher than the flashover rate of a standard line (see §5.3.4).

3.6 Touch and Step Voltage Reduction

Line arresters may be used in urban areas in order to significantly reduce the risk of having dangerous touch or step voltages due to power frequency earth potential rise following the insulation flashover. This is a favoured approach that was adopted for example by RTE (the French transmission utility) at 63 / 90 / 220 kV levels in urban areas [20]. Generally, using the new IEC 60479 [21] standard implies that touch potential coordination will automatically provide step potential coordination on the basis of a significantly lower heart current factor for the leg-to-leg contact path.

Issues of touch potential coordination become especially important when surge arresters are used to substitute shield wires as the only form of lightning protection on MV and HV lines.

3.7 Live line working: Protection Function

In case of live line working, NGLA could be used to reduce the minimum approach distance if there was a practical way to ensure the NGLA integrity prior to execute maintenance tasks. The application is similar to protective gap. The crest value of the overvoltages which might exist at the work site is determined by the arrester rating. The arrester offers the advantage of protecting the workers from power-arc radiation compared to a protective air gap. The installation of arresters on all phases on structures adjacent to the work (work site structure not being equipped with LSA) site may be sufficient to protect workers, depending on surrounding grounding conditions. As a switching surge is a slow front surge with low dV/dt, the overvoltage present at work site structure will be higher but just slightly over the protective level of the arresters with little dependence on the separation distance between the work site and the LSA installation. When the protective level of arresters, corrected for separation distance, is lower than the slow front impulse flashover voltage of line insulators and live line tools, flashover at work site has a negligible probability of occurence.
NGLA should be used without a disconnection device in this application to ensure better worker protection.

4 Line surge arrester design and selection

The original applications of MO to transmission lines in the early 1980s used both EGLA and NGLA configurations. For transmission lines, each approach has its merits. The gap of the

EGLA should withstand all power frequency TOV and SFO occurring on the system. Since the EGLA does not conduct during SFO, the associated energy duty does not need to be considered when selecting the arrester rating. In contrast, NGLA must be selected to absorb energy during slow front overvoltages. In the case of NGLA failure a disconnector removes the arrester from service. The disconnector and its flexible connections are perhaps the greatest sources of the failure of arrester function [12].

4.1 Gapped and Gapless arresters

4.1.1 Gapped arresters (EGLA)

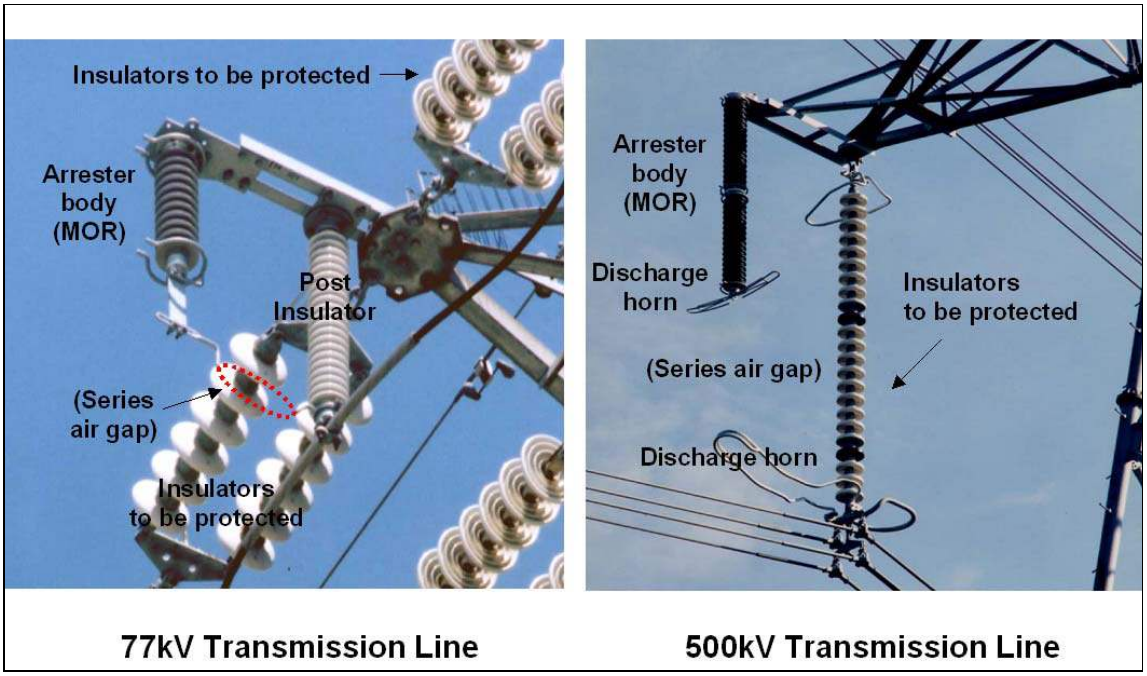


Figure 5: typical mounting structures of EGLA.

According to [10], [20], [13] line surge arresters with series air gap present the following advantages:

<u>Arrester design</u>
The transmission gapped line arrester consists of the series gap and the arrester body, in which the Metal Oxide Resistor (MOR) are inserted.

<u>Absence of permanent stress on the MOR by power frequency voltage</u>
The rated voltage of the surge arrester is lower than the operating voltage, which makes it possible to shorten the length of the live part. Ageing of the housing is slower and reliability is enhanced. If the housing becomes contaminated or coated with ice, the absence of voltage stress means there is no increase of leakage current to cause degradation along the creepage length.

<u>No deterioration in the quality of service</u>

If the MOR fails, the string-arrester assembly continues to ensure "continuity of service" but the significantly lower LIFV has to be taken into account ; there is no sparkover on a slow front overvoltage and it withstands temporary overvoltages. If a ELGA is properly dimensioned, automatic high-speed reclosing will have a high success rate after an MOR fault. This might not be as evident for NGLA as the flexible lead may cause a fault when disconnected or the disconnector device may not operate if the fault current is not high enough.

Withstand large temporary overvoltage in weakly grounded systems
The dimensioning of the air gap is such that the surge arrester-string assembly does not spark over on a slow front overvoltage. The gap can also be dimensioned to withstand large temporary overvoltages, which may persist for an hour or more.

The main disadvantages of EGLA are:

- they might be difficult to install and, if so, may reduce live working clearances after installation;
- they do not share the energy evenly in case of lightning ; however for shielded application energy sharing by the arresters may not give a significant benefit, because most part of the lightning surge will go to the ground via the tower or the overhead ground wires;
- it may be technically difficult to locate an EGLA with a failed MOR; However some utilities use MOR equipped with a fault indicator;
- EGLA require a careful coordination of the voltage-time curve of the insulator with the one of the air gap;
- if a MOR fails, there is an ongoing reduction in LIWV, making a weak-link structure until the MOR is replaced;
- subsequent operations of an EGLA with a failed MOR may increase the possibility of solid material ejection.

One design modification addresses some of these disadvantages. A flex-arrester, is a line surge arrester with an external gap installed on a series composite insulator as shown in Figure 4. The connection between surge arrester and composite insulator with external gap is made with a lightweight, hinged polymer insulator. There is no gap distance change in service and arrester can be easily installed “live”. However some issues like pollution, icing, vibration and conductor motion remains to be resolved. This configuration may offer more advantages for compact lines using stacks of two or more post insulators to achieve the same fixed, controlled gap spacing, such as the Current-Limiting Arcing Horn (CLAH) used widely in distribution systems in Japan.

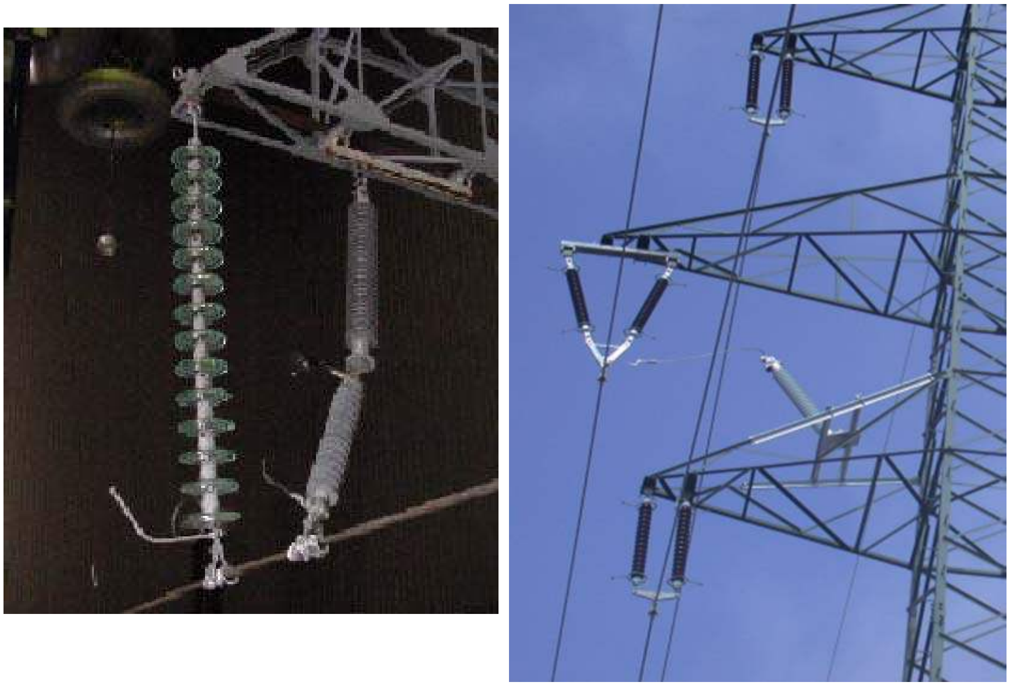


Figure 6: Left picture: Example of a flex-arrester with an external gap installed on a series composite insulator. Connection between surge arrester and composite insulator with external gap is made flexible. Right picture: Line surge arrester mounted on a 110 kV line (Austria). The arrester is a customary metal oxide arrester, which is connected to the middle phase via a disconnection device.

4.1.2 Gapless arrester (NGLA)

The main advantages of NGLA are:

- they may be easily installed, in some cases with live-line work methods;
- they may control slow front overvoltages;
- failed NGLA can be detected by helicopter or long-range visual inspection when the disconnect link falls away from the arrester;
- all NGLA participate in energy sharing.

Their main disadvantages are:

- the disconnector and flexible lead which removes the arrester from service in case of arrester failure is often a weak point; it often fails mechanically from vibration, galloping, conductor restraint, corrosion or other stress;

- the disconnector may not operate if there is insufficient short circuit current on the line;
- the disconnector may also have an internal explosive device which can be an issue for transportation in some countries;
- MO blocks are permanently stressed by power frequency voltage, occasional temporary overvoltages and slow front overvoltages;
- contamination may be an issue in heavy polluted area;
- snow or ice accretion may be an issue in cold climates.

4.2 Line surge arrester energy duty evaluation

A LSA is composed of many varistors in series. The volume of metal oxide in a LSA establishes the energy characteristics that give them a limited ability to withstand temporary overvoltages.

The active part of the surge arrester (varistors) must withstand power frequency voltage, TOV, SFO and fast front transient overvoltages (FFO).

For LSA with a series air gap, the MOR must withstand TOV in the period after flashover on the series air gap caused by a lightning overvoltage. The duration of this period depends on the clearing time of the gap. This clearing time (number of cycles) depends in turn on the magnitude of the current conducted through the arrester while the TOV is applied across its terminals.

There are differences regarding energy duty for the arrester, depending on whether or not the line is protected by shield wires. When the line is efficiently protected with shield wires, the high peak lightning strokes will impact the shield wire and will be partly diverted to ground. Only a fraction of the total lightning current will circulate through the arresters. The shape of the line arrester current will be different than the shape of the original stroke. Thus, the line arrester current tail will be shorter and less energy will be injected in the arrester.

For unshielded line, a phase conductor can be hit directly by high peak current lightning strokes. This may produce line surge arrester to be severely stressed. The shape of the line arrester current will be similar to the shape of the original lightning stroke. The energy absorbed by the arrester will be essentially proportional to the charge transfer. This may be a reasonable value for negative flashes, but may exceed energy duty of LSA for positive flashes that have at least ten times more charge than negative ones. The risk of failure of arresters due to energy breakdown is an important parameter to make a rational and economical design for an unshielded, LSA-protected line.

4.3 Dimensioning the series air gap of EGLA

The air gap in series with MOR must be dimensioned to flashover before the insulator string for lightning overvoltages but must not flashover on switching surges to limit the energy absorbed by the arrester having normally a low energy absorption capability [20], compared to NGLA. The calculation of power frequency AC extinction capability of the series gap, based on the power follow current in the arrester, should be performed using the same mathematical model that is used for pollution flashovers or by tests.

The switching overvoltages generally defines the minimum length of the air gap in series with the MOR. The series air gap is defined in this case by considering a faulted surge arrester as a part of the geometric arrangement when computing the gap factor.
The maximum length of the series air gap is defined based on minimum value of lightning overvoltages for which flashovers is required.

4.4 Selection of the characteristics of LSA

The rated voltage of NGLA is selected based on the highest voltage and on the amplitude of the temporary overvoltages and their duration. It [23] is usually taken one step higher than the rated voltage of the arresters used for the substations of same voltage level. Regarding energy withstand, class 1 and class 2 arresters are usually used for shielded lines and class 2 and class 3 for unshielded lines. IEC 60099-4 specifies tests procedures for the determination of the lightning impulse discharge capability of LSAs.
For general details on surge arresters selection consult [24] which explains how to select surge arresters characteristics from the standards.

5 Improvement of the continuity of service of an overhead line

5.1 General remedies

In general, the poor lightning performance of an overhead line is due to flashovers at a limited number of towers or line segments (e.g. [25]). The first step of a study for improving the lightning performance of a line consists in detecting the portions of the line where line outages occur frequently. This is done by measuring the lightning activity of the region where the line is located, measuring the grounding resistance of towers, checking the specificities of the different segments of the line (portions without shield wires, towers located at the top of hill and being particularly stroked by lightning, etc.).
Once the critical spots along the line have been located, the analysis work can begin. Several classical and well-known improvement techniques can be applied:

1. installation of overhead shield wires above phase conductors at portions where they are missing ;
2. improvement of tower grounding resistance ;
3. installation of an under-built shield wire or OPGW beneath the phase conductors ;
4. increasing the withstand voltage of insulator strings ;
5. addition of line surge arresters.

Although it is point nbr. 5 above which is of interest for this brochure, we think it worth adding some comments also on the other items mentioned above. The first measure may lead to significant modifications of towers due to mechanical reasons, or to an outage of significant duration to install new shield wires, its effectiveness depends on the tower grounding impedance of towers. Clearance distances are generally an issue for the second measure. Generally on existing tower configurations the remaining margin to increase insulation length is limited, therefore an increase of insulator string length has to be combined with an improvement of the tower grounding resistance in order to obtain a significant reduction of the flashover rate.

The effectiveness of the improvement of the tower grounding resistance for the reduction of the back flashover rate depends on the value of resistance which can be achieved in practice. For instance, for the configuration considered in Figure 7 (adapted from [25]) in a rocky area where it is not possible to reach a typical value of 10 Ohms or less for the tower grounding resistance, the reduction of the tower grounding resistance from 200 Ω to 90 Ω does not lead to any performance improvement.

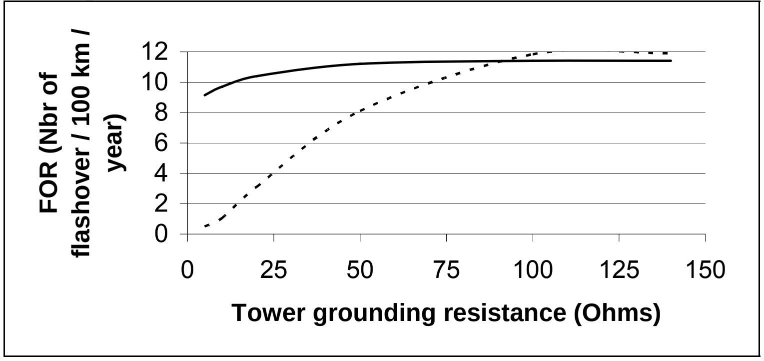


Figure 7: Flashover rate vs. tower grounding resistance for a 90 kV single circuit line having one shield wire (dotted line) and no shield wire (solid line). Ground flash density Ng = 1 (adapted from [25]).

Moreover, in order to improve the tower grounding resistance it would be necessary to know why the grounding resistance is high. Is the grounding electrode too small? Is the soil resistivity very high? In many cases, the knowledge of the grounding electrode is limited to its grounding resistance and does not indicate if the improvement of the grounding electrode performance is feasible or not. This knowledge needs to be completed by the investigation of the grounding electrode structure or of the soil resistivity. An initial indication of the local resistivity can be obtained from the recommended value of conductivity based on CCIR recommendations for medium frequency radio broadcast [26].

The following questions have to be addressed if installation of line surge arresters is planned:

- On what portions of the line are they needed ?
- Is it necessary to install arresters on all phases ?
- What are the energy duty requirements ?

5.2 Calculation of the lightning flashover rate of a line equipped with surge arresters

5.2.1 General concepts

The efficiency of mitigation measures adopted to limit the number of lightning flashovers depends on the characteristics of the overhead line considered and may be evaluated by calculating the flashover rate of the line. The goal of this paragraph is to give some basic insight on an approach applicable to flashover rate calculation, keeping in mind that other possible methods exist [27][28], and to what is contained in reference [25]. Three main groups of aspects are involved in the calculation of transmission lines lightning performance: those related to the lightning current characteristics (e.g. peak value, time to crest and rate of rise); those related to the attachment process between lightning channel and transmission line components; and those related to the electromagnetic response of the line reached by the lightning. Transmission lines may present several different configurations for the towers, overhead conductors and tower-footings. Different configurations of these components establish different transitory responses under lightning stress, which reflect on the calculated values for the resultant overvoltages.

The calculation of the lightning flashover rate of a line includes the following steps (see also [25]):

1. application of an electro-geometric model (EGM) to determine the number of lightning flashes to each element of the line and the probability density of the resulting peak stroke current amplitudes;
2. EMTP simulations of the electromagnetic transients due to first and subsequent lightning strokes to the line;
3. evaluation of the flashover rate of the line segment under consideration. The stochastic nature of lightning is taken into account and the results of the previous stages are included.

Note that for a line equipped with surge arresters, point nr. 2 above, which in [25] is mentioned as one of the possible tools besides some simpler analytical methods, acquires crucial importance. The calculation process may be represented by

Figure 8 below.

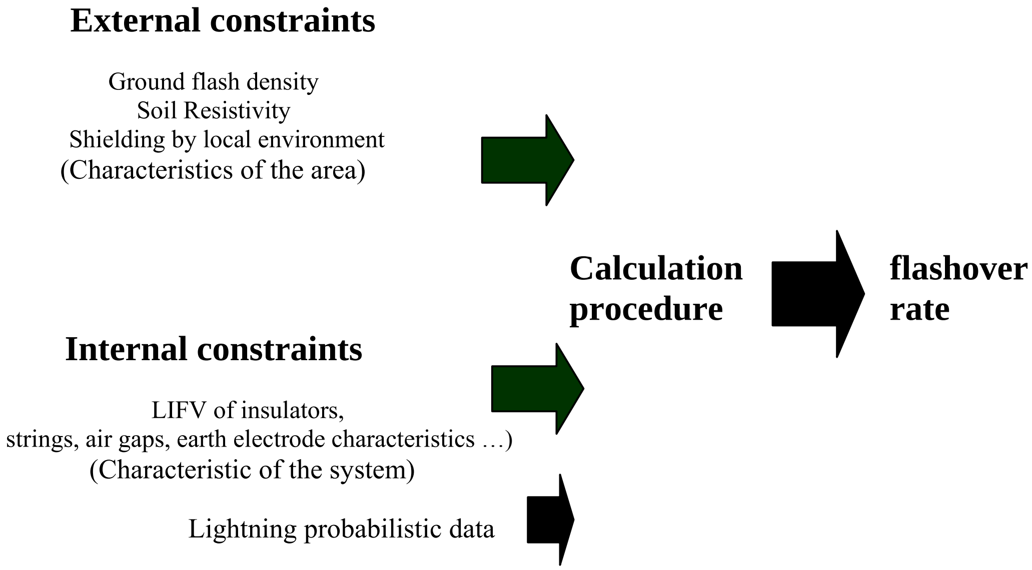


Figure 8 : Type of data used for the calculation of the flashover rate.

5.2.2 Calculation methodology

The evaluation of the flashover rate of a line segment may be accomplished by splitting the segment into elements (section of shield wires, section of phase conductors, etc.) which will be considered separately in the flashover rate calculation (see Figure 29 in attachment A). Only one point of impact is considered per element when performing the transient simulations, which is assumed for simplicity in the middle of the segment. It is supposed that overvoltages due to a lightning stroke impacting an element do not change significantly with the position of the point of impact inside the element. This technique allows reaching a sufficient accuracy with an acceptable number of transient simulations. On a line segment, the elements correspond to the tower, sections of shield wires and sections of phase conductors. The evaluation of the flashover rates of a segment of line involves two successive steps:

- the evaluation of the lightning incidence; the number of lightning strokes impacting each part of the line is deduced from the ground flash density and the law of probability of the crest value of the lightning current on ground [25]; the law of probability followed by the lightning stroke current impacting each part of the line is also determined;
- evaluation of the flashover rate based on transient simulations.

These steps are detailed in Attachment A.

As it has been written before, other types of calculation procedure might be used to perform the flashover rate calculation. For instance Monte-Carlo methods could be used [27]. It should also be pointed out that the EMTP software has been mentioned in this paragraph but other software tools may be used for transmission line lightning performance evaluation with special reference to LSA, like TFLASH, Sigma slp or NETOMAC.

5.2.3 Modelling guidelines

References [15],[29], [30], [31], [32], and [33], and attachment A give detailed discussions on the modelling to be used when performing this type of calculation, the goal of this sub-paragraph is to provide a summary useful for the purpose of interest:

- the line (shield wires and phase conductors) is modelled by means of several spans on each side of the point of impact. Each span can be represented as a multi-phase untransposed distributed-parameter line section with either frequency-dependent or constant parameters (calculated at 500 kHz);

- in order to avoid reflections that could affect the simulated overvoltages around the point of impact, the line termination on each side of the above model is represented by means of either matching impedances or a long enough section, whose parameters are calculated as for the line wires;

- a tower is represented as an ideal single conductor distributed parameters line;

- a lightning stroke is represented as an ideal current source with a concave waveform. The return current stroke waveform is defined by the peak current magnitude, I_{100}, the rise time, t_f (= 1.67 ($t_{90} - t_{30}$)), and the tail time, t_h, that is the time interval between the start of the wave and the 50% of peak current on tail.

5.3 Case studies

5.3.1 Case 1: Base case: 100 kV line in a mountainous region

5.3.1.1 General Remarks

As earlier mentioned, for the application of line arresters on overhead line systems numerical tools (transient calculation software) are essential to calculate the transient stresses considering the standards for insulation coordination. The quality of the results is mainly based on the numerical line and component models and on the representation of the lightning current source. In what follows we provide some more detail concerning this point that was earlier mntioned.

The following information are required to have a proper modelling of the configuration to be studied :

- tower type;
- tower geometry;
- span length;
- grounding resistance and earthing configuration;
- shield wire(s);
- air gaps;
- arresters.

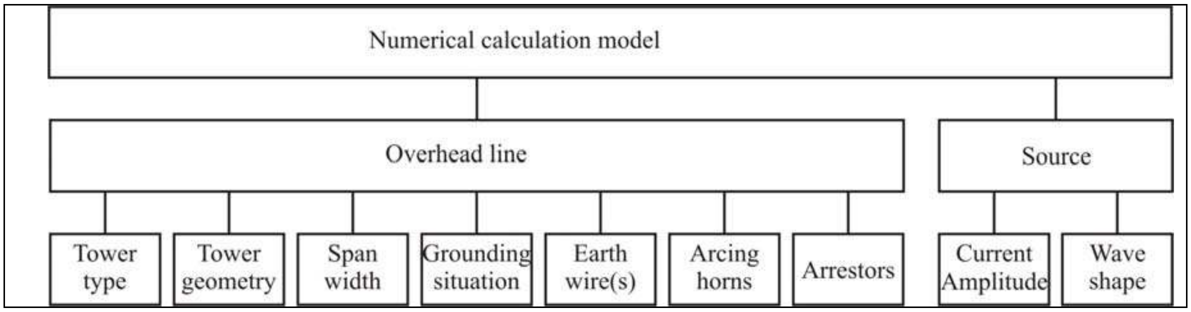


Figure 9: information required to model the system.

The characteristics of the lightning stroke such as steepness (dI/dt) and peak current have important effects on the transient results. Therefore in this study the parameters of the lightning current have been selected according to the following assumptions:

Current magnitude and wave shape based on standards ;

Current magnitude and wave shape based on worst case approximation, for example using an upper peak current limit of 200 kA as it is done in [34];

The current magnitude based on average values detected by a lightning location system in the region of interest ;

The current magnitude based on the observed values detected by a lightning location system in the region of interest.

Several indications provided by the lightning location system, especially the measured rise time but also the peak current, may be affected by the local soil resistivity. Current magnitude data from regions with conductivity of 1 mS/m or less (1000 Ωm or more) should not be used without a careful study of the signal attenuation rates.

5.3.1.2 Electrogeometric model application

To determine the amplitude of lightning surge, additional studies based on the electrogeometric model are helpful. With this procedure the specific situation of the tower location with respect to the surrounding area (flat or hilly surface, slopes, extreme steepness, mountain peaks) can be observed. With on-site evaluations, photographs and electronic maps the landscape can be reconstructed. With the electrogeometric model one calculates the probability of direct impacts to the phase conductors, towers and sky wires.

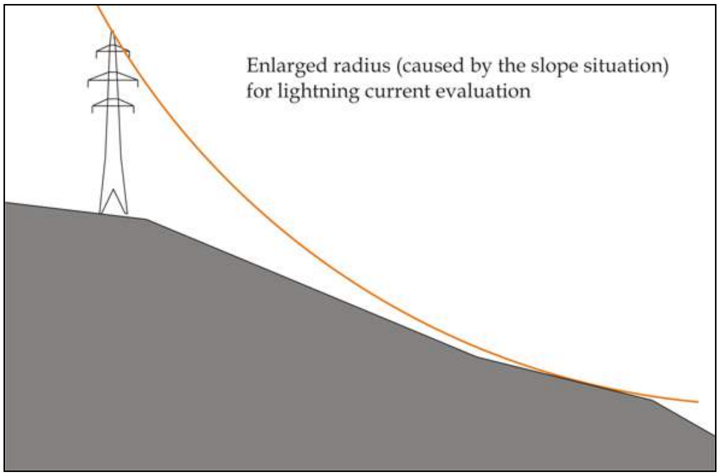


Figure 10: Example of a tower profile, which is located at a slope, with enlarged lightning sphere radius of 200 m corresponding to a large-current flash.

The calculation of the lightning flashover rate for a line located in complex topographic conditions presents difficulties. In case of slope it might be possible to represent the slope by an equivalent horizontal ground.

The leader progression model [35] might also be used for calculation of the lightning incidence and the shielding performance in these situations.

5.3.1.3 Transient stress situation

The transient voltage stress has been numerically calculated based on a lightning stroke having the following parameters:

Amplitude 15kA;

Wave shape 1,2/50µs.

The following graphs were produced with the EMTP program. They show a lightning transient analysis on a double circuit 110 kV tower stroke by lightning. The blue curve represents the lowest phase, green is the middle one, whereas the phase at the top of the tower is red. The tower grounding impedances are 500 Ohms and 10 Ohms.

Figure 11 (left graph) shows the ideal voltage transients across the insulator strings (differential voltage between tower and phase conductor) as it is assumed that the insulation has an infinite withstand. In that case, the voltages would rise up to more than 2.2 MV.

It can be observed that the lowest phase (blue) is the most heavily stressed one.

The right graph shows the same configuration as above, except that now the tower is equipped with air gaps on all phases. It can be shown that the lowest phase (blue) is the first one to reach the ignition voltage of the air gaps.

Because of the high tower impedance also the central and the uppermost air gap also flashes over.

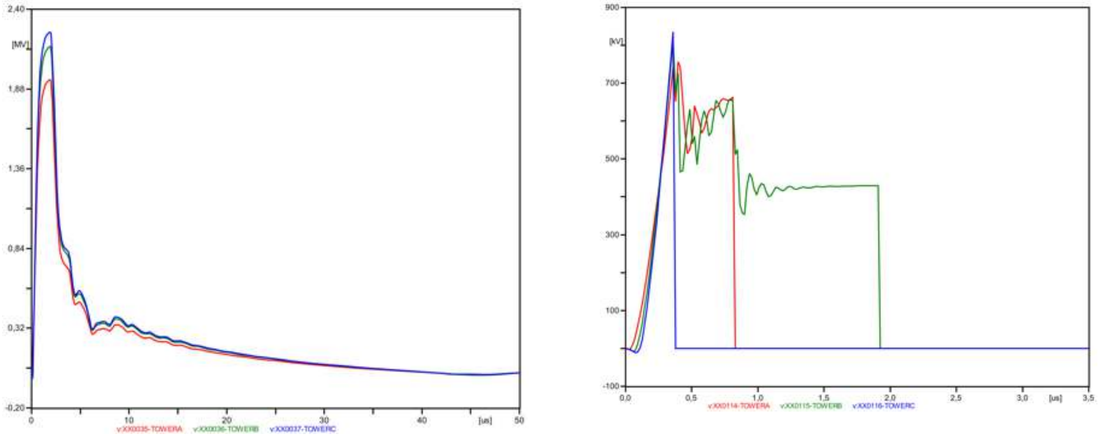


Figure 11: Overvoltage between the terminals of the insulators strings for a 110kV tower hit by a +15kA lightning strike – without any protection (left), with air gaps (right).

Figure 12 shows a tower equipped with line surge arresters. The arresters are placed in the upper phase (red curve) and in the lower phase (blue curve). The tower earth impedance is varied from 10 Ohms (left picture, good earthing conditions) to 500 Ohms (right picture, bad earthing conditions).
In both cases it can be easily seen that the middle phase is the most stressed phase, which is obvious because it is the only unprotected phase. The difference between the two cases is in the total amplitude of the transients and the trend and duration of the oscillating voltages.

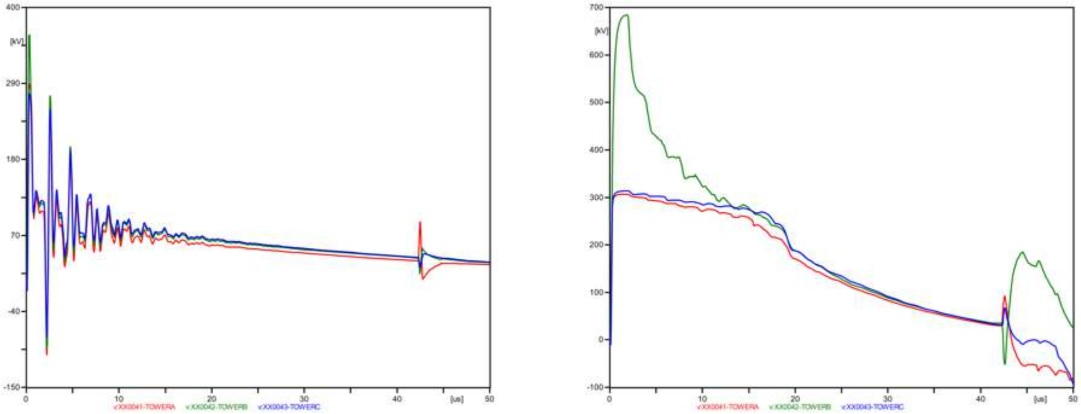


Figure 12 : 110 kV Tower equipped with line surge arresters on the top and low phase and hit by a +15 kA lightning strike. The tower grounding resistance is either 10 ohms (left graph) or 500 ohms (right graph

It was observed from transient calculations that, without protection device, the crest value of the lightning overvoltages applied between the terminals of insulator strings is in a range of approx. 2,2 to 3MV.
Air gaps at the insulators reduce this value to a range of approximately 650 to 750kV and line arresters to a value of approximately 300 kV (see Figure 13 below).

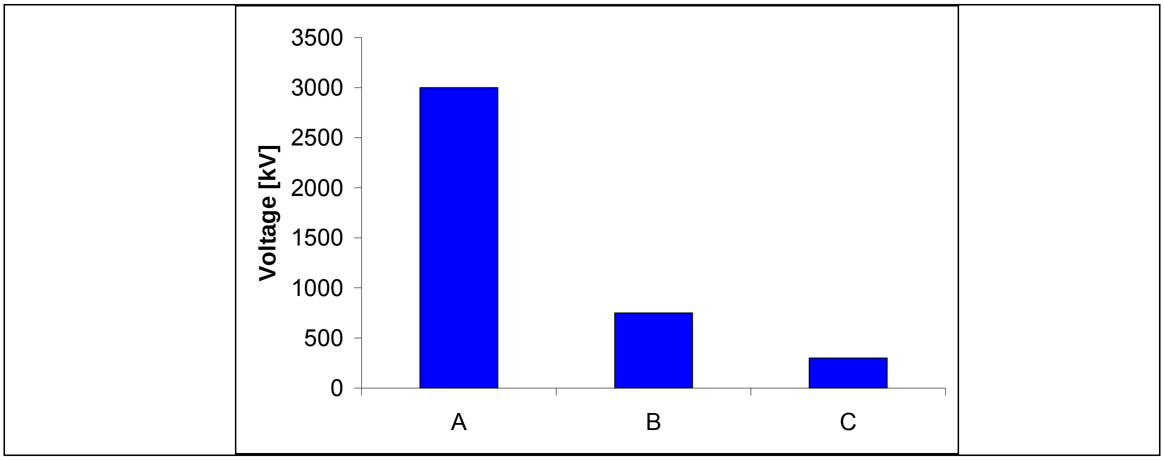


Figure 13: Comparison of the maximum overvoltage magnitude for different protection systems

A	…	without any protection ;
B	…	air gap protection ;
C	…	line arrester protection.

5.3.1.4 Grounding considerations

In the configuration studied in this example the soil resistivity can vary from very low values around 100 Ωm (good conductivity of the soil) up to extremely high values such as 10000 Ωm (extremely poor conductivity of the soil).

5.3.1.5 Tower rearrangement

To reduce the amount of direct lightning flashes to the phase wires, the effectiveness of the shield wire is important and depends on the protection angle given by the shield wires to the phase conductors. In areas with extreme slopes, cliffs or river crossings, additional shield wires or a lower protection angle may be necessary to obtain an acceptable shielding failure rate. The performance of a shielding configuration can be evaluated by example with the electrogeometric model.

In Austria for special situations one method to get additional shielding protection was the rearrangement of a double three phase systems into one active three phase system with three spare conductors in reserve. The two upper phase conductors of the towers have been connected and grounded to each steel tower. As a result of these connections, the two conductors on top of the tower act as two additional shield wires with a better protection angle and better coupling coefficient to insulated phases. Shielding failures are reduced by the former effect, and backflashover failures are reduced by the latter. Adopting such a measure can be done only if there is no impact on the load being fed by the line.

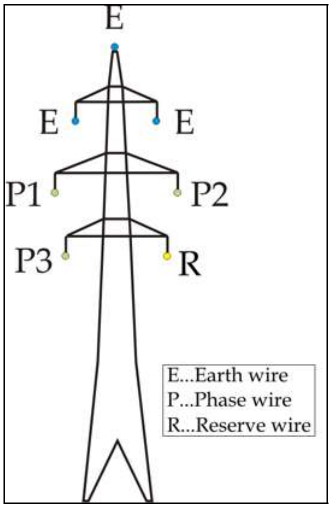


Figure 14: Modified tower configuration after system rearrangement (now: single 110 kV system) with 3 shield wires and 1 spare wire.

Note that the coupling in this case could be improved further by grounding the remaining spare wire at every tower.

5.3.1.6 Line arrester installation

One measure to reduce the line outage rate of overhead lines is the installation of line arresters. For an effective choice of the location of the line arresters along the line and also for the evaluation of the number of arresters to be installed, numerical calculations are generally required as well as the record of the lightning activity along the line.
For the installation of line arresters on steel towers the following issues need to be considered carefully :

1. type of tower;
2. installation feasibility considering the geometry of the towers;
3. static forces on the towers;
4. wind forces on the arresters;
5. fixed or flexible installation of the arresters;
6. connection of the arrester to the phase wire (connection lead);
7. position of the disconnection device.

Taking into account all these issues several installation configurations of line arresters on the towers are feasible. Figure 15 shows one of them with gapless arresters.

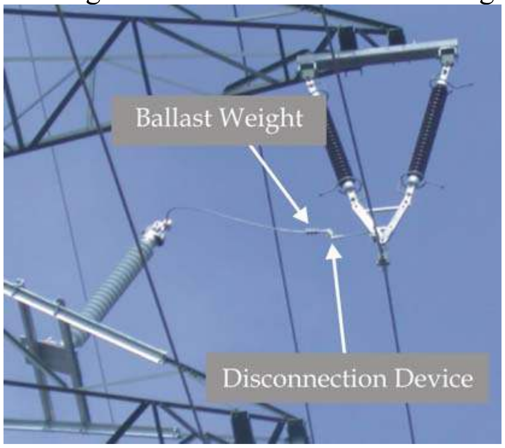


Figure 15 : Line arrester with a disconnection device mounted on a 110 kV tower.

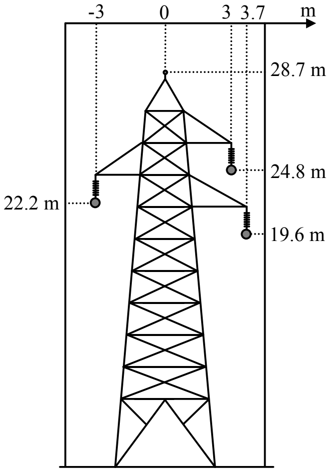
Electrical clearances must be taken into account to get the correct installation location of the line arresters as well as the flexible lead to the arrester. If the disconnection device in Figure 12 is activated the flexible lead to the arrester falls down and may blow in the breeze if there is not enough ballast weight. Thereby the possibility of an electric arc and the resulting fault has to be taken into account. With this additional weight on the flexible lead the rebound of the lead can be better controlled, although it may oscillate like a pendulum for some time after disconnection.

5.3.2 Case 2: Calculation of the flashover rate of a 90 kV line with shield wires

The goal of this paragraph is to study the influence of both, the grounding resistance and the withstand voltage of the insulator strings on the flashover rate of the line. Due to the structure of the 90 kV network, multiphase flashovers are more likely to produce severe voltage dips than single phase flashovers; therefore both multi-phase and total flashover rates are evaluated.

Description of the configuration

A 90 kV overhead line having one shield wire is considered. Figure 16 gives the position of conductors at towers. The lightning impulse flashover voltage of the insulator strings is 520 kV. The ground flash density is equal to 1. In both calculations 6 power frequency angle values are considered for the 50 Hz voltage when calculating the back flashover rate. No ionization model has been considered for representing the grounding of towers.



Type of conductor	Horizontal position (m)	Vertical position (m)
Phase A	3.7	19.6
Phase B	-3	22.2

Phase C	3	24.8
Shield Wire	0	28.7

Figure 16 Geometrical configuration of towers

Results

Influence of the Tower grounding resistance

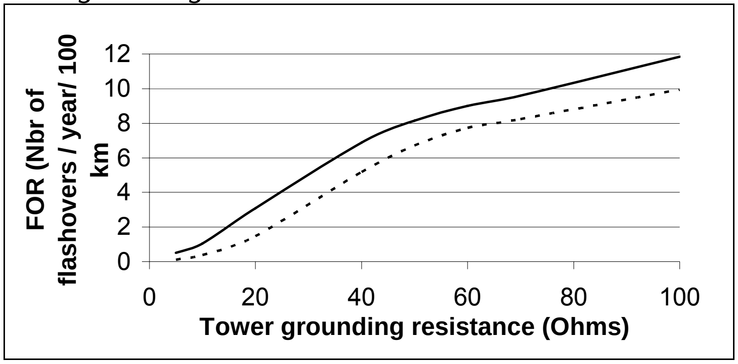


Figure 17 : Total flashover rate (solid line) and multiphase flashover rate (dotted line) of a 90 kV single circuit line having one shield wire.

It can be seen from Figure 17, that for a tower grounding resistance above 25 Ω, more than half of the flashovers are multiphase flashovers.

Effect of the withstand voltage of the insulator strings

Figure 18 shows that increasing by 10 % the lightning withstand voltage of the insulator strings gives only limited improvement if tower footing resistance is high.

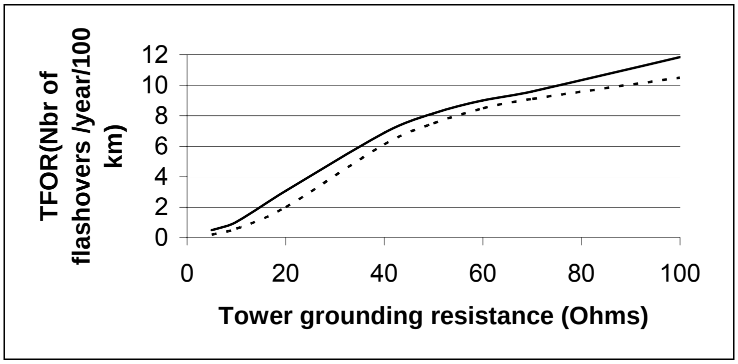


Figure 18 Total flashover rate of a 90 kV single circuit line protected by a shield wire: LIFV of 520 kV (solid line) and 10 % increased LIFV (dotted line).

5.3.3 Case 3 : Line surge arresters to improve the lightning performance of a 90 kV single circuit line with shield wires

Line surge arresters are installed on phase A of the line described in the previous paragraph. In this case the LIFV of the insulator strings is 350 kV.

Figure 19 compares the total flashover rate of the line equipped with line surge arresters on phase A, with the total flashover rate of the line without arresters. It can be seen that the improvement of lightning performance is limited for high tower grounding resistances. No ionization model has been considered for representing the grounding of towers.

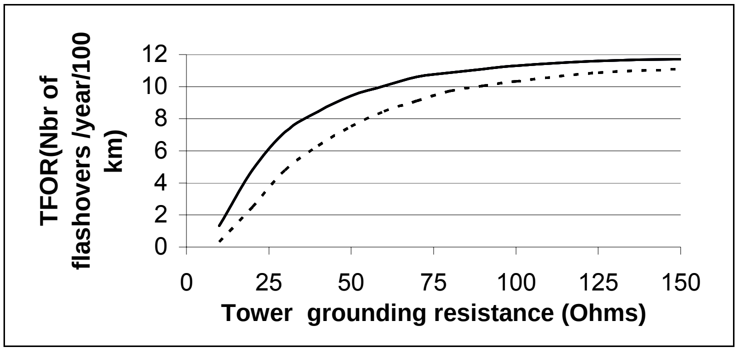


Figure 19 Total flashover rate of a 90 kV single circuit line without arrester (solid line) and total flashover rate of the same line protected by line surge arresters on phase A (dotted line).

Figure 20 shows that the improvement of the lightning performance due to the presence of line surge arresters is more effective when the multi-phase flashover rate is considered.

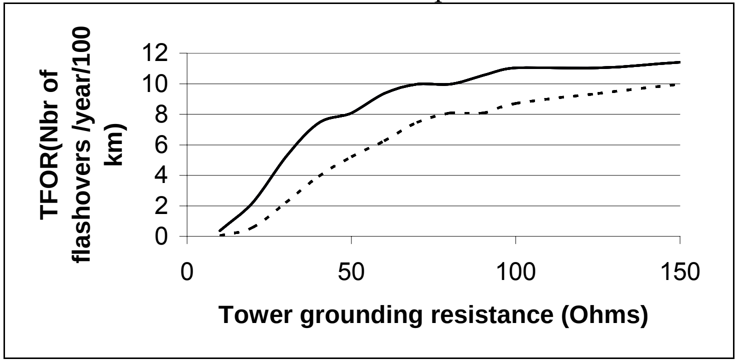


Figure 20 Multiphase flashover of a 90 kV single circuit line without arresters (solid line) and multiphase flashover rate of the same line equipped with line arresters on phase A (dotted line).

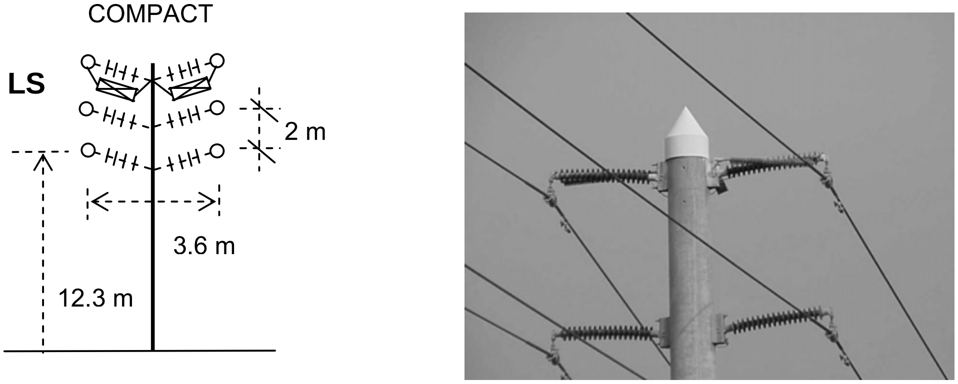
5.3.4 Case 4 : Use of line arresters on a double circuit compact unshielded line

The lightning performance of a double circuit 138 kV unshielded compact lines with and without line surge arresters was studied and compared. Line geometry is given in Figure 20. The following assumptions were used in all simulations :

- the line insulation critical flashover voltage is 770 kV ;
- the ground flash density is 8 strokes/km^2/yr ;
- the line span length is 100 m ;
- the tower surge impedance is 180 Ω.

The ratio between soil resistivity and tower low current grounding resistance is equal to 30. A total number of 1000 statistical cases is used for each value of tower grounding resistance and arrester installation configuration. The line total flashover rate and double circuit outage rate for different arrester installations is evaluated.

Gapless polymer housing line surge arresters, having MCOV equal to 98 kV are installed in parallel with line post insulators of the 2 upper phases (Figure 21).



a) Line geometry

b) LSA on the top conductors only

Figure 21 Double circuit 138 kV compact line (Florida Power & Light).

Results of the simulations for the different tower grounding resistance and different line surge arrester installation configuration are presented in table 1 and 2. Table 1 presents line total flashover rate, while line double circuit outage rate is given in Table 2.

For line without line surge arresters almost all stokes collected by the line produce line insulation flashover (87 Flashes /100km/yr). The installation of line surge arresters on the two top conductors only, substantially improve line lightning performance (less than 1 flashover per 100 km per year if the grounding resistance is less than 40Ω).

Line double circuit outage rate, which highly depends on the tower grounding resistance, may be improved by the installation of line surge arresters as can be seen in table 2 (reduce to zero with arresters on the top and bottom phases).

Table 1 Line total flashovers rate (Flashovers / 100km /yr)

R (Ω)	LSA 0 ○ ¦ ○ ○ ¦ ○ ○ ¦ ○	LSA 1,4 ● ¦ ● ○ ¦ ○ ○ ¦ ○	LSA 1,3,4 ● ¦ ● ○ ¦ ○ ● ¦ ○	LSA 1,3,4,6 ● ¦ ● ○ ¦ ○ ● ¦ ●
10	86,47	0	0	0
20	86,47	0	0	0
30	86,47	0,08	0	0
40	86,47	0,6	0,08	0
50	86,47	1,91	0,26	0
60	86,47	3,47	0,95	0
70	86,47	5,21	1,91	0
80	86,47	6,87	3,3	0,34
90	86,47	8,26	4,08	0,52
100	86,47	11,65	5,13	0,95

Table 2 Line double circuit flashover rate (Flashovers / 100 km /yr)

R (Ω)	LSA 0 ○ ¦ ○ ○ ¦ ○ ○ ¦ ○	LSA 1,4 ● ¦ ● ○ ¦ ○ ○ ¦ ○	LSA 1,3,4 ● ¦ ● ○ ¦ ○ ● ¦ ○	LSA 1,3,4,6 ● ¦ ● ○ ¦ ○ ● ¦ ●
10	0	0	0	0
20	0,08	0	0	0
30	1,21	0	0	0
40	4,26	0	0	0
50	7,22	0	0	0
60	10,09	0	0	0
70	14,52	0,43	0	0
80	18,09	0,69	0,08	0
90	22,09	1,47	0,08	0
100	26,09	1,65	0,26	0

● - LSA installed
○ - Without LSA

5.3.5 Case 5 : Transmission line with different circuit voltages

This paragraph presents results of the study dealing with the application of line surge arresters on a quadruple circuit transmission line. Considered transmission line consists of two 275 kV circuits and two 132 kV circuits protected by 2 shield wires. Line surge arresters with external gap are installed on the 132 kV circuits. Different arrester installation configurations are studied and compared. Line surge arrester installation strategy is presented.

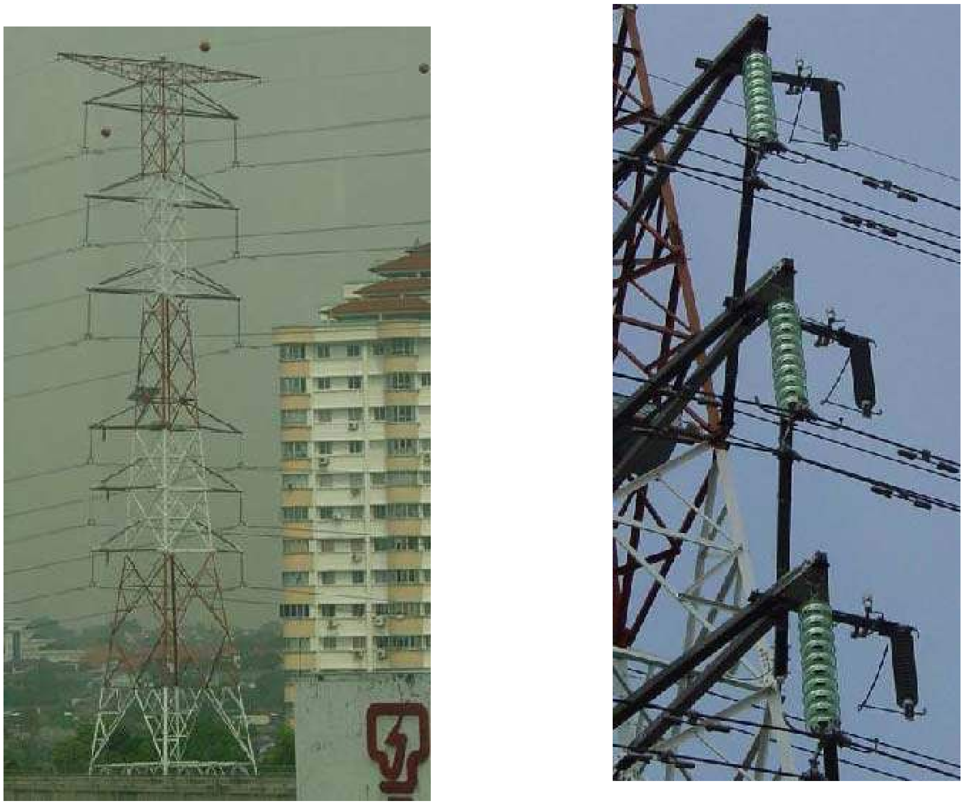


Figure 22 Quadruple circuit transmission line with line surge arresters installed on the 132 kV circuit.

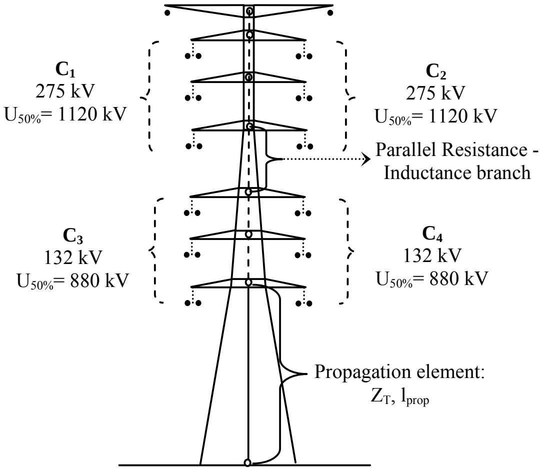


Figure 23 Representation of the quadruple circuit line with some modelling information.

Line lightning performance is first determined for the line without arresters. Then, several arrester installation configurations are studied, taking into account that the maximum number of arresters to be used is less or equal to three. Arrester installation configurations are only considered on the 132 kV circuits. Each tower in the analyzed section of the line has the same arrester installation configuration.

A total number of 2000 electromagnetic transients statistical simulations are performed for each studied case (different tower grounding resistance or arrester installation). All presented results are for a ground flash density of 20 strokes/km^2/yr.

Lightning performance of the line without LSA is presented in Table 1 (per circuit flashovers). As expected, the majority of the flashovers happens on 132 kV circuits. Line lightning performance strongly depends on the tower grounding resistance. For tower grounding resistance less than 10 Ω, zero flashover rate is obtained (the line is protected by two shield wires having a negative shielding angle).

In Table 2, the line total, single, double and triple circuit flashover rate is presented (no quadruple simultaneous flashovers).

The number of double circuit flashovers depends on the tower grounding resistance, and may reach value of 35 % of the line total flashover rate, for the tower grounding resistance of 40 Ω. Number of the triple circuit flashovers (simultaneous flashovers on two 132 kV circuits and on one 275 kV) is very low.

The results of the simulation for the different line arrester installation configuration are presented in Table 3 and Table 4. The arrester installation configuration is graphically indicated in the corresponding tables : empty - white circle - no arrester installed; black circle - arrester installed.

Table 3 presents the total line flashover rate (data for line without line arresters is also given for the comparison).

A substantial improvement in the total line flashover rate is obtained by the installation of line arresters on the two bottom conductors of the 132 kV circuits. These two conductors have the lowest coupling factor with the ground wires. It is interesting to note that the two arrester configuration gives better total flashover rate than the one with three arresters installed on all the phase conductors of one 132 kV circuit.

Table 1

Flashover rate for different circuits

without line surge arresters

(Flashovers / 100 km / yr)

R_T (Ω)	C_1 [275]	C_2 [275]	C_3 [132]	C_4 [132]
10	0	0	0	0
15	0	0	0.78	2.14
20	0	0	5.66	4.88
25	0	0.19	12.69	10.92
30	0.19	0.39	20.69	20.69
35	0.19	0.58	29.67	33.58
40	0.19	0.19	42.55	46.85

Table 2

Line total and multi circuit flashover rate

Without line surge arresters

(Flashovers/ 100 km /yr)

R_T (Ω)	Total	Single	Double	Triple
10	0	0	0	0
15	2.93	2.93	0	0
20	8.39	6.24	2.14	0
25	18.35	13.08	5.07	0.19
30	32.60	23.81	8.19	0.58
35	49.26	32.41	14.64	0.78
40	65.64	41.98	22.84	0.78

The best improvement in the line total flashover rate is obtained by the installation of the arrester on the bottom conductors of both 132 kV circuit and on the top conductor of one 132 kV circuit (the best three arrester installation configuration).

When line surge arresters are installed on all phase conductors of one 132 kV circuit, double circuit flashover are completely eliminated (actual installation on the considered transmission line). But, it is to be noted that with this arrester installation configuration the total line flashover rate remains high.

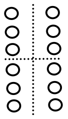
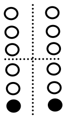
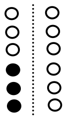
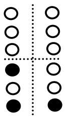
Arrester installation configuration with the arresters on the bottom conductors of both 132 kV circuits and on the top conductor of one 132 kV circuit is very attractive, because this configuration substantially reduces the line total flashover rate, while reducing at the same time line double circuit flashover rate. With this arrester installation configuration coupling between 132 kV circuits conductors is substantially improved. This installation configuration will be used in the future for the existing and for the new quadruple circuit transmission lines in Tenaga Nasional Berhad transmission network.

Table 3

Line total Flashover rate

Different arrester installation configurations

(Flashovers/100km/yr)

R_T (Ω)				
10	0	0	0	0
15	2.93	0	0.19	0
20	8.39	0.78	2.14	0

25	18.35	2.53	6.24	0.58
30	32.60	5.66	9.37	0.97
35	47.83	8.78	15.62	3.12
40	65.64	13.08	23.62	3.89

○ - Without LSA

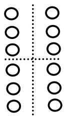
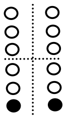
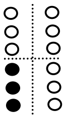
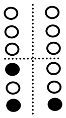
● - LSA Installed

Table 4

Line double circuit flashover rate

Different arrester installation configurations

(flashovers/100km/yr)

R_T (Ω)				
10	0	0	0	0
15	0	0	0	0
20	2.14	0	0	0
25	5.07	0.19	0	0
30	8.19	0	0	0
35	14.64	0.58	0	0.19 (*)
40	22.84	1.17	0	0.39 (*)

○ - Without LSA

● - LSA Installed

(*) Simultaneous Flashovers on C_2 and C_4

5.3.6 Case 6 : Double-circuit flashover reduction on a 225 kV line

Double-circuit flashover on double circuit overhead lines are most of the time very detrimental to power quality. This section compares 2 solutions to reduce the lightning flashover rate of a 225 kV overhead line (presented in the paragraph below) having insulator strings with a LIFV slightly low (800 kV) [36]. The studied solutions are namely an increase of the insulation level of one circuit and the installation of line arresters on one circuit.

5.3.6.1 Description of the configuration

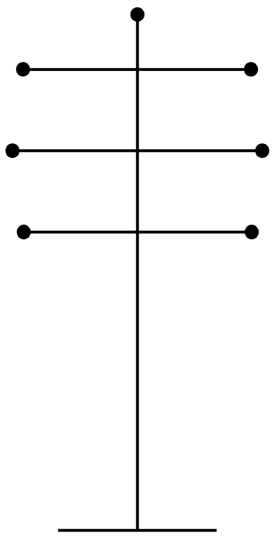
	Abscissa of conductors at tower (m)	Height of conductors at tower (m)	Height of conductors at mid-span (m)	
Phase a1	-4.1	24	18	
Phase b1	-4.8	27.3	21.3	
Phase c1	-4.1	30.6	24.6	
Phase a2	4.1	24	18	
Phase b2	4.8	27.3	21.3	
Phase c2	4.1	30.6	24.6	
Shield Wire	0	32.6	26.6	

Figure 14 Position of phase conductors and shield wire

AAAC conductors of 2.7 cm diameter and resistance of 0.0698 Ω / km are considered. The shield wire is an AAAC conductor of 1.2 cm diameter and has a resistance of 0.24 Ω/km. The span length is 300 m. The gapless arresters have a rated voltage of 228 kV and a residual voltage of 615 kV with a standardized lightning current of 10 kA.

5.3.6.2 Lightning flashover rate without line surge arresters

The lightning back flashover rate is calculated as described in §5.2. The lightning incidence on the line is determined using a three-dimension version of the electrogeometric model proposed by Love (other alternatives are presented in [14]). The striking distance of this model $s(i)$ is given by:

$$s(i) = 10 i^{0.65} \qquad (1)$$

The ground flash density is normalized at 1 flash / km^2/ yr. An EMTP-type tool is used to calculate lightning overvoltages and simulate flashovers. The modelling of the components is made according to § 5.2.3 and [29]. Spans are represented using the FD-LINE model, towers are modelled as lossless transmission lines with a surge impedance of 185 Ω. The grounding impedance of line towers is modelled as a constant resistance. Insulator strings models are based on the equal area criterion. Three spans are modelled on both sides of the point of impact, where the flashover rate is calculated. After three spans the line is represented by a matching impedance.

5.3.6.3 Double circuit lightning back flashover rate after increasing the insulation level of circuit 2

In order to study the influence of the increase of the insulation of one circuit on the number of double circuit flashovers, 2 configurations are considered. First, the lightning withstand voltage of the insulator strings of circuit 1 is equal to 800 kV and the lightning withstand voltage of the insulator strings of circuit 2 is taken equal to 840 kV. In the second one the lightning withstand voltage of the insulator strings of circuit 1 is still equal to 800 kV and the lightning withstand voltage of the insulator strings of circuit 2 is taken equal to 890 kV. For both configurations the double circuit lightning back flashover rate (flashovers due to a lightning stroke on towers or on shielding conductor) involving a simultaneous flashover of the insulation of circuit 1 and circuit 2) is evaluated versus the value of the grounding resistance of towers.

Figure 24 below shows a strong increase of the double circuit simultaneous back flashover rate versus grounding resistance of towers. It also shows that the reduction of double circuit simultaneous back-flashovers depends strongly on the increase of the insulation on circuit 2.

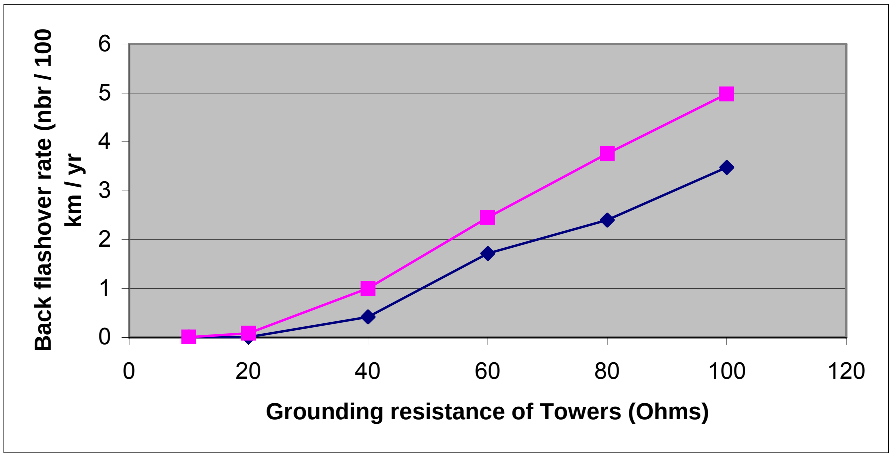


Figure 24 : Double circuit back flashover rate versus grounding resistance of towers when the insulation of one circuit has been increased. -■- The lightning withstand voltage of circuit 1 and 2 are respectively equal to 800 kV and 840 kV. -♦- The lightning withstand voltage of circuit 1 and 2 are respectively equal to 800 kV and 890 kV.

5.3.6.4 Double circuit back flashover rate with line surge arresters on one circuit

The lightning withstand voltage of the insulator strings is equal to 800 kV on both circuits and surge arresters are used on circuit 2. The double circuit back-flashover rate is presented in Figure 25 for two configurations of surge arresters. This figure shows that the double circuit back flashover rate increases with the towers grounding resistance. The solution with only one arrester does provide a lower performance than the increase of the insulation of one circuit as presented in §5.3.6.3. The use of 2 surge arresters seems to be the most effective solution, especially for high values of tower grounding resistances. Obviously the use of line arresters on the 3 phases of one circuit would prevent any double circuit outage.

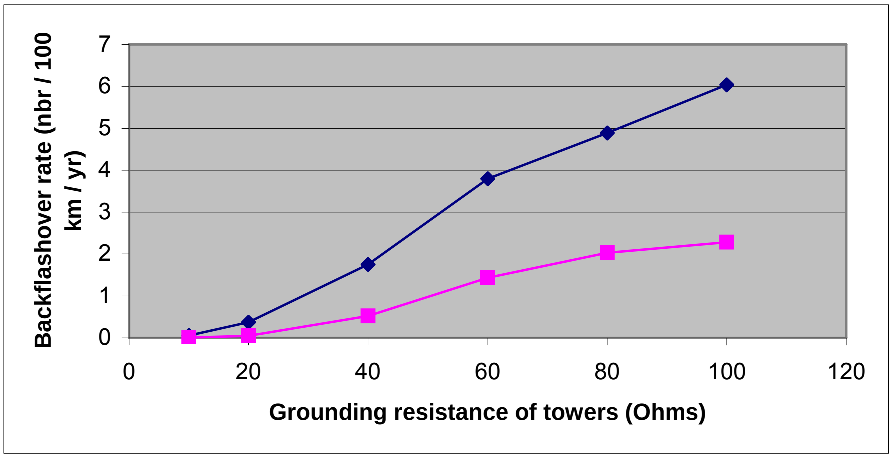


Figure 25 : Double circuit back flashover rate versus grounding resistance of towers, when line arresters are used to protect one circuit. -◆- surge arresters are installed on phase a (bottom) of circuit 2. -■- surge arresters are installed on phase a and b of circuit 2.

5.3.7 Case 7 : Arrester energy duty evaluation

5.3.7.1 General

The energy stressing line arresters depends on several factors such as :

- line design (shielded or unshielded);
- lightning activity characteristics;
- number of multiple strokes;
- lightning polarity and resulting charge levels in first stroke;
- protective level;
- shape of the current flowing through the arrester;
- arrester design (gapless or with a gap);
- tower footing resistance (especially for unshielded lines) of the tower considered and of the neighbouring towers;
- installation configuration.

The goal of this paragraph is mainly to show an example of the strong influence of the presence of shield wires on the energy stressing arresters.

5.3.7.2 Influence of shield wires

The presence of shield wires has a strong influence on the energy stress on line arresters because they avoid the impact of strong lightning strokes on phase conductors.
As it will be shown in the example below lightning strokes impacting phase conductors are leading to severe energy stress on LSAs.
One considers a shielded line, whose description is given in table 6 and table 7.

Table 6 : Description of the conductors

Conductor No	Horizontal distance of conductors	Height at tower	Radius of the conductor	Sag (m)
1	2.5	22.7	8.54	8.6

2	-3	20.5	8.54	8.6
3	3.5	18.3	8.54	8.6
4	0	28.9	4.5	7.6

Table7 : Line data

Tower height	28.9 m
Tower surge impedance	184.7 Ω
Line span	305 m
Tower footing resistance	40 Ω
Soil resistivity	1200 Ω.m

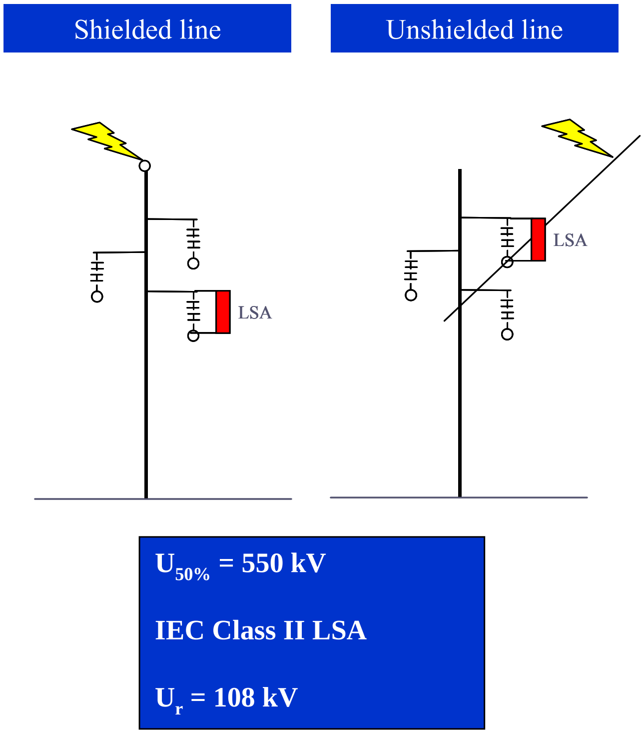
2 configurations are considered :

- the line is shielded and a surge arrester is installed on the lower phase ;
- the shield wire is removed and a surge arrester is installed on the higher phase (see figure below).

The current flowing through the surge arrester and the energy stressing the arrester is calculated in both configurations. The parameters of the lightning strokes used for the study are given in Table 5. The current wave shape is a double-ramp.

Table 5 : Parameters of the lightning strokes

	Crest value (kA)	Front time (μs)	Time to half value (μs)
First stroke	31.1	3.83	77.5
Subsequent stroke	12.3	0.67	30.2



$U_{50\%}$ = 550 kV

IEC Class II LSA

U_r = 108 kV

Figure 26 : Representation of the towers for the shielded and unshielded lines.

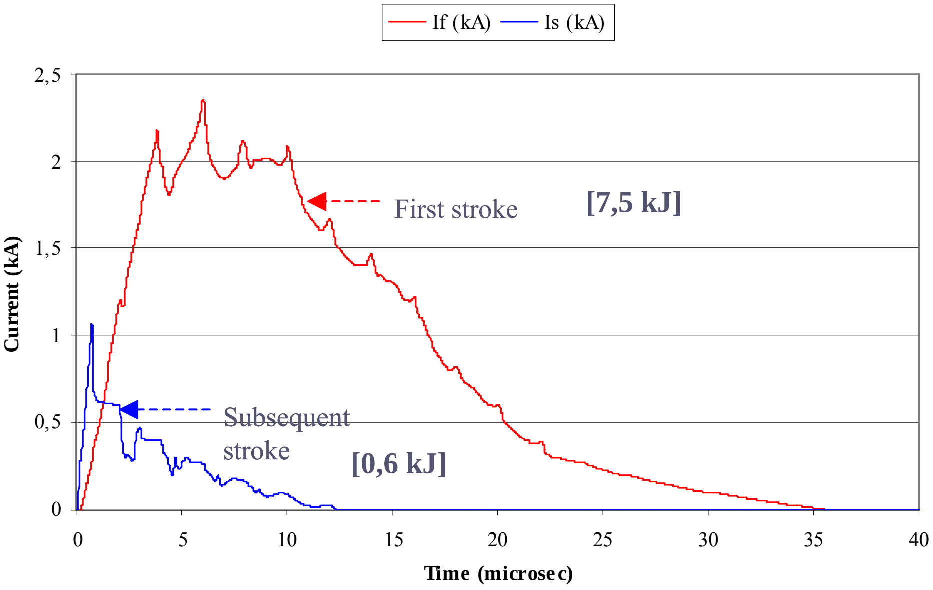


Figure 27 : Current circulating through the arrester and corresponding energy in the case of the shielded line.

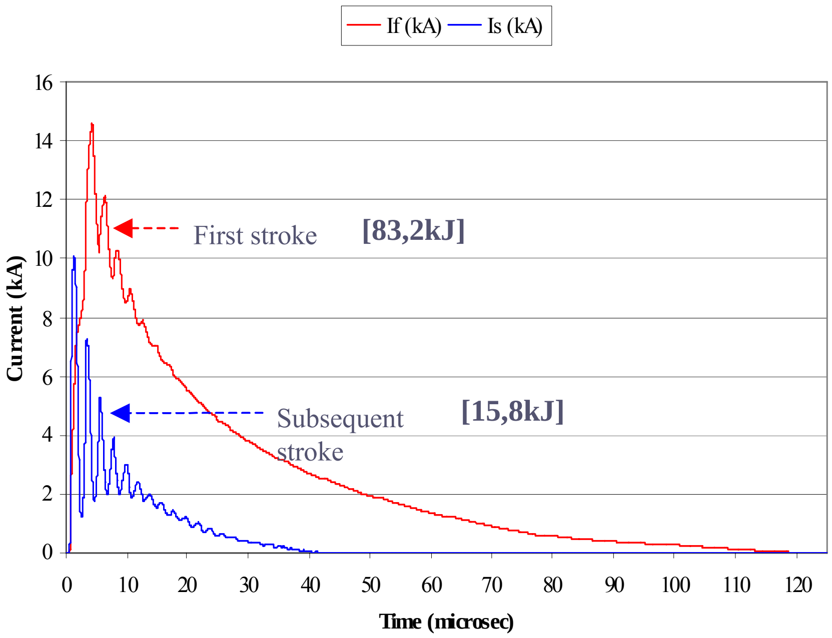


Figure 28: Current circulating through the arrester and corresponding energy in the case of the unshielded line.

Comparison of Figure 27 and Figure 28 shows that a lightning flash striking the top conductor is much more stressing in terms of energy than a lightning stroke of same electrical characteristics impacting the tower. This example illustrates that, when energy alone is considered, LSAs of lower energy class may be suitable for installation on lines equipped with shield wires. If the line were without shield wire, NGLAs with higher energy capability would be required

It should be pointed out also that the value of grounding resistance of the towers located in the vicinity of the tower where the NGLAs are installed has an influence on the level of energy stressing the NGLAs. This aspect has to be carefully taken into account when performing energy calculation. Generally, a tower with low footing resistance among a set with constant resistance will have the greatest energy dissipation, and a 3 to1 ratio between the grounding resistance of the tower where energy is calculated compared to the other one in the simulated line is recommended.

6 Line surge arrester installation

6.1 Live line working: Installation

Some utilities are confident in the integrity of new arresters and install them with live-line techniques. Others may pre-install the arresters while the line is energized, and then take a short line outage to secure the phase-to-arrester connections. There are safety issues around working on lines insulated with polymer insulators because they cannot be practically inspected. This may eventually be raised with NGLA as well.

6.2 Handling of explosive disconnects

The storage, transportation and handling of explosive disconnects is another issue that relates mainly to procedures that need to be organized by the transmission line maintenance groups that carry out work.

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Attachment A – Some remarks on the flashover

A1. Evaluation of the lightning incidence

Negative downward lightning strokes being the most frequent (around 90 % of all the lightning strokes) the approach concentrates on this type of lightning strokes. An electro-geometric model based on the notion of striking distance is used to evaluate the lightning incidence on each element of the line. The principle is the following:

The step leaders are supposed to propagate vertically from the cloud to the ground and are a function of the crest value of the current and of the intersection between their trajectory and any object at ground level. A set of step leaders is considered, defined by:

Equation 1 $I_m = k_1 I_{mbonds}$

$x = k_2 x_{bonds}$

$y = k_3 y_{bonds}$

with $(k_1,k_2,k_3) \in Z^3$ (three-dimensional signed integers). Typical values of I_{mbonds}, x_{bonds}, y_{bonds} are respectively 1 kA, 1 m and less than 1 m. To reach a sufficient precision when determining shielding failure it is required to use a small value for $y_{bonds.}$

The point of impact of each step leader (the ground or one of the elements of the line) is determined based on a three-dimensional application of the electro-geometric model. From this calculation and based on lightning statistics as well as ground flash density, the incidence on each element of the line is determined. **The probability distribution that should be**

considered for the crest value of the lightning current is the one at ground level. This distribution is derived from the measurement of strokes to tall structures according to the EGM selected.

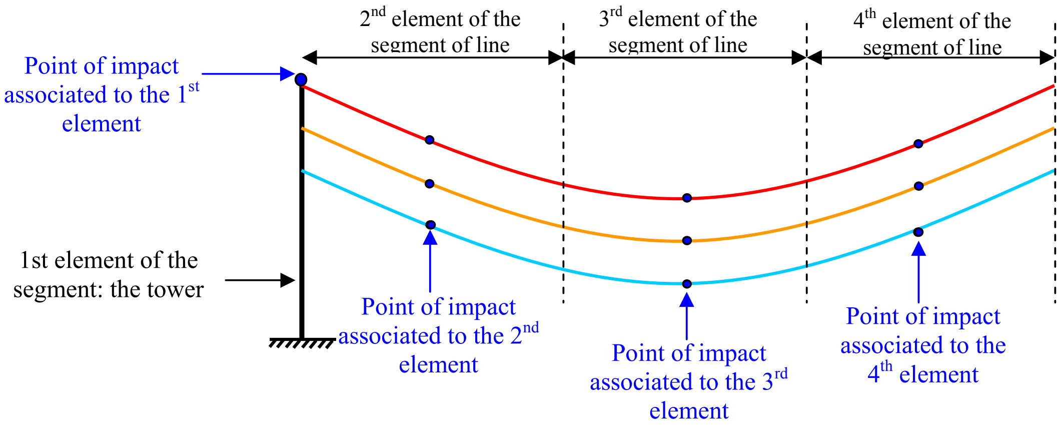


Figure 29 Representation of the elements and points of impact considered for the calculation of the overvoltages.

A2. Evaluation of the back flashover rate

The back flashover rate corresponds to the flashover rate due to lightning impacting the towers and shield wires.

The first step when evaluating the back flashover rate of a line is to determine for each element j of the line (with transient simulations) the set $D_{j\theta_k}$ of lightning strokes (str) impacting the element j and leading to a flashover for a given power frequency phase angle θ_k. Generally speaking, it is sufficient to consider the crest value I_F of the lightning current as the only random variable, the other parameters characterizing the lightning wave shape are considered equal to the median value of the corresponding correlated distribution. The probability of back flashover due to element j is given by:

Equation 2 $$P_j = \frac{1}{M}\sum_{k=1}^{M} p_j(\text{str} \in D_{j\theta_k})$$

Where:

- M is the number of uniformly distributed phase angles considered;
- p_j corresponds to the probability law of the lightning strokes impacting the element j.

The back flashover rate of the line is given by:

Equation 3 $$\text{BFR} = \frac{100}{\ell}\sum_{j=1}^{N} N_j P_j$$

Where :

- ℓ is the length of line (km) ;
- N_j is the average number of lightning strokes impacting the element j of the line ;
- N is the number of elements.

N_j and p_j are calculated from the application of the electro-geometric model. An electromagnetic transients software is used to estimate $D_{j\theta_k}$. The electromagnetic transient following the impact of a lightning stroke is simulated to determine if this lightning stroke leads to a flashover. The system is modelled according to the recommendations given in literature. Subsequent lightning strokes are not taken into account because they are significantly lower in magnitude. Since numerical simulations are being time consuming one major issue is to optimise the number of numerical simulations when estimating $D_{j\theta_k}$. Direct Monte-Carlo methods may be in some cases not so efficient because they lead to numerous simulations for lightning strokes with current parameters close to the median value, and need to be adequately improved to avoid long calculation times.

A3. Evaluation of the flashover rate due to shielding failure

The approach to be used to calculate the flashover rate of a line due to shielding failures is similar to the one used to calculate the back flashover rate. However in case of shielding failure lightning over-voltages do not depend significantly on the exact position of the lightning stroke along the span, it is recommended for a conservative approach to make the calculations for one point of impact located in the middle of the span, using the power frequency phase angle at which the highest overvoltage imposed on line insulation can be observed. This angle, in general, corresponds to the crest system voltage with the same polarity as that of the lightning stroke.

A4. Evaluation of the total flashover rate

When the only random variable considered for the lightning current is the crest value, it is possible to determine for an element of the line and a value θ_k, the so-called critical current, based on transient simulations. The critical current I_{cr} is the minimum value of the crest current of the lightning strokes leading to a flashover. A dichotomy is applied.

If :

- I_{min} is the highest value of the lightning current which is known not to lead to a flashover;
- I_{max} is the lowest value of the lightning current which is known to lead to a flashover

then a transient simulation is performed to determine if the lightning stroke of current $I_d = \frac{I_{min} + I_{max}}{2}$ leads to a flashover. If this is the case then I_{max} is replaced by I_d, otherwise I_{min} is replaced by I_d. The process is completed when the following condition is fulfilled:

Equation 4

$$\int_{I_{min}}^{I_{max}} f_{Ij}(i)di \leq x$$

where :

- $f_{Ij}(i)$ is the probability density function of the crest value of the current for the element j;
- x determines the acceptable error on the critical current based on its cumulative probability function.

From Equation 2 we have:

Equation 5 $p_j(\text{str} \in D_{j\theta_k}) = F_{Ij}(I_{crj\theta_k})$

where :

- F_{Ij} is the cumulative probability function of the lightning current on the element j;
- $I_{crj\theta_k}$ corresponds to the critical current for a phase angle θ_k and the line element j.

A5. Evaluation of the multi-phase flashover rate

The notion of critical current may lead to difficulties because it is possible to find in some configurations lightning current leading to a multiphase flashover when a higher lightning current leads to a single-phase flashover. So in that case when the crest value of the lightning current is the only random variable considered for the lightning current, for an element j of the line and a power frequency phase angle θ_k , EMTP simulations are performed for a set of lightning currents $[I_k]$ chosen such as the following condition is fulfilled:

Equation 6 $$\int_{I_k}^{I_{k+1}} f_{Ij}(i)di \le x$$

The set $D_{j\theta_k}$ (see Equation 2) is deduced from EMTP simulation results.

A6. Lightning parameters

For convenience, in this section we summarize the state of the art of statistical lightning data relevant for studies aimed at predicting the lightning performance of electrical systems.

A6.1. The regional lightning activity

The regional lightning activity is either characterized by the number of flashes to ground per unit area (lightning ground flash density expressed in number of flashes to ground per year per square kilometer N_g) or by the annual number of thunderstorm days (keraunic level T_d). For lightning engineering studies, one would rather need the ground flash density. Although those two indexes are poorly correlated one may use, when the ground flash density is not available, the following relation to estimate N_g from the keraunic level T_d [15]:

$N_g = 0.04{T_d}^{1.25}$ (Eq. 1)

The variation within the years of the average value N_g at any location may also be of interest. For such a concern, a normal distribution may be considered with the following standard deviation :

$\sigma_{N_g} \approx 0.32.N_g$ (Eq. 2)

It may be worth noting that the ground flash density is a fundamental parameter, providing the basis for any estimation of the frequency of lightning effects upon electrical systems. Any uncertainty of the ground flash density is directly translated to the final estimation result.

A6.2.Lightning data

Lightning flashes are classified into four categories based on the direction of propagation of the flash leader and the polarity of the cloud charge (downward or upward flashes which may be of negative or positive polarity).
Most lightning studies of power systems consider only negative downward flashes since (a) most downward flashes are of negative polarity and (b) upward flashes occur mainly from mountain top installations or from high structures taller than transmission towers. The analytical models and lightning data presented hereafter are valid under this assumption of negative downward flashes.
The statistical data are extracted from the CIGRE report [15], which gives a comprehensive summary of the current knowledge about various lightning aspects involved in the lightning performance estimation of transmission lines including the probability distributions of the various lightning parameters.

The distribution of the crest value of the lightning current is approximated by two straight lines (drawn through the measured data in a log-normal representation), which intercept at about 20kA). It subdivises the current values into two regimes, namely, a”shielding” regime comprising currents below 20kA, and a “back-flash” regime comprising those currents in excess of 20kA, for which the parameters of a log-normal distribution approximation are [15]:

Parameter	Shielding Failure Domain (I<20kA)	Back flash Domain (I>20kA)
M	61	33.3
β	1.33	0.605

Table VII Log-normal distribution parameters for the lightning crest current

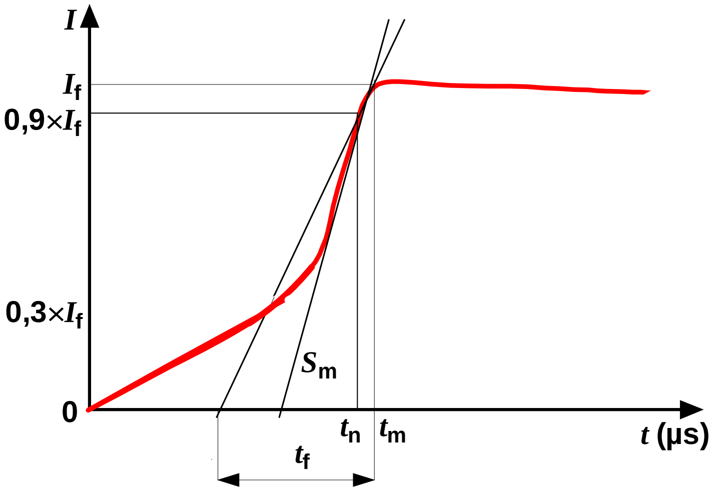


Figure 30 Cigre concave shape (I_f is the crest current, S_m is the maximum front steepness, t_f is the equivalent front duration) (Source: from Figure 12 [15]).

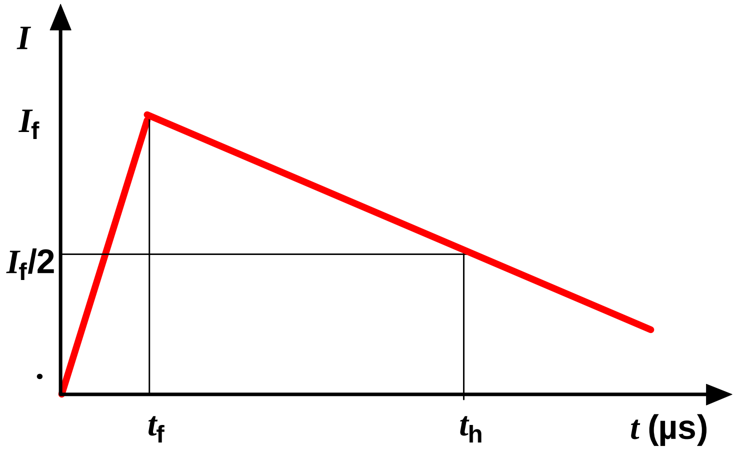


Figure 31 Double ramp shape (t_f is the front time, t_h is the time to half-value and I_f the crest value of the current).

The probability density of a log normal distribution is given by the following equation.

$$f(x) = \frac{1}{\sqrt{2\pi}\beta x} e^{-\frac{z^2}{2}} \quad \text{where } z = \frac{\ln(x/M)}{\beta}$$

M is the median parameter value and β is the slope parameter; x is the variable log normally distributed.

We have, for a log normal distribution, $E(X) = M \times \exp(\frac{\beta^2}{2})$ and

$$\sigma(X) = M \times \exp(\frac{\beta^2}{2})\sqrt{\exp(\beta^2) - 1}$$

$E(X)$ is the mean value and $\sigma(X)$ is the standard deviation.

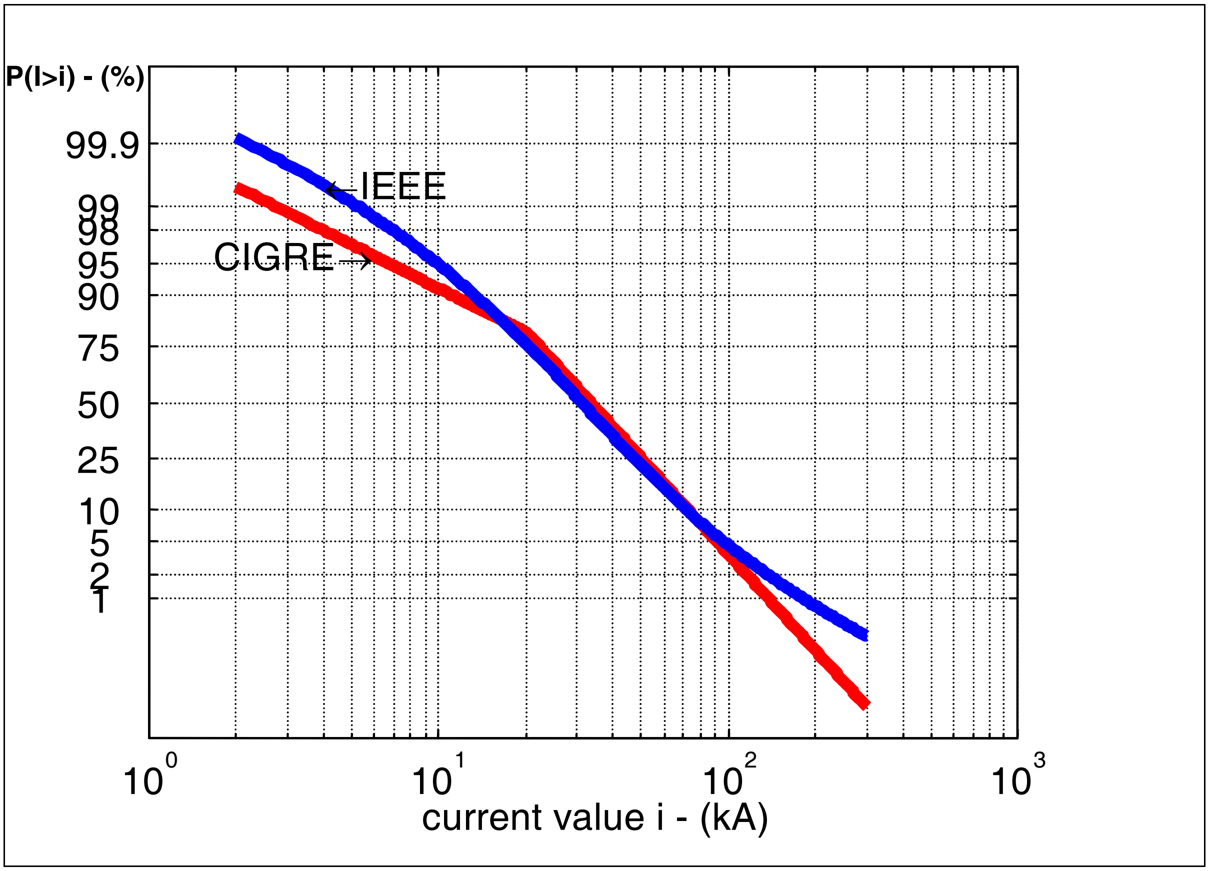


Figure 32 Reference distributions of I_F for negative downward strokes [15].

	3 < I < 20 kA		I ≥ 20 kA	
	M	β	M	β
S_m / I_F (kA / µs)	$12I_F^{0.171}$	0.554	$6.5I_F^{0.376}$	0.554
t_f / I_F (µs)	$1.77I_F^{0.188}$	0.494	$0.906I_F^{0.411}$	0.494

Figure 33 : Parameters of the density of probability of S_m and I_F [14] for the distribution on ground.

A6.3.Lightning incidence calculation

Lightning incidence calculation is based on the application of an electrogeometric model. The principle of the classical electrogeometric model is presented below.
Experiments have shown that the final stage of a lightning leader progressing downward involves the initiation of an upward rising connecting leader as the downward leader approaches within a certain critical distance the earth or a structure. This distance referred to as the striking distance is the key concept of the electrogeometric theory for which several ElectroGeometric Models (EGM) have been proposed. It permits to predict the point of

impact of a stroke, that is the origin of the upward rising leader. The striking distance $s(i)$ is a function of the return stroke peak current *i*, of the form:

$$s(i) = a.i^b \qquad \text{(Eq. 3)}$$

where *a* and *b* are constants, for which different values have been proposed according to the authors (Table 6).

In the case of Love's EGM for which all striking distances, to the shield wire, to the phase conductors, and to earth are considered equal for a given current, the downward lightning leader would terminate on the nearest object during its progression to ground.

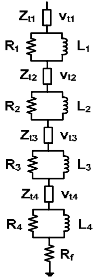
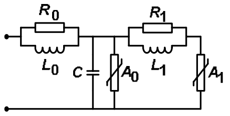
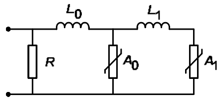
	striking distance to :			
	Earth		phase conductor and shield wire	
Source	A	B	a	B
Armstrong	6.0	0.8	6.7	0.8
Brown	6.4	0.75	7.1	0.75
Love	10.0	0.65	10.0	0.65
Anderson	6.4, 8 or 10	0.65	10.0	0.65
IEEE WG	$0.36 + 0.168\log(43 - h)$	0.65	10.0	0.65
Eriksson	Na	na	$0.67h^{0.6}$	0.74
Rizk	Na	na	$1.57h^{0.45}$	0.69

Table 6 : Constants a and b according to the different Electrogeometric Models.

The different parameters a and b result in a 2:1 variation for the striking distance. Therefore estimates of lightning strike incidence on transmission lines would vary accordingly with the assumed EGM. Note that no consensus exists among the research community regarding the form of striking distance.

A7. Modelling

	Model description	Equations/scheme	Items/explanation
Lightning Stroke	**1. Double ramp function:** it is the simplest representation to apply, which is appropriate for some kind of studies. [30] **2. Double exponential function:** it expresses a lightning current more realistically than double ramp function. [23] **3. Cigré concave shape:** mathematically described by equations for the current front (*) and tail (**) regions respectively. [15]	**Double exponential function:** $I(t) = I_0(e^{-\alpha t} - e^{-\beta t})$ **Cigré concave shape:** $I(t) = A \cdot t + B \cdot t^n$ (*) $I(t) = I_1 \cdot e^{\frac{-(t-t_n)}{t_1}} - I_2 \cdot e^{\frac{-(t-t_n)}{t_2}}$ (**)	I_0 – peak current [kA] α, β – inverse of time constants **A, B** – constants [kA/μs] t_1, t_2 – time constants I_1, I_2 - constants t_n – time dependent on the exponent n at which current shape reaches 90% of amplitude
Line, Conductors and Earth Wires	**Frequency-dependent model** The transmission line, conductors and earth wire have to be represented by several multi-phase untransposed distributed parameter line spans at both sides of the point of the lightning stroke impact. A line termination should be connected in each side of the modeled line to prevent reflections that could affect the simulated over-voltages.	Several available; See for instance Ref [29]	See Ref [29]
Towers	**1. Simple distributed line model:** it is appropriate for shorter towers. **2. Multistory tower model**: was originally developed for representing	**Simple distributed line model (replacing the tower with a cylinder):** $Z = 60\left[\ln\left(\frac{H}{R}\right) - 1\right] \qquad R << H$ **Multistory tower model:**	H – tower height [m] R – tower base radius [m] Z_{t1} – surge impedance of upper part [Ω] Z_{t4} – surge impedance of lower part [Ω] r_1 – damping resistance per unit length of upper part [Ω/m] r_2 - damping resistance per unit length of lower part [Ω/m]

	towers of UHV transmission lines. It is composed of four sections representing the tower sections between cross-arms. Each section consists of a lossless line in series with a parallel ***R-L*** circuit, included for attenuation of the travelling. [29]	 $Z_{t1}=Z_{t2}=Z_{t3}$ $v=v_{t1}=v_{t2}=v_{t3}=v_{t4}$ $\gamma=0.8944$ $\tau=2H/v$ $r_1=-2xZ_{t1}x\ln\gamma/(l_1+l_2+l_3)$ $r_2=-2xZ_{t4}x\ln\gamma/l_4$ $R_1=r_1xl_1$ $R_2=r_2xl_2$ $R_3=r_3xl_3$ $R_4=r_4xl_4$ $L_1=R_1x\tau$ $L_2=R_2x\tau$ $L_3=R_3x\tau$ $L_4=R_4x\tau$	***v*** - surge propagation velocity [300 m/μs] γ - attenuation is constant along the tower τ - time constant (travel time on tower x 2) [μs] ***l_1, l_2, l_3, l_4*** - real lengths [m] ***L_1, L_2, L_3, L_4*** - inductance in parallel with a damping resistance [μH]
Line insulators air gaps,	***Flashover trigger*** **1. Volt-time curve:** The instant of breakdown is considered as being point of intersection of voltage ***U(t)*** between the two terminals of the air gap with volt-time curve of insulation. It is only adequate for relating the peak of the standard impulse voltage to the time of flashover. For non-standard impulse two models presented below are used: **2. Area criterion model:** This model is recommended for air gap smaller than 1,2 m. [29] **3. Leader progression model:** The physics of discharge in large air gaps greater than 1m involves 3 successive phases: corona inception, streamer propagation, leader propagation. The LPM is a realistic representation of an insulator, although parameters have to be selected very carefully and taking into account atmospheric conditions. [15] ***Breakdown process*** **1. Ideal switch:** An air gap, once the flashing condition has been verified, can be simply represented by an ideal switch. **2. Use of inductance:** Air gap is represented as a small inductance (1 μH/m) connected to ideal switch (it corresponds to the inductance of the arc).	**Volt-time curve:** $U(t)=K_1+\frac{K_2}{T_{front}^{\;0.75}}$ **Area criterion model:** $A_0=\int_{T_0}^{t}(U(t)-U_0)^k\,dt=const.$ **Leader progression model:** $\frac{dl}{dt}=k_l\,U(t)\left[\frac{U(t)}{g-l}-E_{10}\right]$	***K_1***=0.4 L [m] ***K_2***=0.7 L [m] ***L*** – flashover distance [m] ***T_{front}*** – front duration [μs] ***U(t)*** – voltage applied to the air gap terminals at the time ***t*** [kV] ***U_0*** - minimum voltage to be exceeded before any breakdown process can start or continue [kV] ***T_0*** - time from which ***$U(t)>U_0$*** ***k, U_0, DE*** - constants corresponding to an air gap configuration and over-voltage polarity (they are determined by using volt-time curve). Flashover occurs when ***A_0*** becomes equal ***DE***. ***g*** - gap length [m] ***l*** - leader length [m] ***E_{10}*** - critical leader inception gradient [kV/m] ***k_l*** – leader coefficient [$m^2v^{-2}s^{-1}$]
Grounding	**1. Constant resistor (conservative approach)** **2. Current dependable resistor** The ionization model takes into account the soil ionization caused by the lightning currents. The tower footing resistance remains ***R_i =R_o*** if ***$I<I_g$*** and varies according to the given equation if ***$I > I_g$***	$R_i=\frac{Ro}{\sqrt{1+\left(\frac{I}{I_g}\right)}}$; $I_g=\frac{\rho\cdot E_0}{2\cdot\pi\cdot R_o^2}$	***R_o*** **-** footing resistance at low current and low frequency [Ω] ***I*** **-** stroke current through the resistance [kA] ***I_g*** - limiting current to initiate sufficient soil ionization [kA] ρ - soil resistivity [Ωm]; ***E_0*** -soil ionization gradient ≈ 400 [kV/m]
Arresters	**1. The frequency-dependent arrester model proposed by IEEE**: Iterative procedure needed for identification of parameters. The non-linear U-I characteristic is obtained by means of two non-linear resistors (tagged A_0 and A_1) separated by an R-L filter. [36] **2. Simplified IEEE model**: Model parameters are identified using a formula that does not require any iterative correction and that makes use only of the data reported on manufacturers' datasheets. [37] [22] The arrester leads can be modelled as conductors whose lumped parameter inductances have a value of approximately 1 μH/m	**Frequency-dependent model:**  **Simplified model:** 	***A_0, A_1*** - non-linear resistor characteristics ***C*** – arrester capacitance [pF] ***L_0, L_1*** – dynamic parameters [μH] ***R_0, R_1*** – damping resistances in parallel with inductances [Ω] ***R*** - resistance (about 1 MΩ) between the input terminals, with the purpose of avoiding numerical instability
Boundary conditions	**Phase voltages** at the instant at which a lightning stroke impacts the line must be included. The largest voltage difference across insulator/arrester terminals occurs during the peak value of phase voltage, which has the opposite polarity of the lightning surge. For statistical calculations, phase voltages can be deduced by randomly determining the phase voltage reference angle and considering a uniform distribution between 0^0 and 360^0.	……………..	……………..