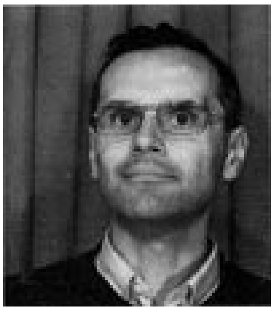
n° 168

lightning and HV electrical installations



Benoît de Metz-Noblat

Following graduation from the ESE engineering school, worked for Saint-Gobain first as a research engineer, then in maintenance and new projects on a production site. Joined Merlin Gerin in 1986 and is currently in the Network Research Section where he directs a group investigating overvoltages, harmonics and the dynamic stability of networks.

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glossary

BIL: (Basic Impulse Level): the impulse voltage that the insulation of a device is designed to withstand.

Gas-insulated metal-enclosed substation: a substation which is made up of only gas-insulated (generally SF6) metal-enclosed switchgear, often referred to in as **GIS** (Gas-Insulated Switchgear) in EHV applications.

Must not be confused with **metal-clad switchgear** which is placed in separate compartments with metal partitions (see IEC 298).

MCOV: (Maximum Continuous Operating Voltage): the maximum continuous voltage that a lightning arrester is designed to withstand.

pace voltage: voltage that may appear between the feet of someone walking.

Note

Voltage levels have been classed in various manners, defined by national and international standards as well as by specifications issued by certain electricity distribution utilities. The following are definitions for alternating voltages greater than 1,000 V:

- the French regulation dated 14 november 1988 defines two voltage levels:

HTA (High Voltage A) = 1 kV < U ≤ 50 kV,
HTB (High Voltage B) = U > 50 kV.

- CENELEC (European Electrotechnical Standardisation Committee) defined two levels in a document issued on 27 july 1992:

MV = 1 kV < U ≤ 35 kV,
HV = U > 35 kV.

- IEC 71 defines a range of maximum voltages for equipment:

range A = 1 kV < U < 52 kV,
range B = 52 kV ≤ U < 300 kV,
range C = U ≥ 300 kV.
A revision is planned and will result in only two ranges:
range I = 1 kV < U ≤ 245 kV,
range II = U > 245 kV.

- the French electrical authority (EDF) presently uses the definition laid out in the French regulation mentioned above.

Note: The acronyms EHV and UHV, though occasionally used, have never been officially defined by a standard. In this document, EHV is used for voltages greater than 300 kV.

lightning and HV electrical installations

summary

The goal of this «Cahier Technique» publication is to:

- present an overview of lightning phenomena and their effects on electrical installations,
- present currently available means to protect installations and limit detrimental effects,
- discuss problems concerning continuity of service,
- indicate the main steps in lightning studies on the basis of an example involving an EHV installation developed by the Network Research Department at Merlin Gerin.

This document deals in particular with the transmission and distribution of electricity over medium and high-voltage networks. When designing these networks, the effects of lightning must be taken into account for insulation coordination. Low-voltage aspects are also mentioned, but in no great detail.

A short bibliography is included in the appendix.

1. introduction

Lightning is a major source of disturbances for all electrical installations and can affect them in several manners:

- all power and voltage levels are concerned, ranging from EHV transmission systems to integrated circuits and including LV power supplies and data transmission circuits,
- it can cause transient disturbances to the continuity of service, thereby reducing the quality of the power supply system,
- it can damage equipment and result in long interruptions in installation operation,
- it can be dangerous for life (pace voltage, increased potential of exposed conductive parts and earthing circuits).

Lightning has always been a source of disturbances for users of electricity, yet the fairly recent and growing demand for quality electrical systems (reliability, availability, continuity of service, etc.) must be taken into account, as well as the permanent necessity to minimise the costs of the production and the use of electrical power. It may be said that in the efforts to improve the above factors, lightning has come to constitute an obstacle. That explains why it is now one of the major preoccupations of everyone in the sector, whether they are distributors (EDF, private companies), manufacturers (Merlin Gerin, etc.), designers (design offices, engineering firms) or installers.

A study on the effects of lightning comprises two steps, but first requires in-depth knowledge of the phenomenon. Starting in the 1970's, major international research programs were initiated, notably by EDF in France, and today, sufficient knowledge on lightning mechanisms is available.

The two steps are:

- anticipate what can happen in a given installation and recommend improvements. This is possible using dedicated software, validated by experience, that simulates installation behaviour.
- carry out an engineering and cost study on insulation coordination, taking into account the cost of installations, maintenance and disruptions in operation.

Note: insulation coordination consists in defining, on the basis of the voltage and overvoltage levels likely to occur in an installation, one or several levels of protection against overvoltages, then in selecting installation equipment and protection devices. This subject is covered in the «Cahier Technique» n° 151.

2. lightning

Following a few general indications on atmospheric electrical phenomena, this section presents:

- the main characteristics of lightning, considered from an engineering point of view,
- information on forecasting,
- the impact mechanism using the electro-geometrical model.

general

The earth and the electrosphere (conductive zone of the atmosphere, ranging in thickness from roughly 50 to 100 km) constitute a natural, spherical capacitor which charges by ionisation, producing an electrical field, some several hundred V/m (Volt/ meter) in strength, directed toward the earth.

In that air being a poor conductor, there is a permanent conduction current associated with the electrical field, of approximately 1,500 A for the entire earth. Electrical equilibrium is maintained by discharges via points, rain and lightning strikes.

The formation of storm clouds, in effect masses of water in the form of aerosols, is accompanied by electrostatic phenomena in which differently charged particles separate. The light, positively charged particles are drawn upward by ascending air currents and the heavy, negatively charged particles fall under their own weight. There may also be clusters of positive charges at the bottom of clouds where there is intense rainfall. On the overall macroscopic scale, a dipole exists.

When the limiting gradient of the breakdown voltage is reached, a discharge takes place in the cloud, between clouds or between the cloud and the earth. The latter case is called lightning.

The cloud-to-earth electrical field may reach up to -15 to -20 kV/meter on flat terrain. However, the presence of obstacles locally increases and deforms the electrical field by a factor of 10 to 100, or even 1,000, depending on the form of the irregularities (sometimes referred to as the point effect). The air ionisation threshold (approximately 30 kV/cm) is then reached and discharges due to the corona effect take place. For relatively large objects (skyscrapers, smokestacks, towers), these discharges may result in lightning strikes or orient them.

Classification of lightning strikes

A lightning strike between a cloud and the earth comprises two phases, first the development of a predischarge or leader (an ionised channel), which provokes the lightning strike itself, a discharge of a visible, high-current arc.

Two main criteria distinguish lightning strikes, their direction and their polarity:

- descending lightning strikes, in which the leader runs from the cloud to the earth (relatively flat terrain),
- ascending lightning strikes, in which the leader runs from the earth to the cloud (mountainous terrain),
- negative lightning strikes when the negatively charged part of the cloud discharges (80 % of lightning strikes under temperate climates),
- positive lightning strikes when the positively charged part of the cloud discharges.

main characteristics

Wave form

Lightning, as a physical phenomenon, corresponds to an impulse current source, that is a series of discharges of a quantity of electricity over a short period of time.

The actual wave form is quite variable and comprises a steep front to the maximum amplitude (ranging from a few to 20 microseconds), followed by a long decreasing tail of several tens of microseconds (see fig. 1).

The associated spectral field covers a band ranging from 10 kHz to several MHz.

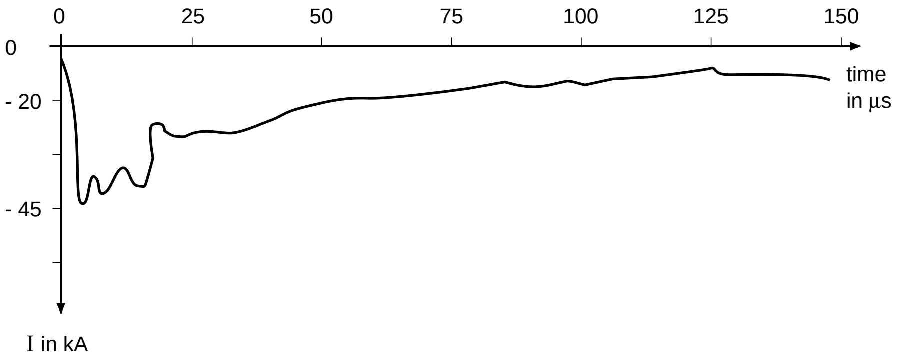


fig. 1: oscillogram of a lightning impulse current.

Amplitude of lightning strikes

The experimental statistical distribution of lightning strikes as a function of their amplitude follows a normal distribution as illustrated in figure 2.

Wave front

The distribution of lightning strikes as a function of front steepness is illustrated in figure 3.

For lightning studies, the following values are generally used:

- amplitudes of 100 kA or 200 kA, with respective probabilities of 5 % and 1 % that the level will be exceeded,
- triangular wave form with a 2 µs front duration and a 50 µs time to half value, i.e. a 50 or 100 kA / µs front.

Note: this front duration is not that of the standardised wave (1.2 µs) defined for laboratory testing (see IEC 60).

Charge of lightning strikes

On average, the charge is a few tens of coulombs, but may exceed 300 C.

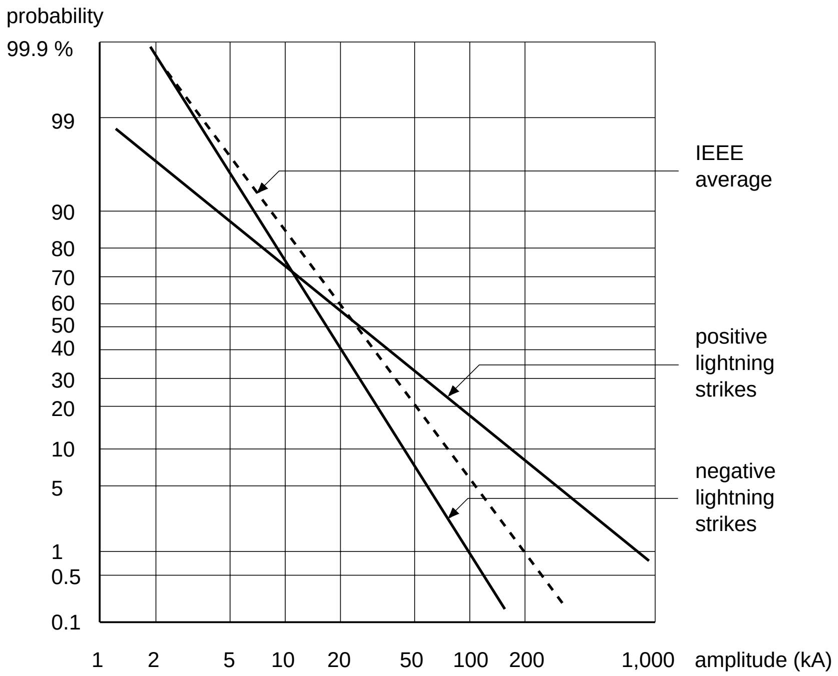


fig. 2: experimental statistical distribution of positive and negative lightning strikes as a function of their amplitude (IEEE).

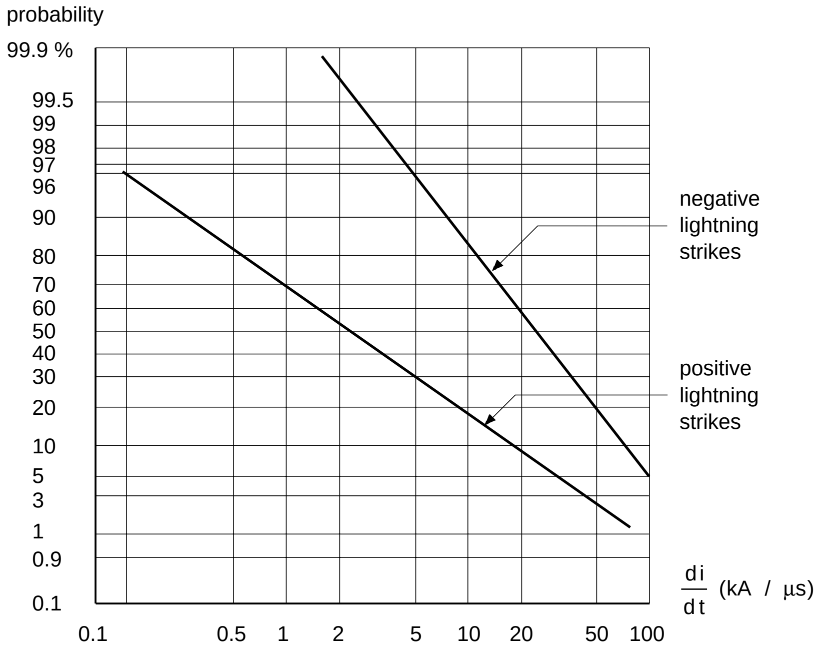


fig. 3: experimental statistical distribution of positive and negative lightning currents as a function of front steepness (IEEE).

lightning forecasting

In France, the Météorage lightning observation network was set up in 1986.

This network comprises detection stations spread over the entire country and linked to the operational computing centre in Paris.
The stations, positioned 200 to 300 km from one another, measure the electromagnetic waves created by storm discharges up to 800 km away.
Storms can be characterised on the basis of the following measured data:

- location,
- date and time (to the millisecond),
- wave polarity (> 0, < 0),
- wave amplitude (0 to several hundred kA),
- number of arcs.

Météorage offers a number of useful services for a wide range of applications, in particular the transmission and distribution of electrical power. Among the services offered are warnings, indications, observations, monitoring, assessments, qualification, consulting and statistics.

The following two forecasting elements are used in lightning studies.

Keraunic level Nk

This corresponds to the number of days per year when thunder is heard at a

given location. Though at first glance, this may seem a highly approximate notion, it is nonetheless a useful value.
In France, the average Nk level is 20, with extremes ranging from 10 in the Channel coast regions to over 30 in mountainous regions.
In other parts of the world, Nk levels may be much higher, for example over 180 in tropical Africa and Indonesia, for example.

Lightning density N
This is defined as the number of lightning strikes hitting the earth per square kilometer and per year, whatever the amplitude.
In France, density N ranges, depending on the region, from 2 to 6 strikes per km^2 and per year.
The general ratio between the two above values may be defined, on the basis of average values, as N = Nk / 7.

impact mechanism and electro-geometrical model

The lightning impact mechanism may be broken down as follows:

- ■ a leader originating in a cloud approaches the ground at low speed. As soon as the electrical field is strong enough, conduction takes place suddenly, producing the discharge of lightning.
- ■ experimental data has been used to derive the relationship between the distance separating the beginning (arc) and the end (discharge) of a lightning channel (i.e. the striking distance), on the one hand, and the amplitude of the lightning strike, on the other:

$$d = 9.4 \; I^{2/3} \quad \text{or} \quad d = 6.7 \; I^{0.8}$$

depending on the authors, where:
d is the striking distance in meters,
I is the lightning current in kA.

- ■ an electro-geometrical model can then be established, similar to the one for a vertical rod in the example below (see fig. 4).

Consider a vertical rod with a height h and its summit at H. The zones defined in the surrounding space are the following:
☐ zone I, situated between the ground and parabola p. The latter defines the points equidistant from H and the ground. At the moment of the strike, a leader located in this zone will hit the ground because it is closer than H.
☐ zone II, situated above the parabola. At the moment of the strike, a leader located in this zone will be captured by H if the distance to H is less than the striking distance d.
It follows that for a given current I, i.e. for the resultant striking distance d, the distance x to the rod, called the capture range, is:

$$\text{if } d > h \quad x = \sqrt{2\,d\,h - h^2}$$

$$\text{if } d < h \quad x = d$$

The capture range of the rod increases with the amplitude of the lightning strike. For very low amplitudes, the capture range drops to less than the height of the rod which can then capture strikes along its length. This has been verified experimentally.

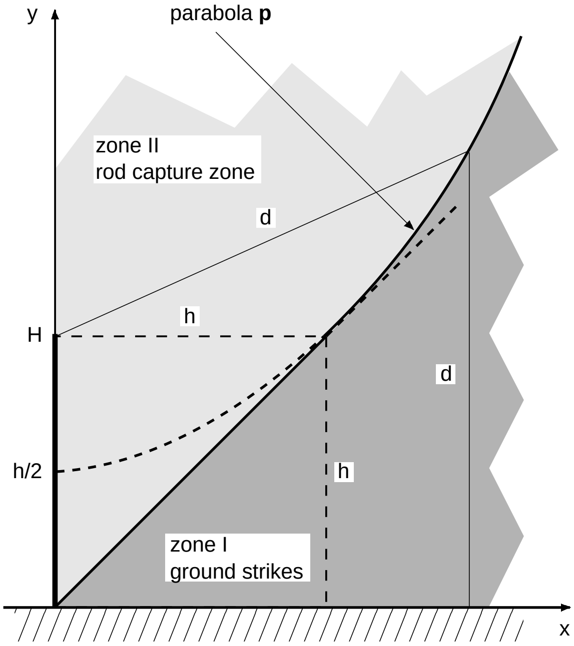


fig. 4 : protection zones surrounding a vertical rod.

3. lightning and electrical installations

This section deals with lightning strikes on a line, wave propagation and the effects of lightning.

lightning strikes on a line

On the basis of the electro-geometrical model, the frequency of lightning strikes can be calculated using the capture range of the considered object.

Figure 5 indicates, for a density N = 4 (4 lightning strikes per km^2 and per year and a corresponding keraunic level of approximately 30), the frequency of lightning strikes (number of strikes per year) for a vertical rod with a height h and for a horizontal conductor with a length of 100 km and a height h.

The general empirical formula for calculating lightning strikes (total number per year) on a line (towers, phase and earth wires) is the following:

$$N_L = Nk \left(\frac{N1}{30} + \frac{l}{70} \right) \alpha \frac{L}{100}$$

where:
Nk = keraunic level,
N_L = strikes on a line,
N1 = strikes on the highest horizontal conductor (see fig. 5),
L = lenght of the line in kilometers,
l = width of the line in meters (distance between outside conductors),
α = influence coefficient taking into account the influence of towers and earth wires (see fig. 6).

This formula takes into account:
- lightning trikes on a conductor (N1),
- presence of outside conductors (l),
- distribution between the tower and the line depending on the structure of the line (α),
- length of the line (L) :
  - for insulation coordination calculations, L ≈ 1.5 km is generally selected because over greater distances, the effect of the lightning strike becomes negligible,
  - for continuity of service calculations, the important factor is the total length of the line exposed to strikes, therefore to interruptions in service.

Direct lightning strikes (on phase conductors)

When lightning hits a phase conductor of a line, the total current i(t) at the point of impact is split in two and the two halves are propagated along the conductor in opposite directions.
The wave impedance Z of the conductor is 300 to 500 Ω (see fig. 7).
The result is an associated voltage wave:

$$u(t) = Z \frac{i(t)}{2}$$

At the towers, the voltage increases and propagates:
- as a full impulse, reaching its maximum value

$$U_{max} = Z \frac{I_{max}}{2}$$

when

$$Z \frac{I_{max}}{2} < Ua$$

where Ua = impulse flashover voltage of the insulators string or of any protective spark-gap devices that may be present. This voltage is roughly

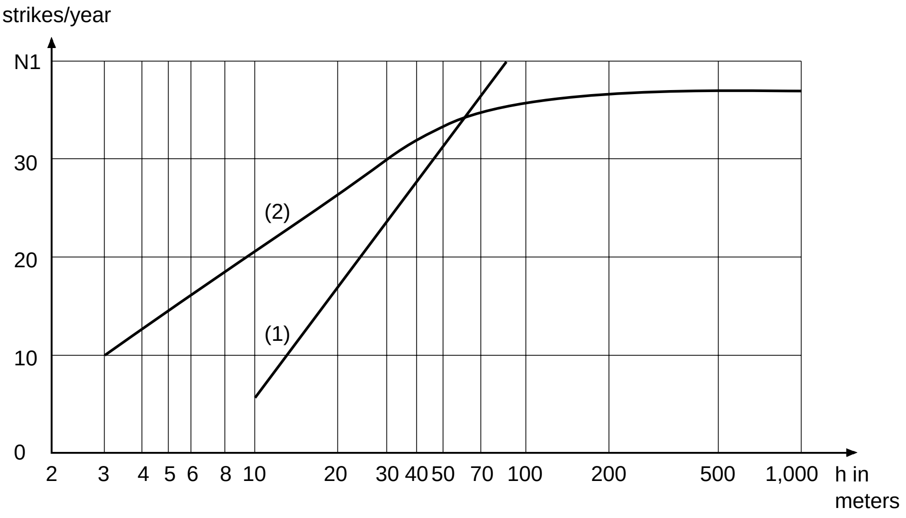


fig. 5: lightning frequency for a density N = 4 lightning strikes per km^2 and per year:
- *curve 1: vertical rod with a height h (with N1 x 10^{-3}),*
- *curve 2: horizontal conductor, 100 km long, at height h (with N1).*

	number of earth wires	**0**	**1**	**2**	**3**
lightning strike	on tower (%)	55	35	20	10
	on wires (earth or phase)	45	65	80	90
influence coefficient	α	1.65	1.40	1.20	1.05

fig. 6: distribution of strikes between towers and wires.

proportional to the distance through air (≈ 550 kV / m) and must take into account a delay in flashover for very steep fronts

- as a chopped impulse, with a voltage limited by flashover, when

$$Z \frac{I_{max}}{2} \geq Ua$$

The lightning current above which flashover, i.e. interruption in service, occurs is called the critical current Ic:
$Ic = 2 \quad Ua / Z$.

The magnitude of Ic is in the region of 5.5 kA for 225 kV lines, 8.5 kA for 400 kV lines and 19 kA for 750 kV lines. The corresponding frequencies of occurrence are respectively 95 %, 90 % and 60 % (see fig. 2). Note that for 20 kV lines, the Ic value is practically 0 and flashover always occurs.

Indirect lightning strikes (on earth wires or towers)
(see fig. 8)
The flow of the lightning current to earth causes an increase in the potential of the metal structures.
The top of the tower reaches a potential that depends on its inductance L and the resistance of the earth R to the impulse.

$$u(t) = R \quad i(t) + L \frac{di(t)}{dt}$$

This voltage may reach the impulse flashover voltage of the insulators, in which case «back-flashover» occurs. A part of the current is propagated along the affected phase conductor(s) toward users. This current is in general greater than that of a direct lightning strike.

On extra high-voltage transmission systems, «back-flashover» is unlikely due to the insulation level of the insulators. Earth wires are therefore a solution in that they limit the number of interruptions in service. However, below 90 kV, «back-flashover» and the resulting interruption in service occur even when earth resistance values are low (< 15 Ω), thus reducing the usefulness of earth wires.

wave propagation

Propagation of lightning impulse waves is a concept with which electrotechnicians are rarely confronted in day to day work.

What actually takes place ?
Any modification in the electrical state of a conductor at a given point travels at high speed, ranging from 150,000 to 300,000 km/s depending on the insulator surrounding the conductor. At a power frequency of 50 Hz, the distance covered in one period is 3,000 to 6,000 km.
In the industrial sector, this distance is far greater than the length of the concerned conductors, except in very particular situations. It is therefore possible to simplify by considering that the transmission of the wave is instantaneous throughout the installation.
Lightning produces «high-frequency» phenomena ranging from several tens of kHz to several MHz, levels far greater than the «low» 50 Hz or 60 Hz power frequencies.

Characteristics of «high-frequency» phenomena
In this range of frequencies, the electrical laws commonly used are no longer sufficient for our purposes:

- first, the system cannot be considered to be under standing (state) conditions, with instantaneous transmission of the wave throughout the installation. The transmission time is no longer negligible with respect to the period of the considered phenomena (at 1 MHz, the period is 1 µs which corresponds to 300 m).
- secondly, stray capacitance from the various elements, skin effect, electromagnetic coupling, etc. become important, even dominant, factors.

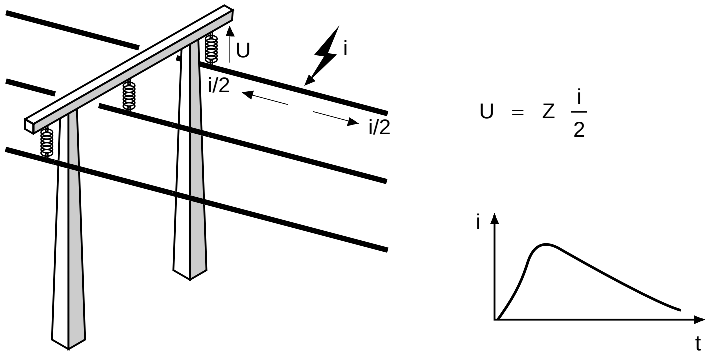


fig. 7: lightning strike on a phase conductor.

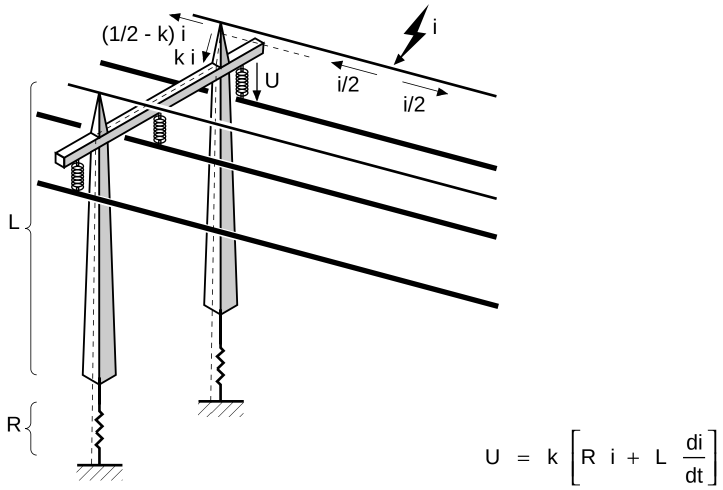


fig. 8: lightning strike on an earth wire.

…and the practical consequences for lightning studies

It follows that to quantitatively determine the effects of lightning (see the example in section five), it is necessary to:

- first, take into account the laws governing wave propagation. Given the distances involved, ranging from a few meters to several kilometers, propagation does not stabilise instantaneously, either in space or in time.
- then, take into account the laws governing reflection, refraction at points of discontinuity and superposition of waves at each point in time and at each point along the line.
- finally, adapt the model describing the physical operation of the various elements to take into account the dominant «high-frequency» phenomena.

Example: under «high-frequency» conditions, a transformer subjected to a transient no longer behaves like a series-connected inductance with a transformation ratio, but as a capacitive divider (HV/earth, LV/earth, HV/LV capacitances), in which case the HV/LV transformation ratio may be quite different from its value at power frequencies.

Propagation attenuation due to the corona effect

Lightning surges travelling along conductors are distorted by the corona effect (losses due to ionisation of the air surrounding the conductor, which can be sizeable when U > 1 MV). The result is an attenuation in amplitude and in front steepness. It is generally considered that over distances greater than 1.5 km, lightning surges no longer represent a danger for substations.

effects of lightning

This section discusses the main effects, both direct and indirect, of the propagation of lightning currents. Note that even if the current is transmitted by the high-voltage lines, it can affect all electrical circuits (conducted and radiated disturbances) at all voltage levels. The effects can be:

- thermal (welding of parts, fire, explosions).
- mechanical, due to the electrodynamic forces exerted on nearby parallel conductors.
- dielectric shock, following increases in potential during wave propagation through the impedance of the conductors.
- insulation breakdown following flashover of a phase insulator, resulting in a follow-on current flowing to earth at power frequency.
- increase in earth potential. Potentials commonly reach several hundred kV at the earthing electrodes of the concerned HV equipment. The relationship describing the potential as a function of the distance to the earthing connector is approximately hyperbolic, resulting in very high potentials and associated gradients near the earthing electrode and even at distances of several tens of meters.
- high-frequency electromagnetic interference (very wide spectrum), including radiated interference, induction and circuit coupling.
- electrochemical, acoustic and physiological.

All the above phenomena can cause:

- damage to equipment, either violent, for example dielectric breakdowns due to overvoltages, or in the form of premature ageing due to non-destructive, but repeated stresses,
- malfunctions in installations due in particular to interference in control/monitoring and communication equipment connected to low-current circuits,
- reduced continuity of service due to interruptions that may be long (damage to equipment) or short (malfunctions in network automatic control systems),
- dangerous situations for people or animals, in particular due to pace voltages which may result in electrical shock or even electrocution.

4. protection

Following a few general remarks on protection, this section discusses in greater detail the means to ensure protection, both primary (direct discharge) and secondary (limitation of the transmitted disturbances).

general

The best protection, in particular of human life, is provided by directing a maximum of the disturbance to earth at the closest possible point to the source of the disturbance.

Effective protection therefore requires the lowest possible earth impedances. This can be ensured by creating earthing networks and interconnections between earthing electrodes wherever possible. On high voltage B systems, an earth impedance of less than 1 Ω at power frequency is commonly specified for substations, whereas for towers, an impedance of 10 to 15 Ω is strived for.

There are several levels of protection against lightning currents and the resulting increases in potential.

These are based on energy levels:

- level 1, consisting of diversion of the major part of the impact to earth and initial clipping. This level applies primarily to objects likely to be struck by lightning (lines and substations).
- level 2, consisting of limitation of the residual voltage by further clipping. This level is intended to protect substation equipment and/or installations against conducted overvoltages. Several protection devices distributed throughout the installation may be required to dissipate the clipped energy.

- level 3, consisting of additional devices such as series-connected filters and/or overvoltage limiters, which may be required in LV systems for sensitive equipment (computer systems, automatic control systems, telecommunications, LV networks, etc.).

Note: All the above protection systems should be considered right from the design phase of installations and systems because subsequent modifications are difficult to implement and costly.

protection level 1

The purpose of level 1 protection is to limit the effects of direct impacts on electrical installations by diverting the lightning current to the desired locations.
Controlled diversion of lightning current to precise points is possible using:

- lightning rods implementing the striking distance principle. These thin rods are placed at the top of the structure requiring protection and connected to earth by the most direct path (via conductors descending around the protected structure and connected to the earthing network). Observations have shown that a good protection against direct lightning strikes is provided in a cone with its summit at the top of the lightning rod and extending downward at 45° angles with respect to the vertical.
- Faraday cages or shields which consist of closed grids of horizontal and vertical conductors connected to an earthing network. The mesh size must be less than 15 m and vertical rods are placed at the nodes on the top part. Coverage of the zone requiring protection is equivalent to that provided by a multitude of lightning rods.

In either case, lightning rods or cages, the electro-geometrical model determines the protected zone using the fictive sphere method.
The point of impact of the lightning strike is determined by the first object on the ground falling within the striking distance d of the leader. It is as if the leader were at the centre of a fictive sphere with a radius d. To ensure proper protection, the fictive sphere, as it moves along the ground with the leader, must encounter a protection device without touching the objects requiring protection (see fig. 9).
For protection against a very low lightning current, approximately 2 kA (cumulative probability ≈ 100 %), the critical striking distance is 15 m. If a 97 % probability is acceptable, the corresponding lightning current is 5 kA and the critical distance is 27 m.

- screens

This category comprises earth wires which are conductors running parallel to and above the phase conductors. Earth wires are connected to the earth via the towers and constitute effective protection against lightning strikes on overhead lines in that they capture strikes with amplitudes greater than the critical current I_c.

The concepts discussed in the preceding section can be used to determine the optimum position of earth wires.

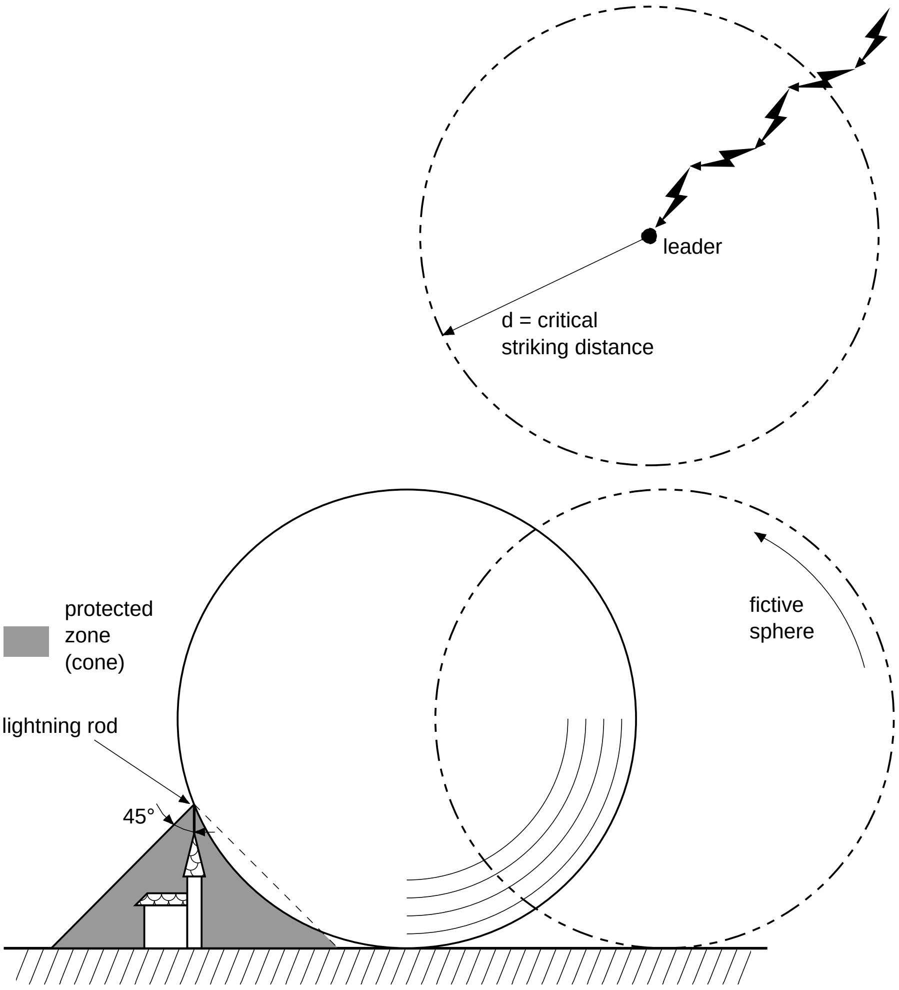


fig. 9: determining the protected zone using the «fictive sphere» method.

The different striking zones for an overhead line are shown in figure 10:

☐ zone I: earth strikes,
☐ zone II: strike on a phase conductor without insulator flashover ($I < I_c$),
☐ zone III: strike on the earth wire.

Protection of the phase conductors by the earth wire is determined by the optimum protection angle θ_{opt}.
When $\theta \neq \theta_{opt}$, screen faults may occur, i.e. lightning strikes with currents exceeding the critical current may reach the phase conductors and provoke faults. The number of screen faults depends on θ.

protection level 2

This type of protection applies to HV systems.
It must ensure that the BIL (Basic Impulse Level) of the various substation elements is not exceeded (coordination of insulation).
It creates an earthing circuit enabling diversion of the lightning current by sparkover or conduction. Two types of devices are used to limit lightning surges, spark gaps, based on a relatively old technique, and lightning arresters, which today are used to replace the former in a wide range of applications.

■ spark gaps, which implement sparkover, have a number of major handicaps:
☐ fairly high dispersion of the sparkover voltage (up to 40 %),
☐ a sparkover delay that is a function of the overvoltage,
☐ the sparkover phenomenon is sensitive to external influences, for example atmospheric conditions,
☐ the spark gap creates a very steep chopped wave front that can destroy the windings of nearby machines,
☐ it also creates a 50 Hz follow current.
The diverted current is detected by the earth-fault protection device which actuates upstream breaking of the concerned line.

■ a lightning arrester (or more generally a surge arrester) is a semi-conductor with non-linear resistance ranging from a few Ω to several MΩ. It is generally made of zinc oxide (ZnO), a material whose characteristics are well understood.
It is connected between the phases and the earth.
☐ operation is similar to that of the spark gap, but it offers better control of the voltage:
- low dispersion of its residual voltage $U = f(I)$,
- virtually no delay in conduction,
- natural return to its initial state (insulator), thus avoiding follow current.

☐ the main sizing criteria for a lightning arrester are:
- maximum continuous operating voltage (MCOV), which must be greater than the maximum network operating voltage with a safety margin of 5 %;
- rated voltage, which must be 1.25 x MCOV;
- protection level;
- capacity to withstand the energy of transient overvoltages, determined by an amplitude vs. duration curve.

■ lightning arresters or spark gaps provide effective protection only when certain installation conditions are respected, in particular the distances separating them from the equipment to be protected and from the earth.
That explains the importance of the protection distance of the lightning arrester, which will be discussed below.

protection level 3

Applied in LV systems and for sensitive equipment, this level of protection against lightning and its effects is not discussed in length in this «Cahier Technique» publication. For further information, consult the documents listed in the bibliography.

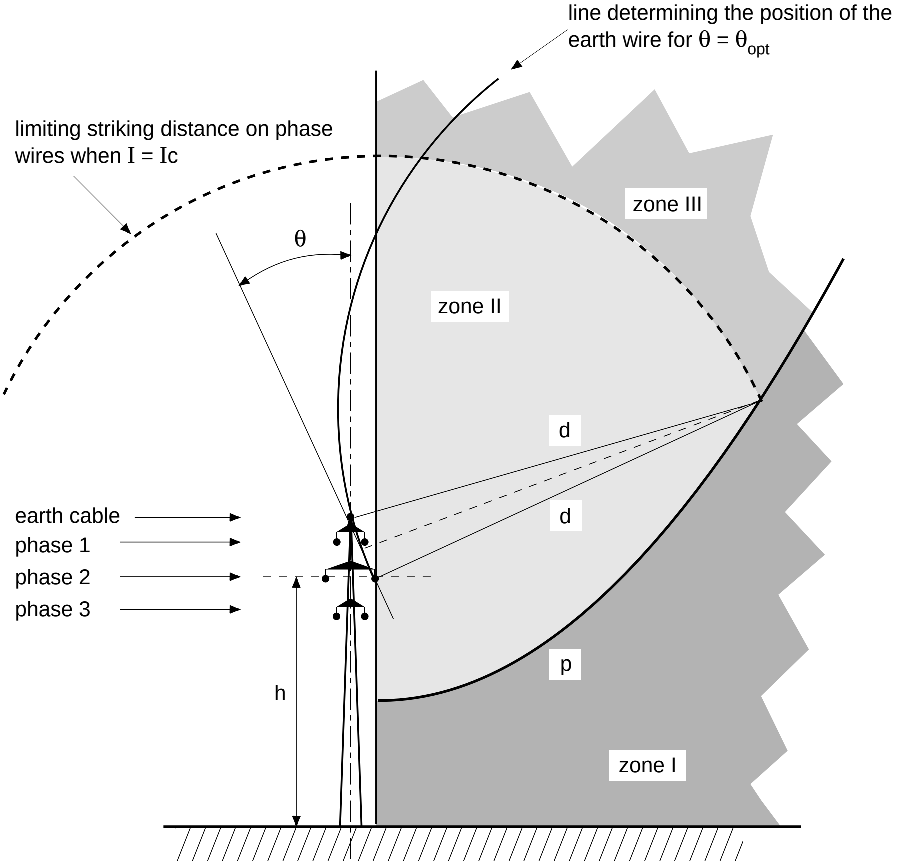


fig.10: different cases for lightning strikes on an overhead line. Note that protection angle $\theta = \theta_{opt.}$

Note that this type of protection is based on the following:

- ■ electromagnetic-compatibility (EMC) studies,
- ■ earthing-network design (interconnections, sizing, etc.),
- ■ coordination of overvoltage limiters with overload, short-circuit and differential protection devices,
- ■ parallel-connected protection to limit impulse voltage using surge arresters: gas spark gaps, varistors (SiC, ZnO), avalanche diodes, RC filters,
- ■ series-connected protection to limit the power transmitted using wave absorbers (or HF filters), shielded isolating transformers, network conditioners or UPS systems.

protection distance

The concept of protection distance is illustrated in the example below, which has been voluntarily simplified.

Example

Consider an overvoltage impulse wave travelling down a line and arriving at a substation comprising a transformer protected by a lightning arrester (see fig. 11).

The various elements are defined as follows:

- ■ line:
  - ☐ surge impedance: Zc,
  - ☐ wave propagation velocity: v,
  - ☐ distance between arrester and transformer: D,
  - ☐ propagation time between A and B:

$\tau = D / v$,

- ■ lightning arrester with perfect characteristics, i.e. for all voltages greater than Vp, conduction is instantaneous and the voltage is limited to precisely Vp,
- ■ earthing electrode with an impedance equal to zero,
- ■ arrester/equipment and arrester/earth connections zero in length,
- ■ transformer with an input impedance, at the considered frequencies, much higher than Zc. An arriving voltage wave is almost totally reflected (voltage doubles at point of reflection),
- ■ incident overvoltage wave with a constant-slope ($r = dV / dt$) front and a constant tail voltage where $T = Vp / r$ is the front duration up to Vp (see fig. 12).

There are three possible cases which are summarised in figure 13.

The diagrams in figures 14, 15 and 16 illustrate the phenomena for cases 1 and 2 (see pages 14, 15 and 16).

Example

If the maximum permissible impulse voltage for the transformer is set at 1.3 x Vp, then

$$1\,3\ x\ Vp \geq Vp + 2\ \frac{r\ D}{v}$$

It follows that the arrester/transformer distance must not exceed:

$$D \leq 0.15\ \frac{Vp\ \ v}{r} = 0.15\ \ T\ \ v$$

Using the applicable figures:

$Vp = 1{,}200$ kV,

$v = 300$ m / µs,

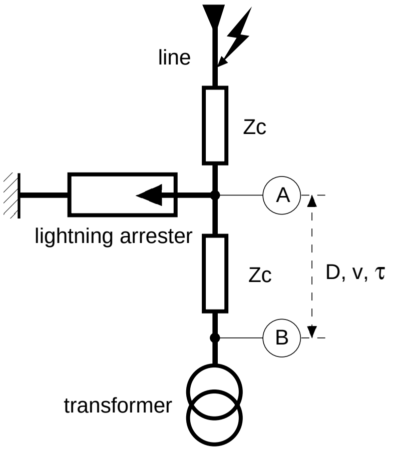
$r = 2{,}000$ kV / µs,

$\Rightarrow D \leq 27$ m.

Note:

In reality, the following elements must be taken into account:

- ■ lightning arrester connections to equipment and to the earth,
- ■ actual lightning arrester characteristics,
- ■ network configuration with impedance breaks and the different propagation velocities,
- ■ capacitive elements, including the transformers.



A and B: measurement points

fig. 11: circuit diagram (line and transformer substation) for study of lightning overvoltage wave propagation.

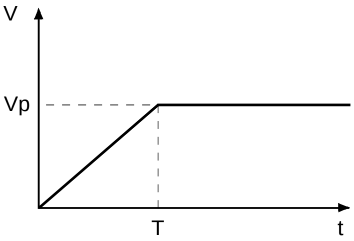
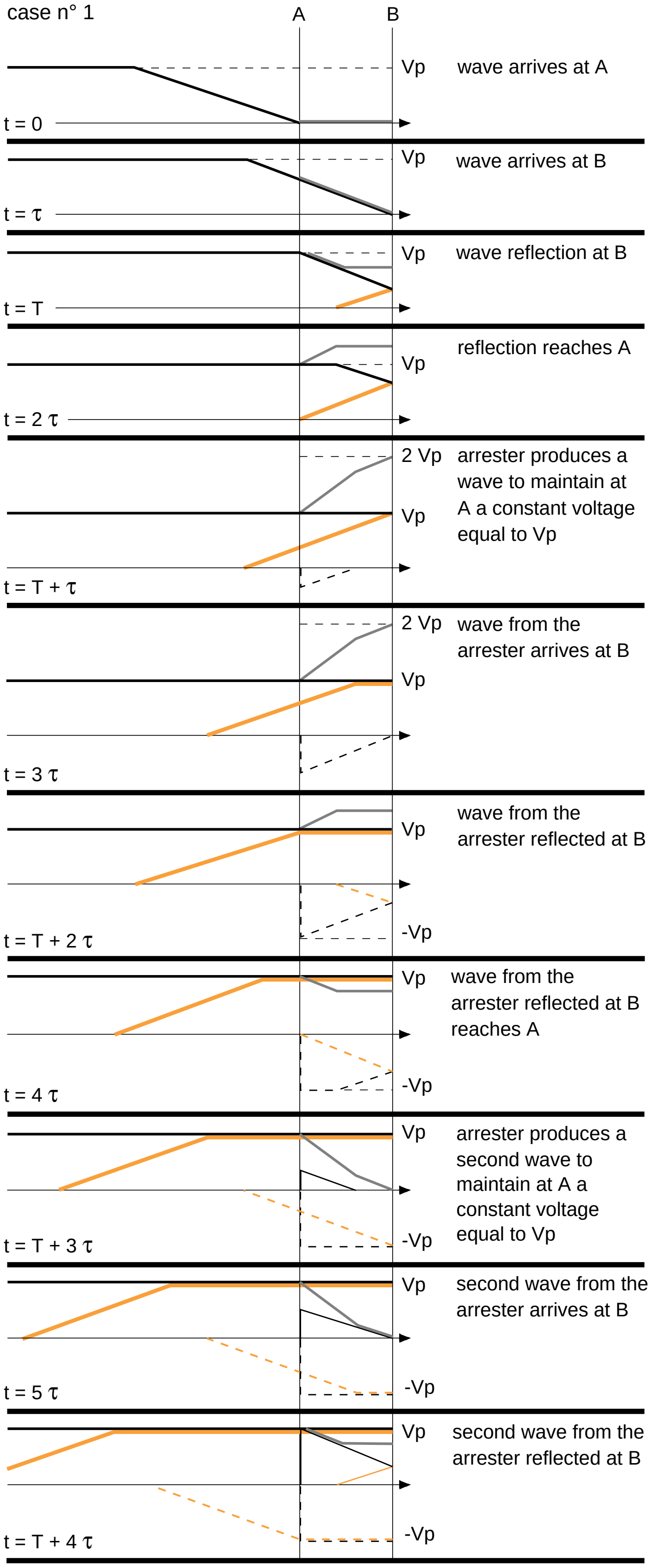


fig. 12: overvoltage wave diagram.

case	criteria	maximum overvoltage on transformer	comments
1	$D > \frac{v\ \ Vp}{2\ \ r}$ i.e.: $T < 2\ \ \tau$	$2\ \ Vp$	steep front slope r, long distance D. Arrester distance has no effect on the maximum voltage on transformer, the arrester limits the voltage to 2 Vp.
2	$D < \frac{v\ \ Vp}{2\ \ r}$ i.e.: $T > 2\ \ \tau$	$Vp + 2\ \frac{r\ \ D}{v}$ overrun $= 2\ \frac{r\ \ D}{v}$ $= Vp\ \frac{2\tau}{T}$ $\Rightarrow Vp + 2\ \frac{r\ \ D}{v} = Vp\ (1 + \frac{2\ \ \tau}{T})$	steep front slope r, long distance D. Arrester presence limits, by the distance effect, the maximum voltage on the transformer. Overrun of threshold Vp is proportional to D and to r, hence the «protection distance» concept.
3	$D = \frac{v\ \ Vp}{2\ \ r}$ i.e.: $T = 2\ \ \tau$	$Vp + 2\ \frac{r\ \ D}{v}$ $= Vp + Vp = 2Vp$	limit case between 1 and 2.

fig. 13: maximum overvoltages on the transformer, a practical example.

case n° 1



case n° 2

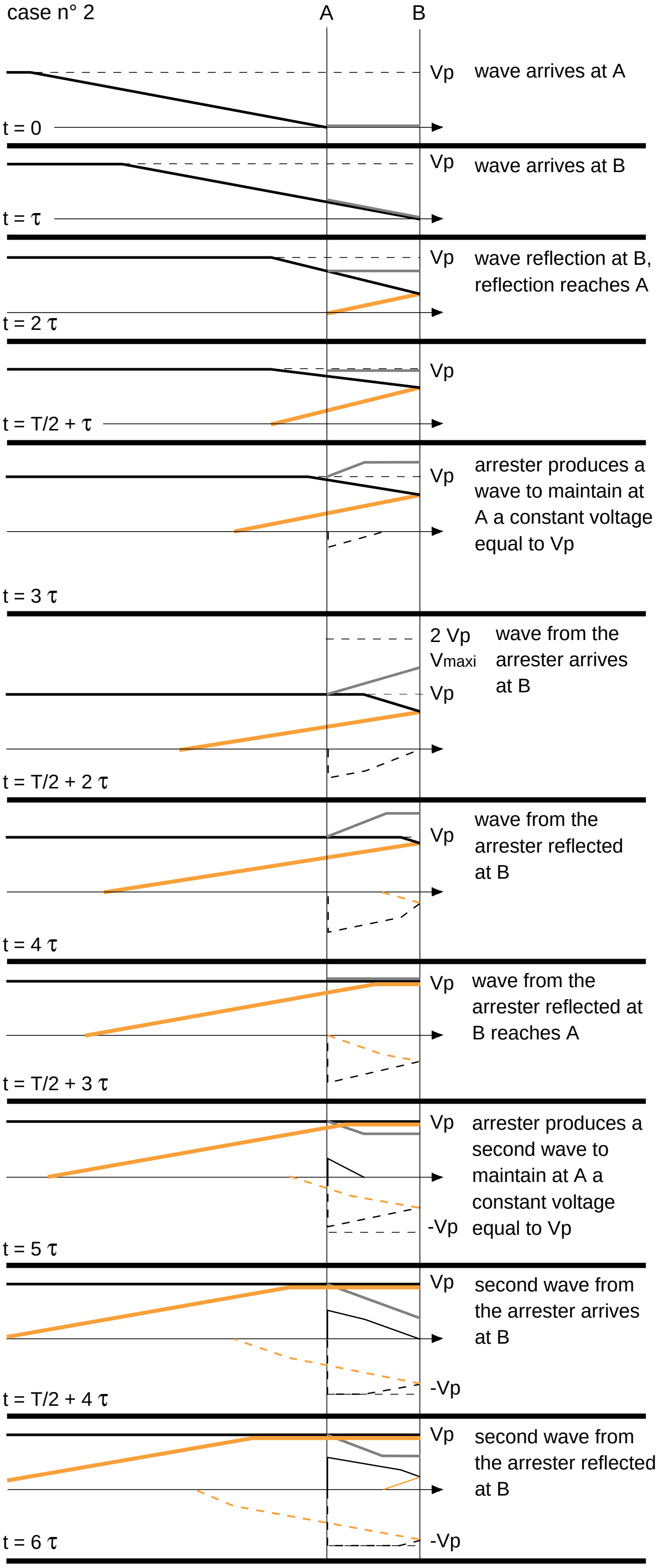


fig. 14 (opposite page): diagrams illustrating lightning wave propagation for cases 1 (steep front slope) and 2 (low front slope) described in figure 13. Positions A and B are shown in figure 11.

━━━ incident wave (T)
- - - - first wave produced by the arrester
──── second wave produced by the arrester
━━━ voltage profile

━━━ reflected incident wave (T)
- - - - first wave produced by the arrester (reflected)
──── second wave produced by the arrester (reflected)

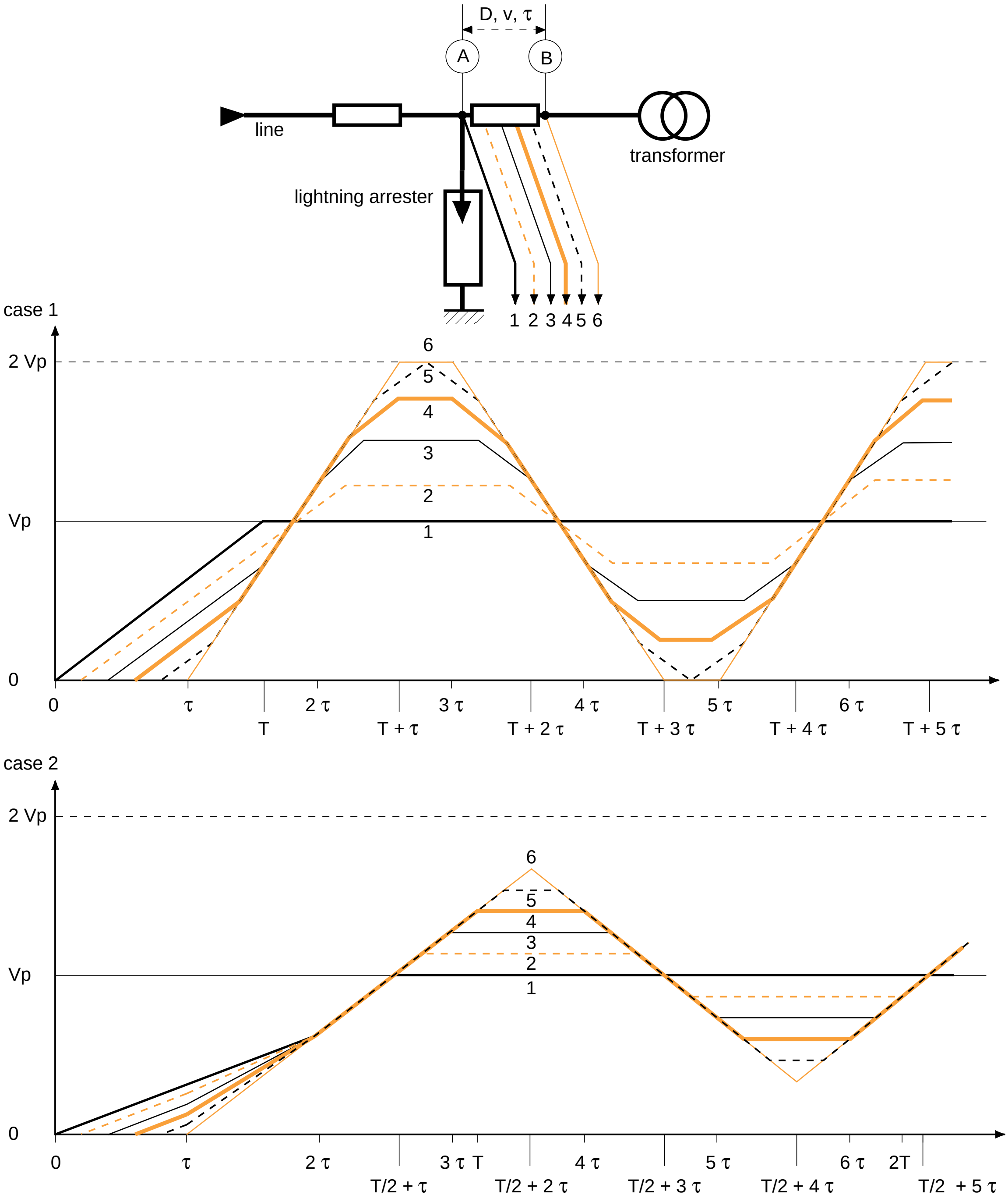


fig. 15: voltages on the line protected by the lightning arrester as a function of time, for cases 1 (steep front slope) and 2 (low front slope) described in figure 13.

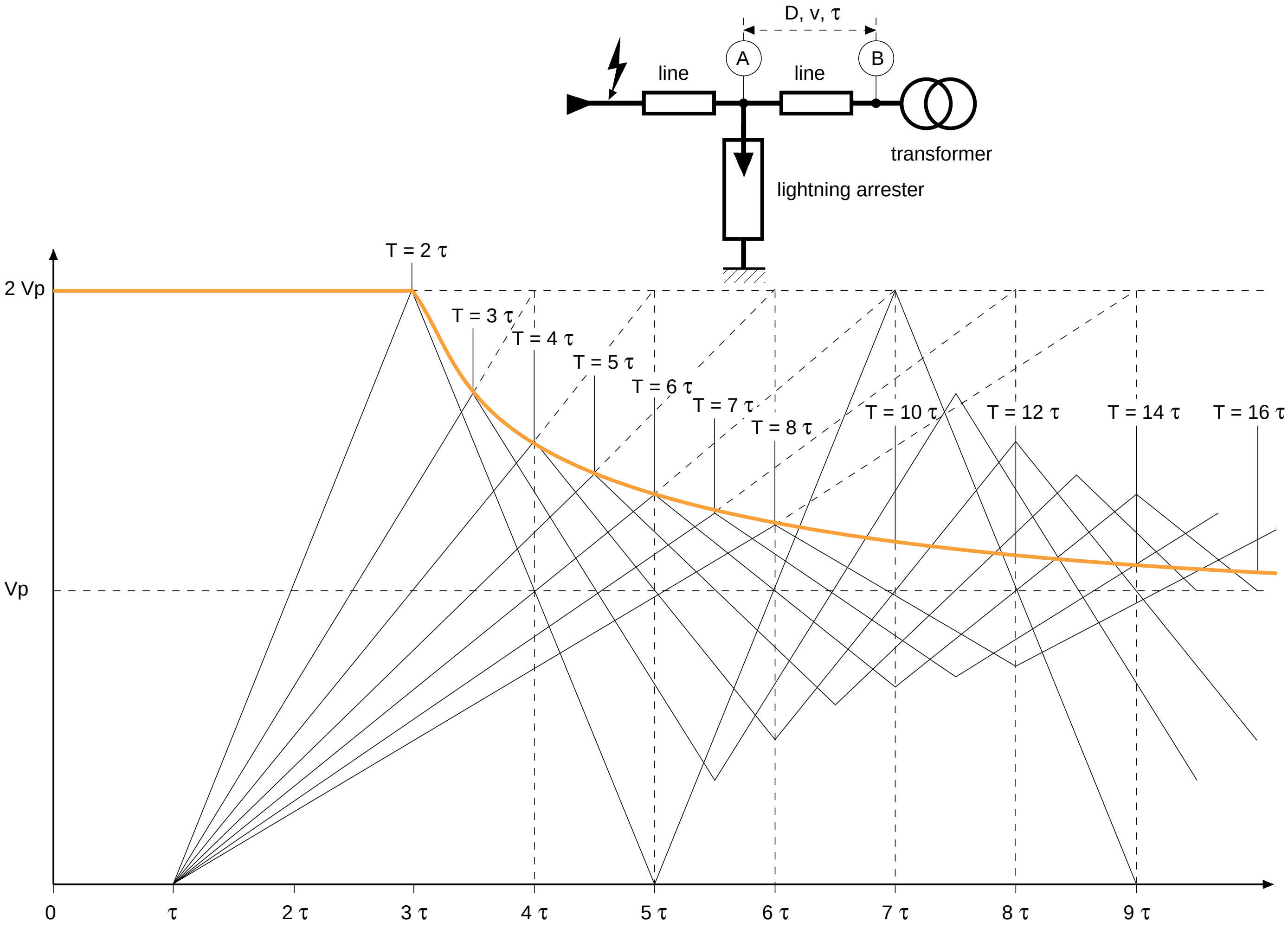


fig. 16: maximum overvoltage at transformer input (point B) as a function of T for a given τ (case 2 in figure 13).

network operation and non-availability

In public distribution networks, lightning is one of the causes (50 %) of voltage dips and brief interruptions.

These interruptions in the supply of power, provoked by the protection devices, are required to clear the fault (end of spark gap discharge or stop of insulator flashover).

To improve continuity of service, interruptions are shortened by automatic reclosing of the protection devices (circuit breakers).

Automatic reclosing cycles differ, depending on the voltage level:

- > 300 kV: high-speed reclosing on single-phase systems (< 0.5 s) or slow on 3 phase systems (1.5 to 5 s),
- 50 kV < U < 300 kV: 3 phase reclosing and the use of shunt circuit breakers on single-phase systems (0.15 s),
- 1 kV < U 50 kV: high-speed and slow 3 phase reclosing (0.35 s, 15 s).

Interruptions are troublesome for users and may be alleviated or eliminated by:

- implementing auxiliary sources such as UPS systems for control/ monitoring applications, computer systems, etc.,
- designing and implementing correct discrimination between the protection devices on the user's network, to ensure rapid clearing of faults caused by lightning,
- preventing isolating of priority consumers during storms. Sensitive loads can then be supplied by an internal power supply, while other loads continue to be supplied by the public distribution network.

standards

Installation designers can use standards to assist in determining:

- the overvoltage situations that must be taken into account when calculating representative electrical stresses,
- the basic impulse levels (BIL) of equipment,
- protection device characteristics.

The main applicable standards are listed in the appendix. A few particular points are listed below.

IEC 60-1: high-voltage test techniques - part 1

- section 6: lightning impulse tests.

Different wave forms are defined (full lightning impulse, impulse chopped on the front or impulse chopped on the tail) with characteristic durations.
Figure 17 shows a standardised lightning strike.

- section 8: current impulse tests. For the tests, four standardised current impulses of the bi-exponential type, defined by their front duration and the time to half value, may be used:
  - 1 µs / 20 µs impulse,
  - 4 µs / 10 µs impulse,
  - 8 µs / 20 µs impulse,
  - 30 µs / 80 µs impulse.

IEC 694: common clauses for high-voltage switchgear and controlgear standards

(French standard: NF C 64-010)
This standard stipulates that the rated insulation levels must be selected from the values contained in a series of tables (see fig. 18 for an example).

It also stipulates that lightning impulse voltage tests must use the standardised 1.2 / 50 µs wave.

IEC 99-1: surge arresters - part 1

(French standard: NF C 65-100)
Section 6: type tests.
This section presents the type tests defined by the standard:

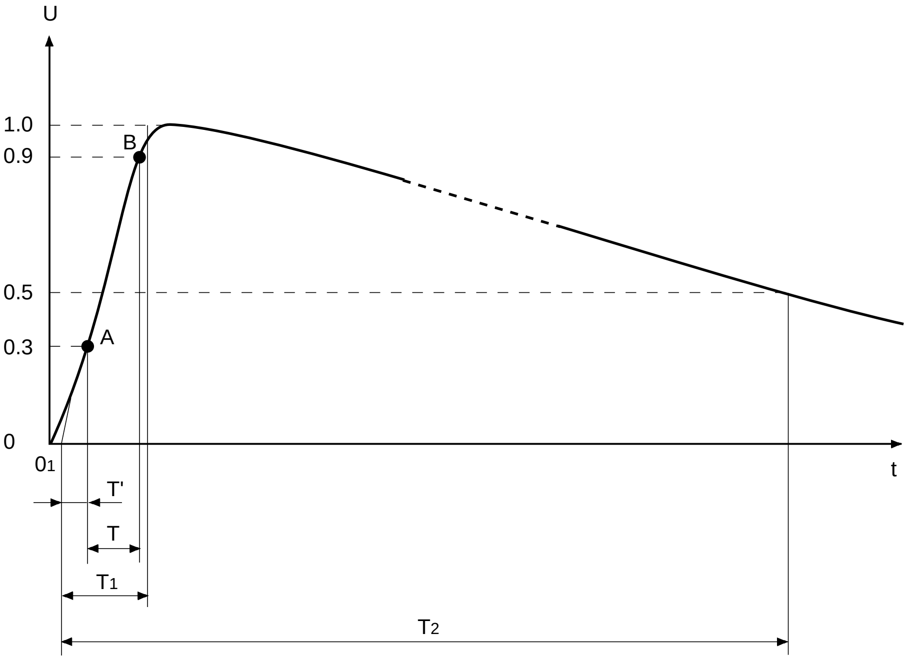
- external insulation withstand capacity;
- verfication of the residual voltage for 8 / 20 µs lightning impulses;
- withstand capacity for long impulse currents;
- tests on operation, accelerated ageing, heat dissipation capacities, thermal stability, lightning and operating overvoltages, etc.

IEC 71-1: insulation coordination - parts 1 and 2

The capacity of insulation to withstand lightning impulses must be determined taking into account foreseeable overvoltages such that insulation coordination requirements are satisfied for lightning overvoltages. Coordination may be based on conventional or statistical methods.

- using the conventional method, the coordination criterion is the margin between the maximum foreseeable value and the withstand voltage indicated by an impulse test. This margin determines a safety coefficient that should not be less than the value derived from practical experience which is approximately 1.25.
- using the statistical method, which accepts that insulation faults may occur, the goal is to quantify the risk of a fault.

The coordination criterion to be determined is the margin characterised by a statistical safety coefficient relating the statistical impulse withstand voltage (withstand probability of 90 %) to the statistical overvoltage (2 % probability of being exceeded).



$T_1 = 1.67\ T$
$T' = 0.3\ T_1 = 0.5\ T$

fig. 17: example of a standardised lightning strike defined by IEC 60. HereT_1 = 1.2 µs, T_2 = 50 µs.

rated voltage (kV rms)	7.2	24	72.5	245	420	525
rated insulation levels for lightning impulses (kV)	40 60	95 125 145	325	850 950 1,050	1,300 1,425	1,425 1,550

fig. 18: examples of voltage levels (defined by IEC 694) from which the rated insulation levels for lightning impulses must be selected.

Figure 19 is an example showing the correlation between the risk of a fault and the statistical safety coefficient. Note that currently, the statistical method is almost exclusively limited to self-regenerating insulation applications where faults do not result in damage to equipment.

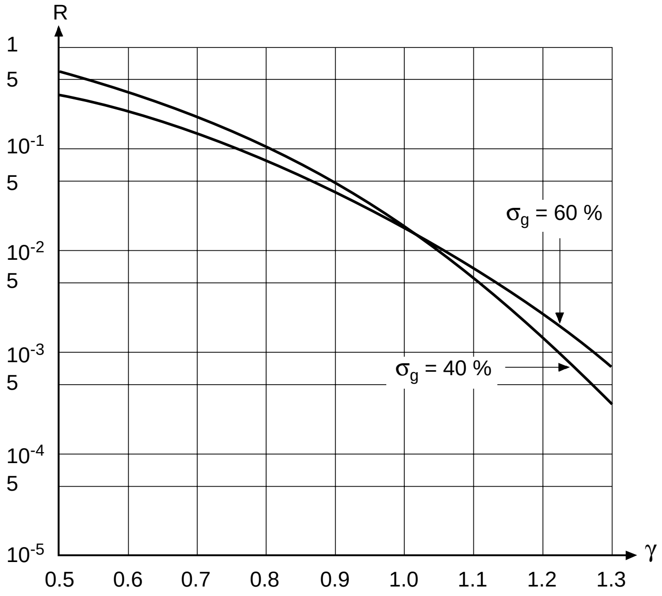


fig. 19 : correlation between the risk of a fault (R) and the statistical safety coefficient (γ) for various distributions of lightning overvoltages (σ_g = standard deviation), as defined by IEC 71.

5. example of a lightning study

This section outlines the procedure for a lightning study, the methods used and the practical conclusions. It deals in particular with calculation methods, substation modelling using the calculation assumptions, deterministic simulations, statistical aspects and the conclusions.

general

This study deals with insulation coordination for an extra high voltage GIS (gas-insulated switchgear) substation. Adequate dielectric behaviour must be ensured for the various elements in the chain comprising the electrical system. The elements have different BILs and practically speaking, the question is whether lightning arresters are required and if so, how to define their characteristics (location, ratings).

This type of study is becoming increasingly common for large substations. Customers require that installers and suppliers of turn-key installations provide numerical data justifying sizing decisions.
This type of study must be carried out by teams of specialised engineers with sufficient experience and know-how and using specific computer software.

Note: The example presented here was drawn from a true study concerning the supply of a 500 kV substation, carried out by the Network Research Section (a part of the R&D Department), on request from the Contracting Department of Merlin Gerin in charge of the project.

calculation methods

A number of successive and complementary calculations are made:

- first, deterministic calculations evaluate voltages present in the installation depending on a number of different parameters such as the type of lightning strike, the intensity and point of impact, the existence and location of lightning arresters, earth impedance, etc.
- secondly, calculations on lightning frequencies and the corresponding risks, on the basis of lightning statistics,
- finally, calculations on substation withstand capacities expressed in probabilistic terms.

Deterministic calculations

- substation modelling

The operation of each network element and its configuration (physical interconnections) in the network topology are described by equations based on the applicable electrical laws. Modelling requires prior analysis of the network to limit the description to pertinent aspects.
The equations are solved by computers using dedicated software, for example EMTP (Electromagnetic Transient Program).

- simulation of lightning current waves and the associated voltages for each proposed solution. Stepwise equation solving makes it possible to express virtually continuously the evolution of current/voltage variables at each point in the network as a function of time. The simulation reproduces actual operation analogically. Lightning is represented by a supply of current comprising a triangular or bi-exponential wave with adjustable front/ tail durations and peak values.

substation modelling

Modelling in this example is limited to a general description that should suffice for a basic understanding of the procedure and does not include a number of details required only by specialists.

General assumptions

- lightning strike on an earth wire, with «back-flashover» of an insulator on the second line tower (most unfavourable case).
- lightning impulse on the earth wire:
  - peak value: 200 kA,
  - triangular shape: 2 / 50 µs.
- length of the struck line taken into account is limited to 1.5 km from the substation (see section 2).
- phase subject to flashing:
  - farthest from the struck earth wire,
  - with a negligible power voltage.
- substation configuration: GIS configuration with the maximum length of in-service busbars (most unfavourable case).
- modelling frequency: 1 MHz.

Main technical data

- 500 kV line:
  - 4 wires per phase, 2 earth wires,
  - impedance data:

$$\begin{pmatrix} \text{Zdirect} \approx 300\,\Omega \\ \text{Zzero} - \text{sequence} \approx 500\,\Omega \end{pmatrix}$$

- towers:
  - surge impedance: 120 Ω,
  - height: 43 m,
  - earth resistance 25 Ω.
- insulators:
  - chain of 29 elements (cap and pin type),
  - flashover voltage: 2,600 kV,
  - discharge delay depends on the shape and the level of the overvoltage defined by a typical voltage-time curve.
- GIS:
  - surge impedance: 70 Ω,
  - substation earthing electrode impedance: < 1 Ω.
- capacity:
  - power transformer: 7 nF,
  - instrument transformer: 4 nF.
- lightning arresters: the U = f(I) characteristic expresses their non-linearity.
- all connections (lines excepted): 1 µH/m linear.

Studied installation
(see fig. 20)

deterministic simulations

The simulations are carried out for a number of cases, e.g. with or without lightning arresters downstream of the substation and at the transformer terminals, and for various arrester characteristics.

For each case, the maximum overvoltages occurring at the instrument transformers, the substation and the power transformer are closely observed and compared to the possible BILs. The results (see fig. 21) show that for a BIL of 1,550 kV, at least two lightning arresters are required (for the instrument and power transformers).

The table in figure 21 and the main curves in figure 22 correspond to the safest case in which three identical lightning arresters (n° 1, 2 and 3) are used.

Note the distribution of the 200 kA lightning strike: the lines and towers absorb the major part of the current and less than 14 % arrives at the substation, where approximately half is absorbed by the lightning arresters. It is a small fraction of the lightning current (< 5 %) that provokes voltage rises approaching the maximum dielectric withstand capacities of the equipment.

Note: it has been demonstrated that direct hits on phase conductors are less of a problem than back flashover. The schielding effect of the earth wires limits the currents resulting from direct strikes, as calculated using the electro-geometrical model, to approximately 12 kA.

That is less than the critical current and the insulators are not subject to flashover. Under these conditions, the calculated currents in the substation resulting from a direct impact are less than those resulting from back flashover.

statistical calculation of lightning frequencies and the associated risks

The average frequency of lightning strikes on a line is calculated using the formula presented in section 3:

$$N_L = Nk \left(\frac{N1}{30} + \frac{l}{70} \right) \alpha \frac{L}{100}$$

hence N_L = 1.03 strikes / year.

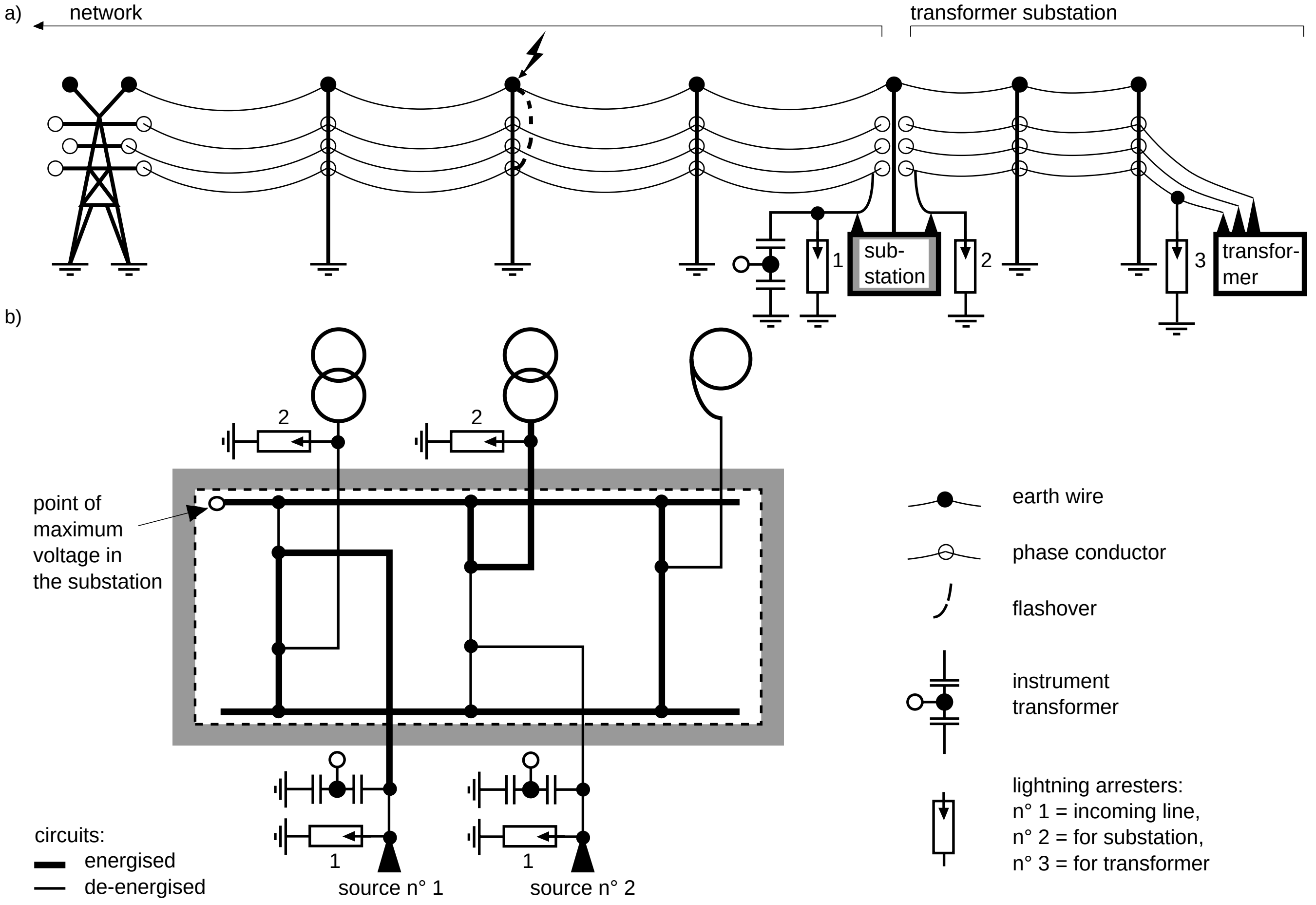
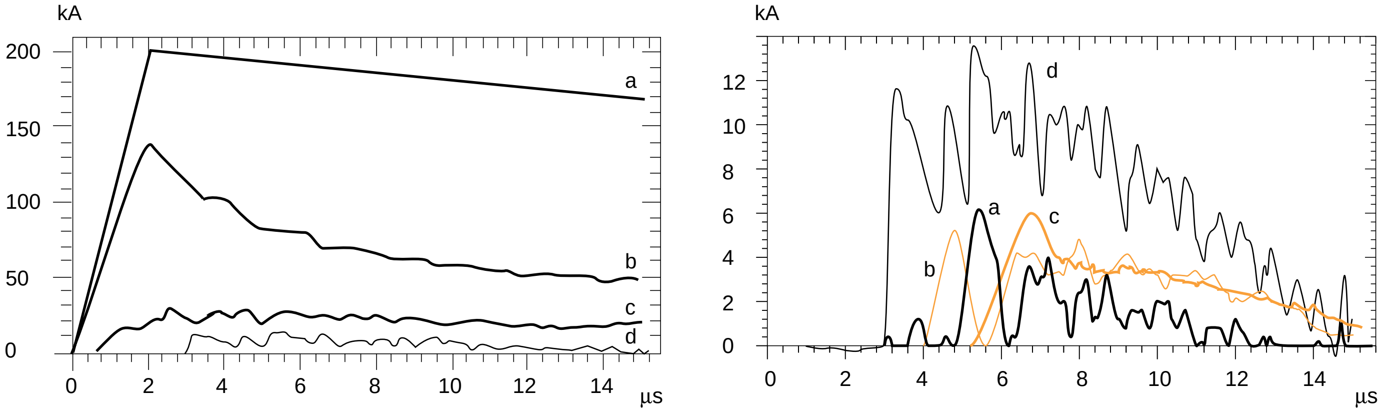


fig. 20: general substation layout and configuration.

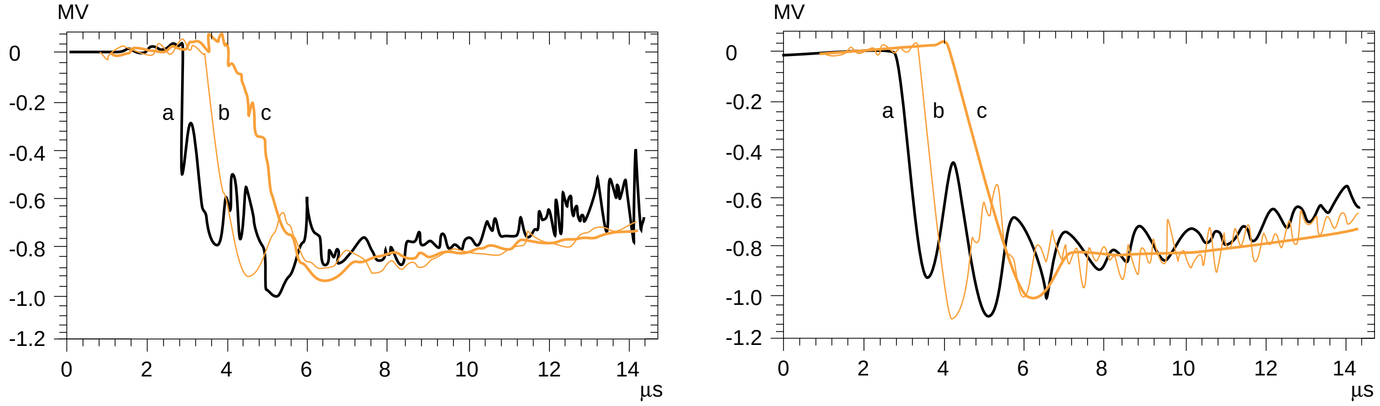
location of lightning arresters			overvoltages (kV) and safety coefficients (%) $= \frac{\text{BIL} - U_{max}}{U_{max}}$ for each element				
near the instrument transformer	downstream from the substation	upstream from the power transformer	instrument transformer		substation	power transformer	
			BIL 1,550 kV	BIL 1,800 kV	BIL 1,550 kV	BIL 1,550 kV	BIL 1,800 kV
yes	yes	yes	1,096 kV		1,103 kV	1,004 kV	
			41.4 %	64.2 %	40.5 %	54.2 %	79.3 %
yes	**no**	yes	1,263 kV		1,235 kV	1,044 kV	
			22.7 %	42.5 %	25.5 %	48.5 %	72.4 %
yes	yes	**no**	1,096 kV		1,103 kV	1,560 kV	
			41.4 %	64.2 %	40.5 %	- 0.6 %	15.4 %

fig. 21: safety coefficients for each element of the studied equipment. The valid figure for the overall installation is 40.5 %.



a = lightning current
portion of lightning current flowing:
b = to earth via the struck tower,
c = to earth via the last tower before the substation,
d = to the substation via the phase subject to flashover.

portion of lightning current flowing:
a = to earth via the lightning arrester at the head of the line (1),
b = to earth via the lightning arrester for the substation (2),
c = to earth via the lightning arrester for the transformer (3),
d = to the substation via the phase subject to flashover.



a = voltage at the lightning arrester at the head of the line (1),
b = voltage at the lightning arrester for the substation (2),
c = voltage at the lightning arrester for the transformer (3).

a = voltage affecting the instrument transformer,
b = maximum voltage affecting the substation (see fig. 20),
c = voltage affecting the power transformer.

fig. 22: curves plotted on the basis of lightning overvoltage simulations.

The probability of surges caused by lightning strikes ≥ 200 kA is indicated by the curve in figure 2:
Probability (P) = 1 %.

The frequency of occurrences is therefore:
$Fd = N_L \times P \approx 0{,}01$ surges / year.

The statistical return period Tr between two occurrences is
$Tr = 1 / Fd \approx 100$ years.

A practical means to express these figures is to determine the corresponding risk R of such a surge occurring during the service life t of the substation.

$$R = 1 - e^{-\frac{t}{Tr}}.$$

For a 30-year service lise: R ≈ 26 %.

interpretation of calculations

The conclusion of this study may be summed up in a single phrase. There is one chance in four (26 %) that, during the service life of the substation (30 years), an overvoltage caused by lightning will reach or exceed 1,103 kV, corresponding to 71 % of the defined BIL (1,550 kV), i.e. a calculated safety coefficient of 40 %.

This result is of use in defining protection levels for equipment, depending on standards, technical possibilities and cost factors, etc.

Note that all the above calculations are based on selected values for important parameters, including a number which are:

- decisive, for example, tower and substation earth impedances, lightning strike amplitudes,
- and/or characterised by very wide dispersion ranges, for example, breakdown voltages and flashover delays of insulators,
- and/or poorly understood, for example, network configuration statistics or the correlation between lightning impulse amplitudes and fronts,
- and/or neglected, for example, ageing processes and corona effect.

The values used for these parameters may lead the reader to suspect inaccurate results. However, practical experience, accumulated and analysed primarily by electrical distribution utilities, confirms their suitability. The methods outlined in the example presented in this section are similar to those implemented by EDF, the French electrical authority.

6. conclusion

This document sums up the main aspects concerning lightning in electrical installations, thus constituting a basic introduction to this often obscure, but nonetheless increasingly important subject.

It deals primarily with medium and high voltage installations. Lightning is a major constraint on equipment and is a decisive factor in ensuring insulation coordination.
In the low-voltage field, lightning is but one of many possible electrical disturbances (see the bibliography).
In this «Cahier Technique» publication, the main practical aspects are discussed in an effort to provide a maximum of information, both quantitative and qualitative, including the physical aspects of lightning itself, its effects on electrical installations, currently available means of protection and standards. However, from all the information contained in this document, two main points should be remembered:

- the concept of the lightning-arrester protection distance, corresponding to wave propagation phenomena at very high frequencies (MHz);
- the example of a lightning study, based on an actual study carried out by Merlin Gerin for a 500 kV installation.

The lightning study, broken down into its component parts, shows how the risk of damage to equipment by lightning can be calculated.

The electrotechnical community is today increasingly aware of the problems caused by lightning and such studies are increasingly carried out for major international projects.
The current trend to take lightning phenomena into account starting from the initial installation design phase will continue to grow in coming years, thus contributing to further improve the quality of electrical power.

appendix: bibliography

Standards

- IEC 56: HV AC circuit breakers.
- IEC 60-1: HV test techniques, part 1 (French standard: NF C 41-101 and 102).
- IEC 71: Insulation coordination (French standard: NF C 10-100).
- IEC 76-1: Power transformers, part 1, insulation levels and dielectric tests (French standard: NF C 52-100, part 3).
- IEC 99-1: Surge arresters, part 1 (French standard: NF C 65-100).
- IEC 289: Reactors (French standard: NF C 52-300).
- IEC 298: AC metal-enclosed switchgear for rated voltages above 1 kV and up to and including 52 kV (French standard: NF C 64-400).
- IEC 694: Common clauses for hifh-voltage switchgear and controlgear standards (French standard: NF C 64-010).
- NF C 17-100: Protection against lightning - Rules governing installation of lightning arresters.

EDF (French electrical authority specifications)

Series HN 65 :

- protection against overvoltages in HV applications,
- spark gaps in HV installations,
- lightning arresters in HV applications.

HN 112: Insulation coordination on 400 kV networks.

HN 115: Design and execution guidelines for earthing systems.

HN 119: Insulation coordination on 225 kV networks.

Other publications

- Dielectric properties of air and extra high voltages.
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- «Lightning: understanding the phenomenon in order to protect against it.»
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Cahier Technique n° 137
B. CAVALADE.
- Les perturbations électriques en BT.
Cahier Technique n° 141
R. CALVAS.
- EMC : Electromagnetic compatibility.
Cahier Technique n° 149
F. VAILLANT.
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D. FULCHIRON.
- Calcul des courants de court-circuit.
Cahier Technique n° 158
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G. THOMASSET.

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