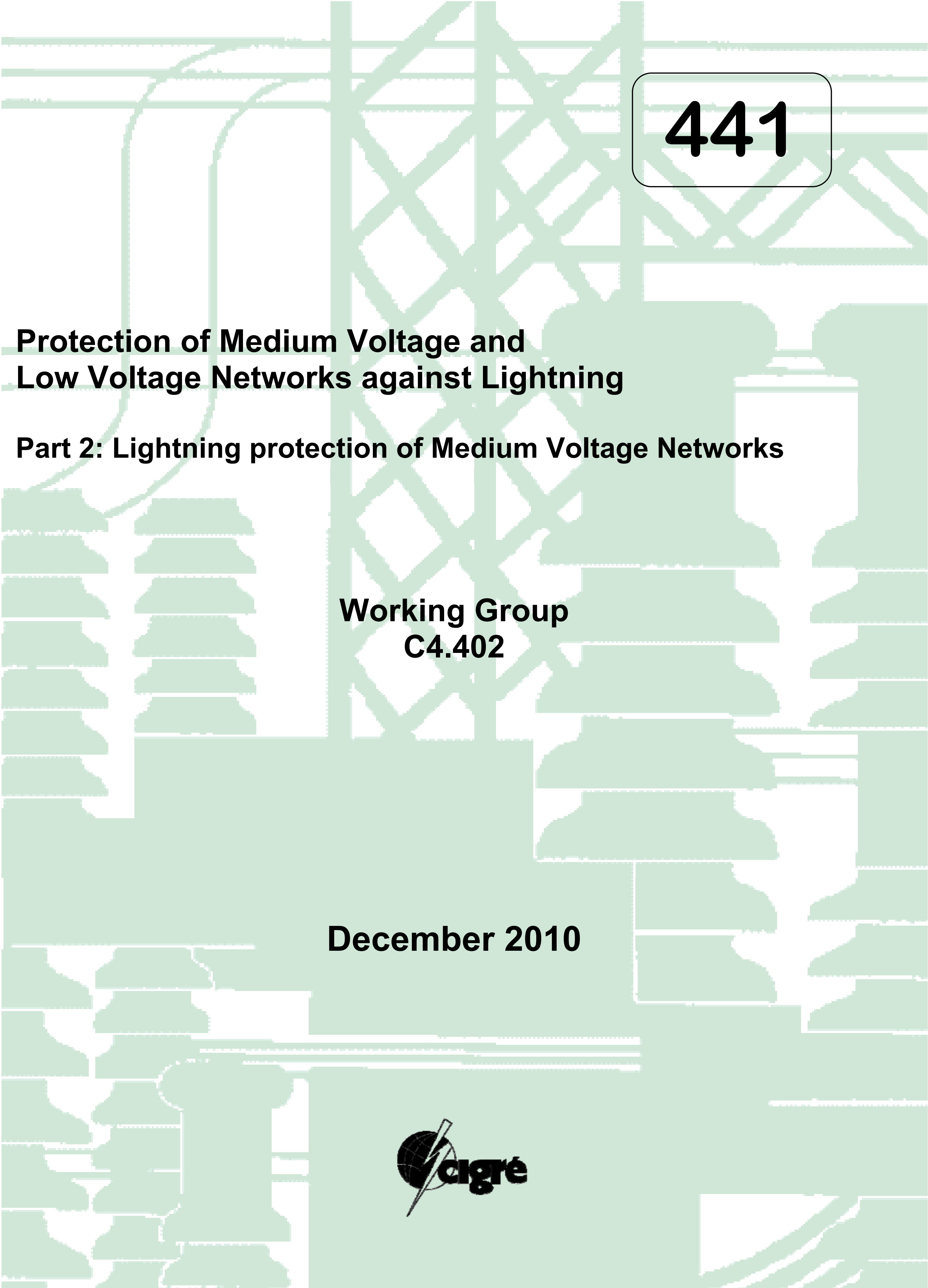

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Protection of Medium Voltage and Low Voltage Networks against Lightning

Part 2: Lightning protection of Medium Voltage Networks

Working Group
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Protection of Medium Voltage and Low Voltage Networks Against Lightning Part 2: Lightning protection of Medium Voltage networks

CIGRE/CIRED

Working Group C4.402

Members

F. Rachidi, Convenor (CH), A. Borghetti (IT), T. Britten (ZA), J. Cook, corresponding member (AU),
A. Galvan Diego (MX), H. Geldenhuys (ZA), L. Grcev (M), A. Haddad (GB), T. Henriksen (NO),
B. Hermoso (ES), J. Hoeffelman (BE), M. Ishii (JP), L. Kocis (CZ), M. Morgado (PT),
J. Mc Daniel (US), J. Michaud (FR); P. Munoz Rojas (BR); C. A. Nucci (IT),
R.G. Olsen (US), M. Paolone (IT), A. Piantini (BR), B. Richter (CH), A. Sekso Telento (CR),
V. Shostak (UA), W.H. Siew (University of Strathclyde, UK); J. Sinclair (GB), H.L. Soibelzon (AR)

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Content

PREFACE

Joint CIRED/CIGRE Working Group 05 "Protection of MV and LV networks against lightning"[1] was established in 1993 with the task to prepare an application guide for Distribution Utilities focusing on practical methods of protection against lightning of MV and LV networks, taking also into account economical aspects and power quality. After an interruption in 1997, the working group resumed its activity in 2002[2].

The application guide is divided into three parts:

- Part 1: basic information common to MV and LV networks already published [2];
- Part 2: application to MV networks object of the present document;
- Part 3: application to LV networks: this last part will be dealt with by a new CIRED/CIGRE Working Group (WG C4.408) established in 2008.

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

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

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

2 damage to equipment or considerable reduction of the residual life of power utilities equipment, with particular reference to:
  - damage to utility power plant;

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[1] Members of the Working Group during the first period 1994-1997: A. Porrino, Convener of the WG (ENEL S.p.A., Italy); I.Alexandri (Public Power Corporation, Greece); M. Clément (EDF, France); G.S. Finlay (The Electricity Association, United Kingdom); T. Henriksen (SINTEF Energy Research , Norway); J. Hoeffelman (Laborelec, Belgium); M. Ishii (University of Tokyo, Japan); P. Martinez Cid (IBERDROLA S.A., Spain); C. A. Nucci (University of Bologna, Italy); František Popolansky (EGU Power Research Institute, Czech Republic); F. Rachidi (Ecole Polytechnique Fédérale de Lausanne, Switzerland); G. P. T. Roelofs (N.V. KEMA, Netherlands); R. Rudolph (ABB Hochspannungtechnik AG, Switzerland).

[2] The members of the WG reestablished in 2002 are: F. Rachidi, Convenor of the WG (Ecole Polytechnique Fédérale de Lausanne, Switzerland), A. Borghetti (University of Bologna, Italy), T. Britten (Eskom, South Africa), J. Cook, corresponding member (Integral Energy, Australia); A. Galvan Diego (Inst. Inv. Electricas, Mexico); H. Geldenhuys (Corresponding member, Eskom, South Africa), L. Grcev (University of Skopje, Macedonia), A. Haddad (Cardiff University, UK), T. Henriksen (SINTEF Energy Research , Norway); B. Hermoso (Public University of Navarra, Spain); J. Hoeffelman (Elia, Belgium), M. Ishii (University of Tokyo, Japan); L. Kocis (EGU, Czech Republic), M. Morgado (EDP, Portugal), J. Mc Daniel (National Grid, USA), J. Michaud (EDF, France); P. Munoz Rojas (Lactec, Brasil); C. A. Nucci (University of Bologna, Italy); R.G. Olsen (Washington State University, USA); M. Paolone (University of Bologna, Italy), A. Piantini (University of Sao Paulo, Brazil), B. Richter (ABB Switzerland Ltd, Switzerland), A. Sekso (Zagreb. Croatia), V. Shostak (Kyiv, National Technical University of Ukraine), W.H. Siew (University of Strathclyde, UK); J. Sinclair (Electricity Ass., UK), H.L. Soibelzon (Fac. Ingenieria Buenos Aires, Argentina).

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

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

Part 2 Lightning protection of MV networks

EXECUTIVE SUMMARY

Overvoltages due to direct and indirect lightning events depend on several factors and are characterized by complex wave shapes. For this reason numerical codes have been developed, aiming at the evaluation of the lightning overvoltages on realistic distribution line configurations. These tools are of fundamental help in the protection scheme design and the insulation coordination of actual distribution systems, as well as in evaluating the overvoltages transferred through distribution transformers to the low voltage part of the system.

Section 2 presents briefly the characteristics of lightning overvoltages due to direct and indirect strikes. Direct lightning overvoltages in MV networks are characterized by a series of very steep spikes (originated from multiple line insulation breakdown), followed by a slower wave. Induced voltages are, in general, characterized by impulses with faster rise time and shorter duration. The peak value and shape of induced overvoltages are strongly influenced by the relative position of the line and the lightning strike, and the earth resistivity. Lightning-induced overvoltages are also very much influenced by the topology of the distribution network. The induced voltages may be substantially affected by the line branches and by the presence of nearby buildings. The buildings may reduce the lightning electromagnetic field along the line and, consequently, the induced voltage magnitudes. On the other hand, tall structures may attract lightning discharges very close to the line and, therefore, large overvoltages may be induced even in the case of stroke currents of moderate intensity.

In Section 3 of this document, the main principles of lightning protection are discussed.
Lightning overvoltages may cause flashovers along the overhead lines and insulation failures in cables, measuring transformers and apparatuses. The insulation breakdown is a permanent failure and it is far more important to prevent such failures than the insulator flashovers along the lines.
An effective reduction of the flashover fault rate of a MV line can only be achieved with special measures, such as converting the overhead line into an underground cable, or installing surge arresters at every pole and every phase (line arresters). Other measures, such as the upgrading of the line insulation or the addition of a shield wire, may reduce the number of faults due to induced overvoltages. However, in order to mitigate the effects of direct strikes, the shield wire should be earthed at every pole, the earth resistances should be low (10 Ω or lower) and the lightning impulse withstand voltage of the line structures should be greater than 300 kV. The cost-effectiveness of these solutions should always be evaluated.
Protective devices are intended to limit transient overvoltages and divert surge currents. They contain at least one nonlinear element. Depending on their principal function they are divided in voltage switching types (typical example being a spark gap), and voltage limiting types (typical example being a Metal Oxide surge arrester (MO surge arrester)). Capacitors reduce the steepness of incoming overvoltages, and they can efficiently reduce overvoltages having a short duration. Old silicon carbide (SiC) surge arresters consist of a spark gap in series with a non-linear resistor element. Modern metal oxide arresters have a more favorable voltage-current characteristic and they do not need spark gaps. New arrester installations use exclusively MO arresters. However, there are still a considerable number of SiC arresters installed in existing networks. The MO arresters are normally installed without spark gaps but the combination of external gaps and MO surge arresters are used in some special cases.
When using a surge protective device, the following basic rules should be applied:

- the apparatus and the protective device shall be connected to the same grounding system and the galvanic connection between the earth side of the surge protective device and of the apparatus should be as short as possible;

- the total length along the connection between the surge arrester connection point and apparatus and between the line and the surge protective device shall be as short as possible.

Section 3.3 describes combined protection measures, namely the combination of shield wires and arresters, surge arresters and spark gaps, and surge arresters and capacitors.

Section 4 deals with the protection of specific equipments used in MV networks, namely, overhead lines, cables and transformers.

The main motivation for protecting overhead lines is to reduce the frequency of occurrence of short interruptions and voltage sags due to flashovers caused by lightning overvoltages. The lightning overvoltages are either caused by direct strikes to the line or induced from strokes in the vicinity. The overvoltages due to direct strikes give in general the most severe overvoltages and it is sufficient to consider these overvoltages when designing the protection of cables, apparatuses and measuring transformers except for overhead lines where induced overvoltages may cause flashover. The number of flashovers due to the induced overvoltages is strongly dependent on the rated lightning impulse withstand voltage (RLIWV) of the line, while most of the direct strokes cause a flashover or a back-flashover when the RLIWV is 300 kV or less.

For overhead lines there are mainly three protective measures that can be utilized to reduce the number of flashovers due to lightning:

i) minimizing the grounding resistance of neutral conductors or shield wires;
ii) installation of surge arresters;
iii) increasing the line insulation level.

Increasing the rated lightning impulse withstand voltage, although not a practical approach for protection against direct lightning, has a beneficial effect on flashovers due to induced overvoltages. The two other measures have normally a minor influence on the flashover rate due to direct strokes but may be of practical interest concerning induced overvoltages.

Concerning the use of surge arresters, it is worth mentioning that the more the basic lightning impulse withstand level exceeds the protection level U_{pl} of the arrester, the better the electrical equipment is protected against lightning overvoltages.

Note that most of the direct strikes to a MV overhead line would cause either flashover or back-flashover. As a result, a reasonable estimate for the number of voltage disturbances can be obtained by assuming that all direct strokes cause voltage disturbances. The number of failures per 100 km of line and per year will decrease with increasing line withstand voltage due to reduced number of failures due to induced overvoltages and the number will approach the number corresponding to the number of direct strikes.

The effect of the shielding wire on the mitigation of lightning-induced voltages on overhead lines depends on the distance between two consecutive grounding points and on the value of the earthing resistance. An overall effective voltage reduction can be achieved only if the spacing between two consecutive grounding points is less than about 200 m. For larger spacings, e.g. 500 m or 1000 m, only the portion of the line in the immediate vicinity of the grounding points appears to experience reduced overvoltages. Simulation results show that the mitigation effect of the shield wire depends, in general, on the spacing between two consecutive groundings rather than on the value of the grounding resistance. It is also shown that the frequently used simplified Rusck formula [1] gives quite accurate results only when the observation point is close to a grounding connection.

The effectiveness of surge arrester sets along the overhead lines in terms of the reduction of the induced voltage magnitudes has been analyzed by means of scale model experiments and numerical simulations. It is shown that the effectiveness of surge arresters depends on different factors. In particular, the lower the grounding resistance and the shorter the spacing distance between two adjacent arrester sets, the better the performance of the arrester sets.

Cables are very commonly used in MV networks and they must be protected against lightning overvoltages. They may constitute a section of an overhead line (e.g. to cross a road or a densely constructed area) or may be used to connect equipment installations to the overhead line. The protective device (arrester or spark gap) is normally connected between conductor and cable sheath and the sheath is connected to ground. In case of pure underground cable networks without aerial connections, usually there is no need for lightning protection.

One or both ends of a cable may be exposed to lightning. If both ends are exposed to lightning, protection installed at one end is sufficient only for very short cables. Longer cables where both ends are exposed to lightning must be protected at both ends. If cables are protected on one end only, one must be aware that there is a certain risk of insulation breakdown due to the stochastic nature of the lightning discharge and it has to be considered that at the unprotected end of the cable, traveling wave

reflections will occur, which may cause overvoltages exceeding the insulation withstand voltage of the cable terminal.
The expected number of insulation breakdown per year can be estimated by a formula presented in Section 4.3.2. It is shown that the protection of a cable at only one end can be applied only in areas with low keraunic level or when the overhead lines are well shielded against direct lightning.

A cable connecting an overhead line to a substation or a cable section between two overhead lines has normally to be protected with arresters at both ends. Protection at one end only may be sufficient for relatively short cables. Section 4.4.1 presents examples of maximum permissible length for cables, protected by one arrester only, for wooden and earthed cross-arm poles.

Finally, Section 5 of the document discusses the benefits of the application of lightning protection for the power quality.

0. INTRODUCTION

The basic information for designers of lightning protection of MV and LV networks has been presented in the part 1 of this guide [2]. This second part presents an application of the basic information to the lightning protection of MV networks containing overhead lines[3].

This part of the guide applies primarily to MV networks with system voltage in the range from 1 kV to 36 kV. It is relevant for higher system voltages as well, but it becomes gradually less relevant when the system voltage increases. It is thus not possible to specify an upper limit for the system voltage, but the guide should not be used for system voltages above 50 kV.

As the prospective overvoltages (i.e. the voltages if no flashover occurs and there are no protective devices, e.g. surge arresters) due to lightning may reach very large values, an economical and safe network design calls for extensive lightning protection. This general statement applies to medium and low voltage networks as well as high voltage networks.

Overvoltage protection can be basically achieved in two ways:

- by reducing the peak value and rate of occurrence of lightning overvoltages at the point of origin (e.g. through shielding the line conductors or improving the footing resistance of towers or poles; or by using surge arresters);
- by limiting the overvoltage at the equipment location (e.g. by surge arresters).

In high voltage networks, both methods of protection are common. In MV networks, shielding the conductors is generally not very effective against direct lightning. Due to the relatively low withstand voltage between the earthed cross arm and the conductors, a direct lightning strike will usually cause a back-flashover. For these reasons, the most effective protection against overvoltages in such networks is the use of surge arresters or spark gaps in the vicinity of the equipment. This document gives guidance for the selection and positioning of such protective devices, and gives some indication on their effect on the power quality.

1. SUMMARY OF TOPICS COVERED IN PART 1 [2]

After an introductory part covering the classification of overvoltages and a general description of the lightning discharge phenomenon, the lightning discharge parameters for engineering applications are reviewed. Statistical data on lightning current parameters (peak value, maximum steepness, front duration, action integral) for both first and subsequent return strokes are summarized, as well as average value for the return stroke speed.
From the point of view of the overvoltage parameters that are important for lightning protection, direct lightning overvoltages and induced overvoltages are quite different. These two events are therefore treated separately. The expected number of direct and indirect lightning events depends on the exposure of the line and on the screening provided by nearby objects such as trees. A specific expression, based on the leader progression model, for the evaluation of the expected number of direct lightning, is presented. This expression allows the evaluation of the expected number of direct strokes per year to a distribution line as function of the following parameters: the ground flash density,

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[3] It is generally accepted that networks without overhead lines are not exposed to lightning overvoltages.

the average height of the line, the horizontal spacing between the outer line conductors and a parameter which takes into account the orography of the line. For a 10-m high line with a horizontal separation between outer conductors of 2 m located in an area with a ground flash density of 1 flash per km^2 per year, the expected number of direct strikes is 11 per year and per 100 km when there are no trees or buildings close to the line.

The evaluation of the expected number of induced overvoltages larger than a given value requires the application of a statistical approach and accurate modeling of the lightning induction mechanism. This document describes an approach based on the Monte Carlo method which consists of generating an adequate number of lightning events, each characterized by random variables such as the peak value of the lightning current, its time to peak and the position of the strike with respect to the distribution line. It is also shown also that the frequently used simplified analytical formulas based on the assumption of infinitely-long lines and perfectly-conducting ground are not adequate. In addition, the number of flashovers due to indirect strikes is strongly affected by the ground conductivity. For a 10-m high single-conductor line characterized by a CFO (critical flashover voltage approximately equivalent to the IEC rated lightning impulse withstand voltage) of 100 kV, the estimated number of flashovers per 100 km per year is about 3 for a perfectly-conducting ground and it increases to a value of about 20 when reducing the ground conductivity to 0.001 S/m.

Overvoltages due to direct and indirect lightning strikes are characterized by complex and very different wave shapes. Overvoltages due to a direct strike have an overall wave shape similar to that of the lightning current, the fast rising portion being superimposed with several spikes, which are due to the insulation flashover. Induced overvoltages are characterized by pulse widths significantly shorter than that of the lightning current, and their wave shape is strongly affected by the ground electrical conductivity. Induced overvoltages can feature a positive, negative, or bipolar wave shape depending on: the ground conductivity, the position of the observation point along the line and the line terminal conditions of the line.

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

- a return-stroke model, which specifies the spatial and temporal distribution of the lightning current along the channel during the return-stroke phase;
- the calculation of the electromagnetic field variation along the line produced by the lightning current distribution, ideally including the effects of field propagation along a finitely-conducting ground;
- the calculation of the induced voltages resulting from the electromagnetic interaction between the field and the line conductors, using a field-to-transmission line coupling model.

As opposed to simple analytical formulas (such as the popular formula by Rusck [1]), which are restricted to unrealistic simple configurations, more elaborate models allow for an accurate treatment of realistic line configurations. Moreover, the presence of distribution transformers, of surge protection devices at the line terminations, as well as the presence of surge arresters and shield wire groundings along the line should be taken into account. The complexity of these models calls for an implementation into computer codes.

Part 1 [2] contains also a review of general characteristics of surge protective devices (SPD) used for the lightning protection of power networks and components. The operating mechanism of SPDs, their classifications and typical V-I characteristics are presented, as well as a summary of the most relevant parameters for different technologies.

The last section of the Part 1 is dedicated to the behavior of earthing systems for lightning frequencies (up to some MHz). Grounding impedance of typical earthing systems is equal to the DC resistance up to a characteristic frequency that depends on the grounding electrodes arrangement and length, and on the ground resistivity. Typically, this characteristic frequency is some tens to hundreds of kHz. Above this frequency, the grounding impedance could be dominantly capacitive (decreasing with increasing frequency), resistive (frequency independent), or inductive (increasing with increasing frequency). Usually, capacitive behavior is typical for electrodes with smaller dimensions in highly resistive soil. In order to minimize the influence of inductive behavior, it is better to use several small electrodes rather than one large electrode. However, this is not always practically possible because to fulfill requirements for lowering the 50/60 Hz resistance to earth it is necessary to use longer electrodes. The significance of the high frequency behavior of the grounding electrodes depends on the frequency content of the lightning current pulse. The inductive behavior for higher frequencies is thus more important for faster varying current pulses (subsequent strokes). It is also shown that the use of multiple grounding rod arrangements improves the impulse efficiency of grounding systems.

Horizontal rods are slightly less effective at power frequencies in comparison to vertical rods, but they have better impulse efficiency.

2. TYPICAL OVERVOLTAGES GENERATED BY DIRECT AND INDIRECT LIGHTNING

As shown in [2], direct lightning overvoltages in MV networks are characterized by a series of very steep spikes (originated from multiple line insulation flashovers), followed by a slower wave. Induced voltages are, in general, characterized by impulses with faster rise time and shorter duration.

A lightning strike hitting a phase conductor within a span of an overhead line generates two equal current waves that propagate away from the strike location in opposite directions. The corresponding prospective voltage is equal to the current multiplied by the characteristic impedance of the line (400 Ω is a typical value). The current associated with each wave is half the injected return stroke lightning current. A lightning return stroke current with peak amplitude of 20 kA, thus, causes a prospective voltage of about 4 MV. This voltage level is well above the withstand voltage, and flashovers will occur. A flashover involving several phases may cause a short-circuit that activates a circuit breaker. The insulation is normally quickly restored after the interruption of the fault current and an auto re-closure is then successful on the overhead line. The described event is typical for a direct strike. The lightning overvoltages occurring at cable terminations or power plant terminals are, however, far more important than the overvoltages along the line since they may cause permanent damage. Exposed cable terminations and apparatus are normally protected by surge arresters that limit the peak value of the voltage wave propagating towards the cables and the equipment. The peak value of the incoming voltage wave from the overhead line is then less important although it has some influence due the non-ideal arrester characteristic and the voltage drop of the leads connecting the arrester to the circuit. The initial portion and steepness S of the incoming lightning overvoltage wave is very important since it plays a critical role in determining the tolerable separation distance between the protective device and the apparatus, assuring that the overvoltage peaks do not exceed the insulation level of the apparatus.

The incoming lightning overvoltage at the end of a line is strongly influenced by the flashovers occurring along the line. The steepness is further affected (reduced) due to corona and frequency dependent losses. The steepness of the incoming voltage wave is in practice a stochastic parameter that can be expressed as a function of the frequency of occurrence. Reference [3] gives as an example S = 1550 kV/µs for lines with wooden poles and 800 kV/µs for lines with grounded cross-arms. These values correspond to a frequency of occurrence of one every 400 years when the line is hit by 8 strikes per 100 km and year. The main reason for the difference in the steepness is that the lightning impulse withstand voltage to ground is much higher for lines with wooden poles compared to lines with grounded cross-arms.

As mentioned earlier, a direct strike to a phase conductor will, generally, result in a flashover. A direct strike to a shield wire of a line protected with such wires will generally result in a back-flashover, except for very low grounding resistance and/or a high insulation level. Surge arresters at one pole prevent efficiently flashover at that pole but flashover may still occur in the span or at the next pole. Line arresters are, however, in general helpful in limiting the magnitudes of direct and induced overvoltages.

In MV lines the steepness S ranges typically from 100 to 2000 kV/µs for direct lightning and from 30 to 300 kV/µs for induced overvoltages. The high values for the steepness makes the separation distance between the equipment to be protected and the protective device very critical.

The slower portion of the overvoltage wave due to direct lightning has an energy content much larger than that associated with the preceding steep spikes. This can be of importance for the protection of cables as will be shown in Section 4.3.

Overvoltages due to direct and indirect lightning events depend on several factors, as described in Part 1. For this reason numerical codes have been developed for the evaluation of the lightning overvoltages on realistic distribution line configurations and they have been verified by means of experimental data (e.g. [2, 4]). These codes are fundamental tools in the protection scheme design and the insulation coordination of actual distribution systems, as well as in evaluating the overvoltages transferred through distribution transformers to the low voltage part of the system.

The peak value and shape of induced overvoltages are strongly influenced by the relative position of the line and the lightning strike, and the earth conductivity [5]. For an illustrative purpose, Fig. 1 shows the lightning-induced overvoltage at both ends of a 1-km long, 10-m high single-wire overhead line (the conductor diameter is 1 cm) matched at the line terminations, for various strike positions and for three values for the ground conductivity. The adopted lightning current parameters are I_p=12 kA and $(dI/dt)max$=40 kA/µs (50% peak current value and maximum front time-derivative), which correspond to a typical subsequent return stroke current according to Berger et al. [6].

The results shown in Fig. 1 illustrate the fact that the amplitude and wave shape of the induced voltages are strongly dependent on the distance and relative position of the lightning strike point and the line, and on the earth resistivity.

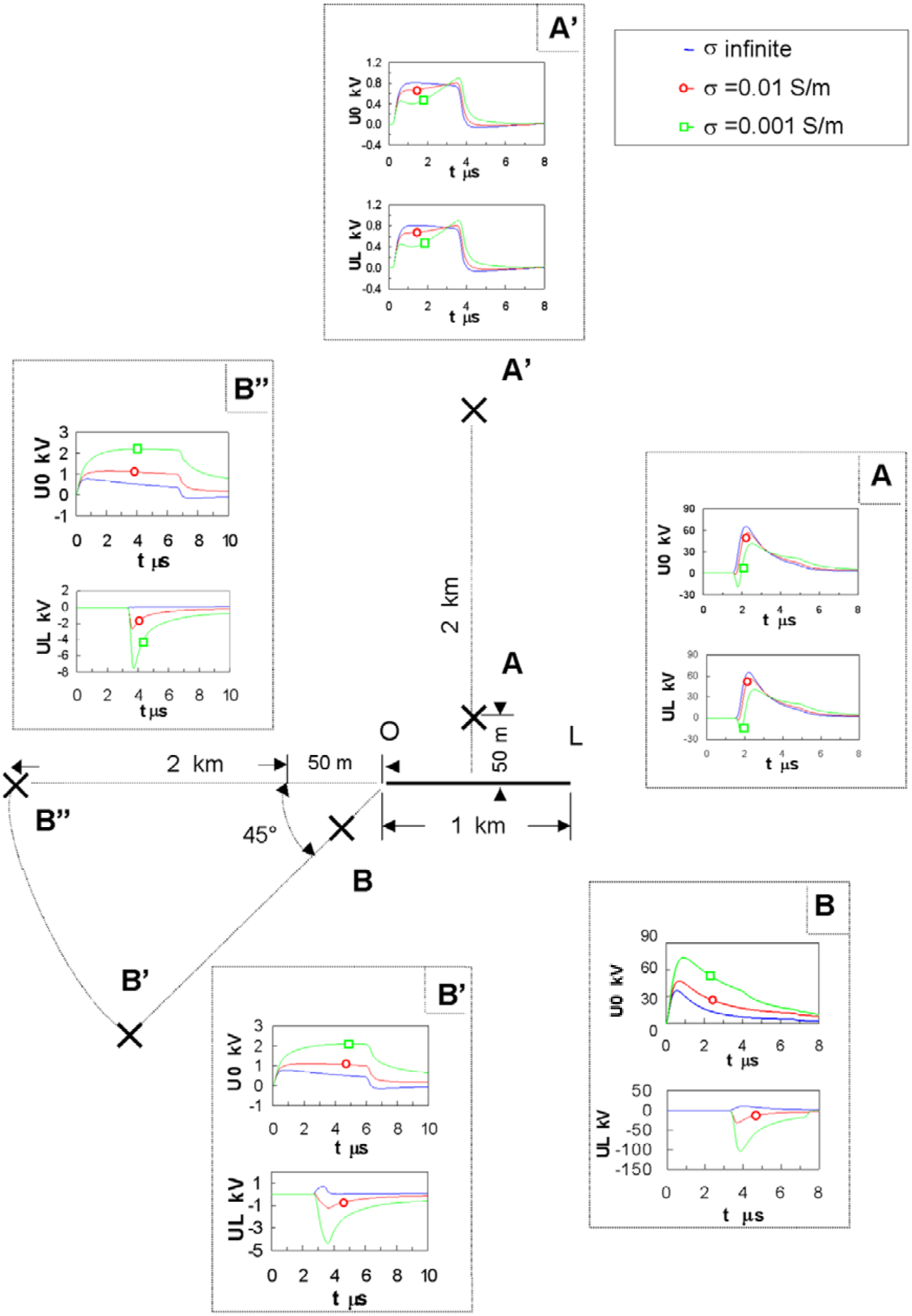

Fig. 1 - *Effects of the earth resistivity and location of the lightning return stroke with respect to the line on the amplitude and wave shape of lightning-induced voltages (from the conductor to the ground) (adapted from* [7]*). Blue: perfect ground, red: earth resistivity 100 Ωm, green: earth resistivity 1000 Ωm.* U_o *and* U_L *denote induced voltages on the left and right terminations of the line.*

The topology of the distribution network has a very strong influence on the lightning-induced overvoltages, and this has been demonstrated by experimental investigations conducted by means of a reduced scale model [8]. The induced voltages may be substantially affected by the line branches and by the presence of nearby buildings. The buildings may reduce the lightning electromagnetic field along the line and, consequently, the induced voltage magnitude. On the other hand, tall structures may attract lightning discharges very close to the line and, therefore, large overvoltages may be induced even in the case of stroke currents of moderate intensity.

Models that reduce the actual network to one single line do not, in general, give realistic results. The application of such methods should therefore be limited to investigations of the general behavior of lightning-induced overvoltages. The situation is rather different concerning overvoltages due to direct strokes where the above simplification often gives results of significant practical interest.

3 MAIN PRINCIPLES OF LIGHTNING PROTECTION

The lightning overvoltages may cause flashovers along the overhead lines and insulation failures in cables, measuring transformers and apparatuses. The insulation breakdown is a permanent failure and it is far more important to prevent such failures than the insulator flashovers along the lines.

An effective reduction of the flashover fault rate of an MV line can only be achieved with special measures, such as converting the overhead line into an underground cable or installing surge arresters at every pole between every phase and the cross arm (line arresters).

Other measures, such as the upgrading of the line insulation or the addition of a shield wire, may reduce the number of faults due to induced overvoltages. However, an efficient mitigation of the effects of direct strike requires: the shield wire to be earthed at every pole, the earth resistances to be low (10 Ω or lower) and the CFO of the line structures to be greater than 300 kV. The cost-effectiveness of these solutions should always be evaluated.

3.1 Shield wires

Shield (or shielding) wires are grounded conductors placed near the phase conductors. Shield wires located above the phase conductors are used to improve the lightning performance of transmission lines. They collect most of the direct strikes that otherwise would hit the phase conductors and they divert the lightning current to the ground through the poles' ground leads. A strike hitting a shield wire causes, by mutual coupling, overvoltages along the phase conductors. These overvoltages cause minor disturbances in the power supply except when flashovers occur. The efficiency of the shield wires depends therefore strongly on the relative number of strokes that do not cause back-flashover. For MV lines with shield wires, most of the strokes would result in back-flashovers. Therefore, shield wires do not reduce the number of flashovers related to direct strikes for MV lines.

Shield wires, located either above or below phase conductors, reduce the induced fields along the conductors caused by lightning strikes in the vicinity. An example mentioned in [2] shows a reduction of the peak values of the induced voltages due to the presence of shield wires in the range of 25% - 35%. Shield wires may therefore be a powerful measure to improve the lightning performance of the lines concerning lightning-induced overvoltages. Shield wires are further used to limit the ground potential rise during a fault involving the ground in networks with high grounding resistance.

3.2 Overvoltage protective devices

Protective devices are intended to limit transient overvoltages and divert surge currents. They contain at least one nonlinear element. Depending on their principal function they are divided in voltage switching types (typical example being a spark gap), and voltage limiting types (typical example being a Metal Oxide surge arrester (MO surge arrester)).

Capacitors reduce the steepness of incoming overvoltages, and they can efficiently reduce short duration overvoltages.

Old silicon carbide (SiC) surge arresters consist of a spark gap in series with a non-linear resistor element. Modern MO surge arresters have a more favorable voltage-current characteristic and they do not need spark gaps. New arrester installations use exclusively MO surge arresters. However, there are still a considerable number of SiC arresters installed in existing networks.

The MO surge arresters are normally installed without spark gaps but the combination of gaps and MO surge arresters (EGLA's) are used in some countries, such as for instance Japan, France and in Scandinavia.

3.2.1 General considerations on using overvoltage limiting devices

Fig.2 shows a typical installation of a MO arrester to protect a transformer. The arrester limits the voltage at its terminals to the residual voltage U_{res} of the arrester. Voltage reflections along connections *a*, between the arrester connection point and the equipment to be protected, and connections *b* in series with the protective device between the connection point and ground, result in a representative voltage U_{rp} at the apparatus higher than U_{res} (Fig. 2). The voltage difference $\Delta U = U_{rp} - U_{res}$ increases with the lengths *a* and *b,* and with the steepness *S* of the initial part of the incoming overvoltage. As *S* (overvoltage steepness) can reach very high values in MV lines, the overvoltage at the apparatus ($U_{rp} = U_{res} + \Delta U$) can also reach large values. In order to reduce the representative voltage U_{rp} at the apparatus, *a* and *b* should be selected as short as possible. The following formula [33] can be used as a reasonable approximation for U_{rp} when all involved conductors are overhead lines with the same characteristic impedance:

$$U_{rp} = U_{res} + \frac{2 \times S \times (a+b)}{v} \quad \text{if } 2S(a+b)/v < U_{res} \qquad (1)$$

$$U_{rp} = 2U_{res} \quad \text{if } 2S(a+b)/v > U_{res} \qquad (2)$$

where v is the speed of light (300 m/μs).

The background for the formula is explained in Appendix I.

As guidance, values of *b* lower than 1 m and 5 m are respectively recommended for the case of wooden pole lines and earthed cross-arm lines.

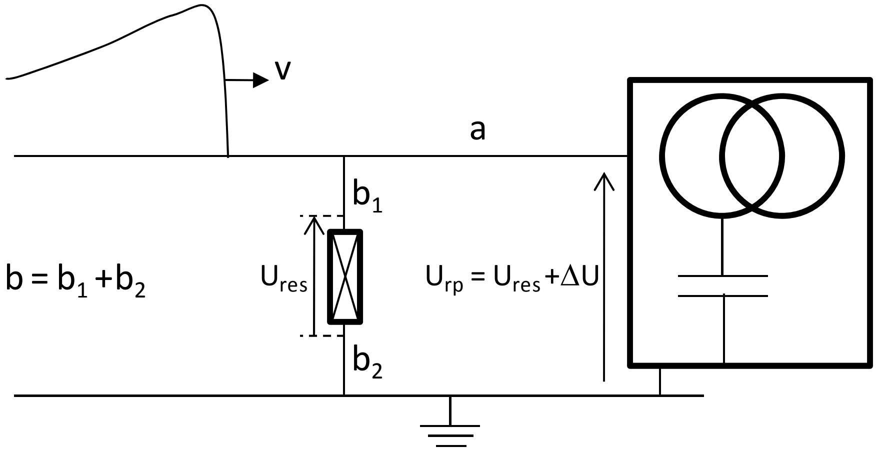

Fig. 2 - *Sketch of the protection scheme of a MV transformer directly connected to an overhead line. The protective device limits the voltage at its terminals to the protective level U_{res} [9].*

Taking a deterministic coordination factor K_{cd} of 1, experience has shown that a safety factor K_s of 1.2 is sufficient between the rated standard lightning impulse withstand voltage (LIWV, in ANSI/IEEE defined as basic lightning impulse insulation level BIL) of the electric apparatus and the representative voltage U_{rp} at the apparatus.

$$\frac{LIWV}{1.2} \geq U_{rp} = U_{res} + \frac{2 \times S \times (a+b)}{v} \tag{3}$$

If the limiting value is set at *L* = *a*+*b*, then the maximum distance can be calculated from

$$L = \frac{v}{2 \times S}\left(\frac{LIWW}{1.2} - U_{res}\right) \tag{4}$$

- All the above considerations are based on the assumption that the apparatus and the protective device are connected to the same grounding system. If they were connected to separate grounding systems, the protection will in most cases become useless due to the ground potential rise at the protective device.

For the correct installation of overvoltage protective devices two basic rules can be concluded from the example above:

1. the apparatus and the protective device shall be connected to the same grounding system and the galvanic connection between the earth side of the protective device and of the apparatus should be as short as possible;

2. the total length along the connection, *a*, between the arrester connection point and apparatus and, *b*, in series with the protective device between the connection point and ground shall be as short as possible.

3.2.2 Spark Gaps

A spark gap is an intentional gap or gaps between spaced electrodes. Two different designs are used: (i) the so called arcing horn, where the insulating gap between the electrodes is in open air, and (ii) plate spark gaps, where the spark gap elements are placed in an insulating gas tight housing, providing a controlled atmosphere between the electrodes. Thus, the spark over voltage is not influenced by external factors such as humidity, pressure and pollution.

The protection against overvoltages is obtained by an intentional disruptive discharge between the electrodes, leading to a collapse of the voltage and a current flow.

The spark over voltage depends mainly on the electrodes separation and shape, the gas between the electrodes, and the steepness of the occurring overvoltage. The time to spark over of a spark gap is the time interval between virtual origin of the overvoltage and the instant of spark over. The typical shape of spark gap characteristic is given by the impulse spark over voltage/time (U-t) curve shown in Fig. 3.

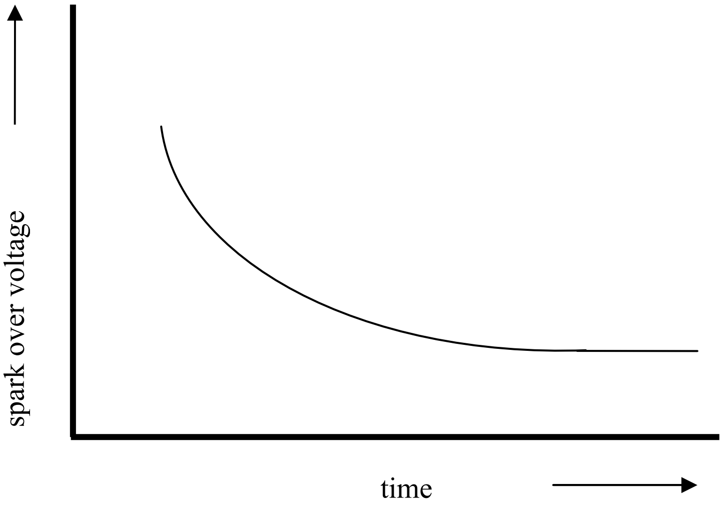

Fig. 3 -*Typical spark over voltage vs time characteristic of a spark gap.*

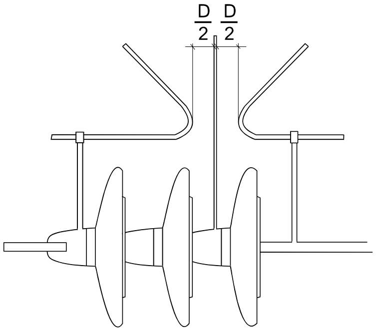

Fig. 4 - *Typical shape of an arcing horn for protection of MV apparatus, mounted on a rigid string of three cap-and-pin insulator units.*

Fig. 4 shows a typical application of an arcing horn. The shape of the electrodes is designed to elongate and cool the arc, in order to facilitate its extinction. A third electrode at floating potential is sometimes installed in the middle between the two main electrodes. The main purpose of this electrode is to prevent birds from causing a short-circuit of the gap when there is no overvoltage.

The voltage of the apparatus to be protected is more or less influenced by the connections *a* and *b* in Fig.2 in the same way as for the overvoltage limiting device and formulae (1) and (2) are valid for the spark gap as well with U_{res} replaced by the spark over voltage. The formulae are, however, less useful due to the variation in the spark over voltage as shown in Fig. 3.

3.2.3 Surge arresters

Two principally different designs of arresters are used in medium voltage networks. The so-called "conventional" surge arresters were mainly used in medium voltage networks up to the middle of the 1980s. They consist of a series connection of SiC resistors and plate spark gaps. In case of an overvoltage, the spark gap flashes over and the following current from the system is limited by the SiC resistors, and extinguished in the first natural current zero-crossing. The disadvantages of this technology are the unfavorable V-t characteristic of the spark gaps and the limited energy capability of SiC resistors. This type of arresters, almost not manufactured anymore, is still installed in MV systems in a large number.

In the 1980s there were two fundamental improvements of surge arrester technology. On the one hand, the series connection of spark gaps and SiC resistors were replaced by metal oxide (MO) resistors without gaps, and, on the other hand, the porcelain housings were replaced by polymer housings.

A fundamental advantage of MO arresters is the fact that, because of the extreme nonlinear voltage-current characteristic of the MO material (Fig. 5), the leakage current is extremely low, so that they do not need any spark gap.

The protective level (B) of the MO surge arrester is set by its residual voltage U_{res}. The residual voltage is defined as the peak value of the voltage at the terminals of the arrester when a specified surge current flows through the arrester.
The most important parameters for the selection of a metal oxide arrester are the maximum continuous operating voltage U_{c}, the lightning impulse protection level U_{pl} and the required energy capability (e.g. line discharge class).The energy handling capability of a MO surge arrester depends on the cross section of the MO resistor and the thermal capacity of the design. The required energy capability to prove the thermal stability of an MO arrester in the system is calculated according to IEC 60099-4.
U_{c} is expressed as r.m.s. value and is proportional to the rated voltage U_{r} of the arrester. The ratio between U_{r} and U_{c} is not a fixed value, but a ratio of $U_{\mathrm{r}}/U_{\mathrm{c}} = 1.25$ is a typical value
An important parameter for the selection of arresters is the ratio of $U_{\mathrm{res}}/U_{\mathrm{c}}$. The smaller the ratio is, the better is the protection.

In three-phase networks, special attention has to be paid to the occurring temporary overvoltages at power frequency in case of an earth fault. The withstand strength of MO surge arresters to temporary overvoltage is defined by its r.m.s. value U_{T} and its time duration t (see Fig. 6). Magnitude and time duration of the temporary overvoltage depends strongly on the method of the neutral system earthing.

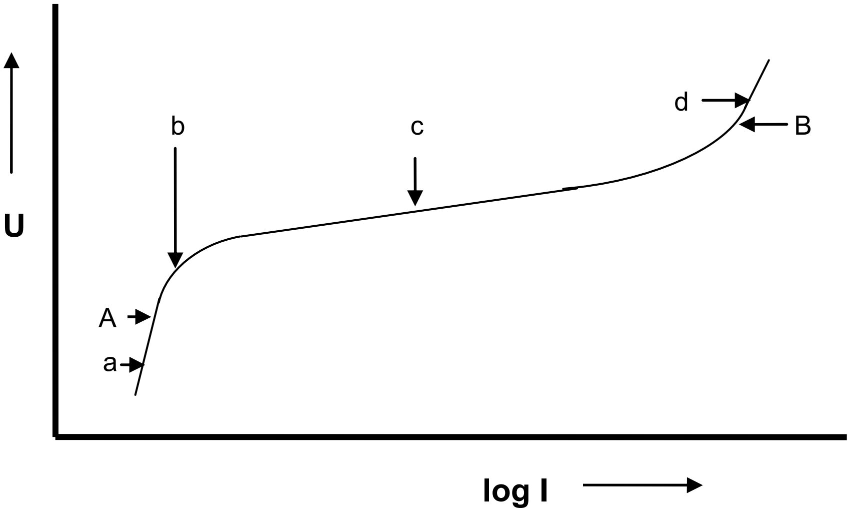

Fig. 5 – *Voltage-current characteristic of a MO surge arrester*:
a - lower part, b - knee point, c - strongly non-linear part, d - upper part ("turn up" area), A - operating point (continuous operating voltage), B - protective level.

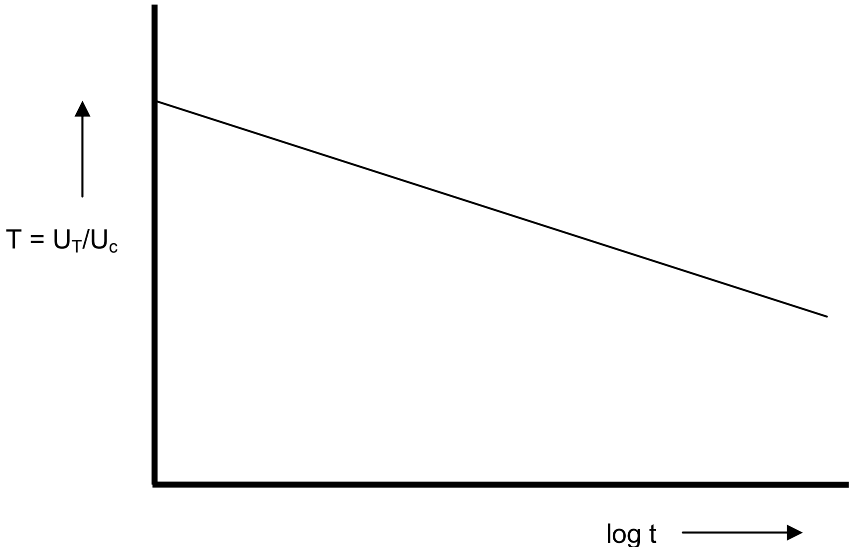

Fig. 6 - *Withstand strength $T = U_T / U_C$ of an MO surge arrester as a function of the time t.*

MO arresters are normally installed without spark gaps but the combination of gaps and MO arresters is widely used, as earlier mentioned, in Japan and other countries, on overhead lines.

3.2.4 Capacitors

Capacitors reduce the steepness of incoming overvoltages, and they can efficiently reduce short duration overvoltages. They are used to limit high frequency overvoltages. Note that the capacitance of any connected apparatus will have a similar positive effect on reducing the magnitude and steepness of incoming voltages.

Fig. 3 shows that the spark over voltage increases with increasing steepness of a transient overvoltage. A capacitor is occasionally connected in parallel to the spark gap or arcing horn, in order to reduce the steepness of transient overvoltages and thereby reducing the maximum voltage across the protective device.

Special surge capacitors are designed to modify the steep front waves and to prevent damage to insulation of transformers and rotating machines. It is advisable to use MO surge arresters together with the surge capacitor to form a comprehensive protective package, see also 3.3.3. A capacitance to earth has, in general, a positive effect in reducing, at the same time, the peak value and the steepness of the incoming overvoltage, as shown in Fig. 7.

However, it has to be noted that capacitors together with inductances may cause resonances producing overvoltages.

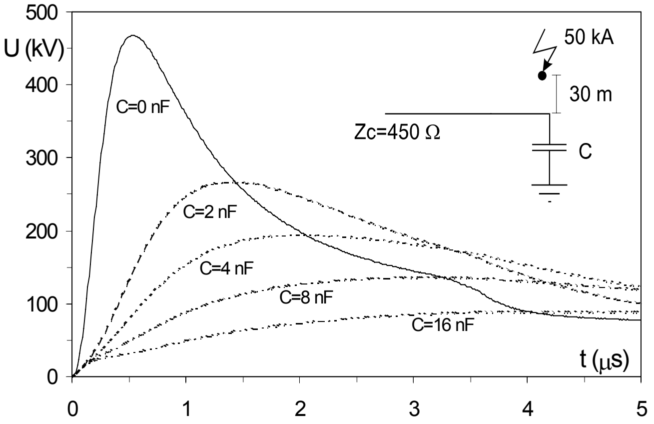

Fig. 7 - *Overvoltage induced by a lightning stroke to the ground close to the termination of an overhead line, as a function of the value C of a lumped capacitance connected to the line termination [10].*

3.3 Combined protection measures

Overvoltage protection can basically be achieved in two ways:
- reducing lightning overvoltages at the point of origin, for instance through shield wires that intercept lightning.
- limiting overvoltages near the electrical equipment, for instance through surge arresters in the vicinity of the electrical equipment.

In high voltage networks both methods of protection are usual. The shield wire protection in medium voltage networks is used only in special cases and critical areas (e.g. line protection).

Combinations of shield wires and arresters are used in some cases, especially in regions with high earthing resistance or areas with high lightning density (e.g. line arresters).

3.3.1 Combination of surge arresters

An arrester is generally considered as a stand-alone device. It protects the electrical equipment, no matter if other arresters of different types are present in the network. Therefore, different types of arresters can be used in the network or even on the same line. However, one has to be aware that in case of parallel connection due to the different functions (gap or no gap) and different (V-I) characteristics, some arresters may be ineffective, and some may be overstressed due to a very uneven distribution of the total current between the parallel arresters

3.3.1.1 Combination of MO surge arresters

MO surge arresters can be combined in parallel for two reasons: to increase the energy handling capability or to realize a somewhat reduced residual voltage.

If the energy handling capability needs to be increased, two or more MO surge arresters can be connected in parallel. The arresters have to be installed very close together to avoid any separation effect, and the voltage-current characteristics need to be very similar. Due to the extreme nonlinear characteristic of the MO resistors, a difference of only some per cent in the residual voltage U_{res} leads to a very high difference in the current. To avoid an overload of one of the MO surge arresters in parallel, current sharing measurements with all MO surge arresters intended for the parallel connection have to be made. In any case, using one MO surge arrester with a larger diameter of the MO resistor is preferable to parallel connections.

In cases where it is necessary to install two MO surge arresters separated one from another (e.g. one arrester at the entrance of a substation, the second one inside just in front of the transformer) two arresters with the different energy ratings and different U_{res} values may be used. When choosing different U_{res} values, the U_{res} of the MO surge arrester outside the substation should be a few percent lower than that of the MO surge arrester inside the substation. In this case, most of the energy of a surge is diverted to earth outside the substation, where a possible overload will have only minor secondary damages. A typical example for such a coordination of the voltage-current characteristics is the use of a MO surge arrester with lower U_{res} and higher energy handling capability outside on the pole and an arrester with less energy handling capability but higher U_{res} inside the building.

3.3.1.2 Combination of MO surge arresters and SiC arresters

There is no reason to install MO surge arresters and SiC arresters in parallel. It is on the other hand no need for removing existing SiC when MO surge arresters are added due to any reason (enlargement of the station etc.). The two types of arresters will work independently except when the arresters are close to each others. If a MO surge arrester and a SiC arrester are close together on the same line the MO surge arrester will normally limit the incoming overvoltage to a value below the firing voltage of the gaps in the SiC arrester. In this case, the SiC arrester is not effective at all.

3.3.2 Combination of surge arresters and spark gaps

Surge arresters and spark gaps can be combined in series. Series connections are used, besides the series connection of plate spark gaps and MO resistors (MOR) inside a common housing (internally gapped arresters according to IEC 60099-6), especially in case of line protection. The externally gapped line arrester (EGLA) is a series connection of a gap and a series varistor unit, normally both installed in parallel to an insulator (Fig. 8). The series varistor unit can be chosen with a low voltage and energy rating, as for instance for a lower system voltage. The gap has to be adjusted to spark over under lightning overvoltage conditions only. Switching overvoltages should not activate the gap.

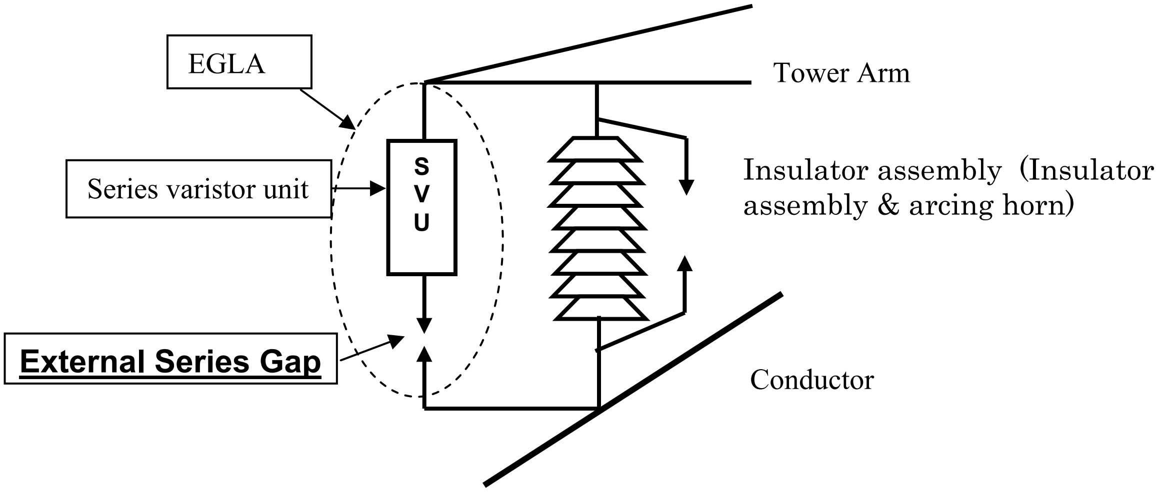

Fig. 8 - *Typical example of EGLA configuration.*

A similar current limiting arcing horn was also developed in [11].

3.3.3 Combination of surge capacitors and MO surge arresters

As earlier mentioned, parallel connections of surge capacitors and MO surge arresters are in specific cases used to protect rotating machines (generators and motors) and in some rare cases transformers. The surge capacitor reduces the rate of rise of the incoming surge, and the MO surge arrester limits the overvoltage. For this application it is advised to use MO surge arresters with a high energy handling capability.

4. PROTECTION OF COMPONENTS USED IN MV NETWORKS

4.1 Introduction

The insulation of the equipment cannot be designed, for economical reasons, to withstand lightning overvoltages that may occur. A more reliable and safe power network, therefore, calls for extensive protection against unacceptable overvoltage stresses. This general statement applies to high voltage as well as medium and low voltage networks.

Concerning the use of MO surge arresters for the protection of MV equipment in general, it is worth mentioning that the more the rated standard lightning impulse withstand voltage LIWV of the equipment exceeds the protection level U_{pl} of the arrester, the better the electrical equipment is protected against fast front overvoltages. Table 1 presents the withstand voltage (LIWV) according to IEC [12] and protection level of surge arresters with U_{pl}=4 p.u. Note that the p.u. reference for U_{pl} is $\sqrt{2}U_m / \sqrt{3}$ (where U_m is the maximum r.m.s. voltage for equipment between phases).

Table 1 - *Withstand voltage (LIWV) according to IEC* [12] *and protection level of surge arresters with U_{pl} =4 p.u.*

U_m	kV	3.6	7.2	12	17.5	24	36
LIWV	kV	40	60	75	95	125	170
U_{pl}	kV	11,8	23,5	39,2	57,2	78,4	118
LIWV/U_{pl}		3.89	2.55	1.91	1.66	1.59	1.44

4.2 Overhead lines

4.2.1. Introductory remarks

The main motivation for protecting overhead lines is to reduce the frequency of occurrence of short interruptions and voltage sags due to flashovers caused by lightning overvoltages. The lightning overvoltages are either caused by direct strikes to the line or induced from strokes in the vicinity. The overvoltages due to direct strikes give in general the most severe overvoltages and it is sufficient to consider these overvoltages when designing the protection of cables, apparatuses and measuring transformers. The situation is somewhat different for overhead lines, where induced overvoltages may cause flashover. Fig. 5 in [2] shows an example where the induced overvoltages causes 10 flashovers per 100 km and year when the CFO is 150 kV. The corresponding number of strikes to the line is 11, according to the Section 6.1.1 in [2] . The number of flashovers due to the induced overvoltages is strongly dependent on the CFO, while most of the direct strokes cause a flashover or a back-flashover when the CFO is 300 kV or less.

There are mainly three protective measures that can be utilized to reduce the number of flashovers due to lightning :

i) minimizing the grounding resistance of neutral conductors or shield wires;
ii) installation of surge arresters;
iii) increasing the line rated lightning impulse withstand voltage.

Increasing the insulation level, although not a practical approach for protection against direct lightning, does have a beneficial effect on flashovers due to induced overvoltages. The two other measures have normally a minor influence on the flashover rate due to direct strokes but may be of practical interest concerning induced overvoltages.

Most of the direct strikes to a MV overhead line would cause either flashover or back-flashover. As a result, a reasonable estimate for the number of voltage disturbances can be obtained by assuming that all direct strokes would cause voltage disturbances. The total number of failures per 100 km and per year will therefore decrease (due to the contribution from induced overvoltages) as function of the line withstand voltage and will approach the total number of direct strikes (given by the equation (6) of [2]).
In the next section, an analysis of the effect of shield wires and surge arresters on the mitigation of lightning-induced overvoltages will be presented.

Finally, it is worth noting that covered conductors are often employed for the phase conductors of lower voltage MV lines to improve public safety. One drawback of a covered conductor is that it tends to suffer from meltdown of a conductor when a ground fault occurs. This happens because the arc root is fixed at the punch-through hole on the insulating cover, leading to meltdown of the conductor on the occasion of prolonged arcing. This frequently happens at lightning faults, and arcing horns at insulators are used to prevent it.

4.2.2 Impact of shield wire groundings on the mitigation of lightning-induced voltages

In [13], the mitigation effect of a grounded neutral or shield wire is expressed by a factor η that is the ratio between the lightning induced voltage *U'* on the line conductor in presence of a shield wire and the value of the induced voltage *U* on the conductor without the shield wire. The factor depends on the grounding resistance and proximity of the grounded conductor to the phase conductors, and is expressed by [1]:

$$\eta = \frac{U'}{U} = 1 - \frac{h_{sw}}{h} \cdot \frac{Z_{sw-c}}{Z_{sw} + 2R_g} \qquad (4)$$

where h_{sw} is the height of the shield wire, *h* is the height of the line conductor, Z_{sw} is the surge impedance of the shield wire, $Z_{sw\text{-}c}$ is the mutual surge impedance between the shield wire and the line conductor and R_g is the DC grounding resistance. Equation (4) was obtained assuming that the shield wire is grounded at a single point, and it applies only to points of the line conductor located in the immediate vicinity of the grounding connection [1]. The network was further limited to one infinitely-long line only.
Other authors have proposed to estimate the mitigation effect by assuming the shield wire at zero potential [14-17]. Such an assumption appears reasonable only when the shield wire is grounded at short intervals along the line. Furthermore, such an approach does not allow determining the distance between two adjacent groundings that would result in the required shielding effect.
The adoption of generalized transmission line coupling models, where the grounded conductor is within each span considered as one of the phase conductors, provides more accurate results concerning the appraisal of the mitigation of lightning-induced overvoltages on overhead lines due to grounding of shield wires. A first example of such an approach is given in [18] using the coupling model proposed by Rusck [1].
In [19], a modification of the transmission line coupling model presented by Agrawal et al. [20] has been proposed and experimentally validated in order to include the presence of line transverse discontinuities such as the grounding points.
The effect of the shield wire, of the distance between two consecutive grounding points and the effect of the value of the earthing resistance on the mitigation of lightning-induced voltages has been analyzed for the simple line configuration of Fig. 9, with a single phase conductor and a grounded shield wire. The chosen strike location is as shown in the figure not directly in front of any of the grounding points. The computed peak values of the induced voltages along the line are shown in Fig. 10 for the case of a perfectly-conducting ground using the method proposed in [19] and the Rusck formula (4).

Fig. 10 shows that an overall effective voltage reduction can be achieved only if the spacing between two consecutive grounding points is less than about 200 m[4]. This value depends on the rise time of the induced voltages originated by the lightning electromagnetic field illuminating the line. For larger spacing, e,g, 500 m or 1000 m, only the portion of the line in the immediate vicinity of the grounding points appears to experience reduced overvoltages.

A closer examination of Fig. 10 shows that Equation (4) gives quite accurate results only when the observation point is close to a grounding connection (see also [19]).

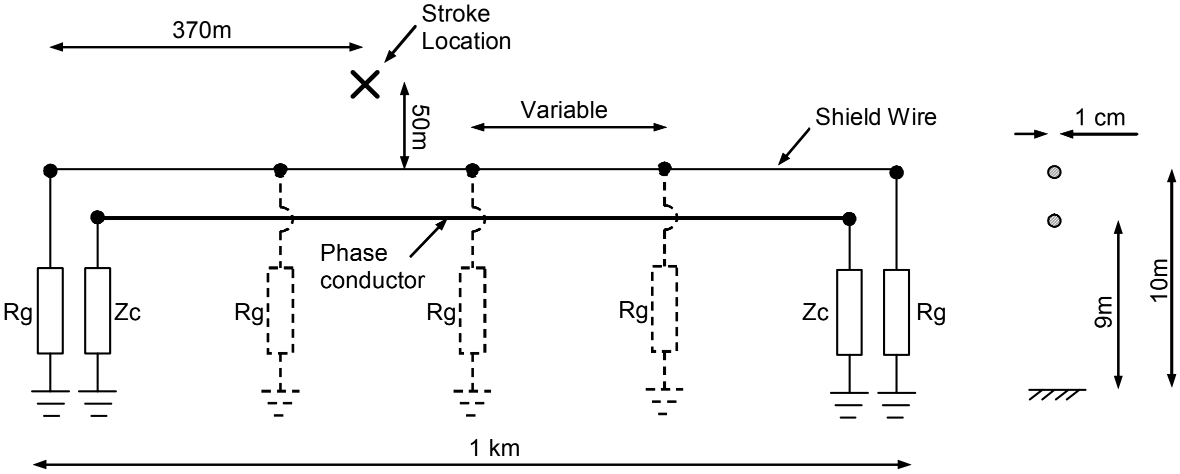

Fig. 9 – *Simple line configuration with shield wire. Lightning data: current amplitude equal to 30 kA, maximum time derivative equal to 100 kA/μs, stroke location located at 50 m from the line and 370 m from left line termination. Adapted from [19].*

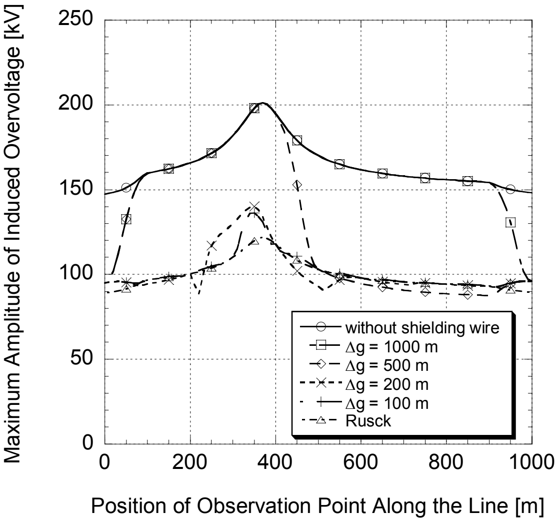

Fig. 10 – *Maximum amplitude of the induced voltage along the line of Fig. 9, as function of the spacing (Δg) between two adjacent groundings. Perfectly conducting ground. Adapted from [19].*

Figs. 11a and 11b present similar results as those presented in Fig. 10, obtained for a finite ground conductivity equal to 0.001 S/m (1000 Ωm resistivity), and applying for the earthing resistance values

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[4] This statement applies only to the considered configuration. In general, the minimum separation distance between two grounding depends on the relative position of the lightning strike and the electromagnetic field rise time.

of 10 Ω. (Fig. 11a) and 300 Ω (Fig. 11b). The results presented in Figs. 11a and 11b show that the mitigation effect of the shield wire depends on the spacing between two consecutive groundings rather than on the value of the grounding resistance[5]. It is only when the strike position is located in front of a grounding point that the attenuation of the induced voltage on the phase conductors is very dependent on the value of the grounding resistance [18].

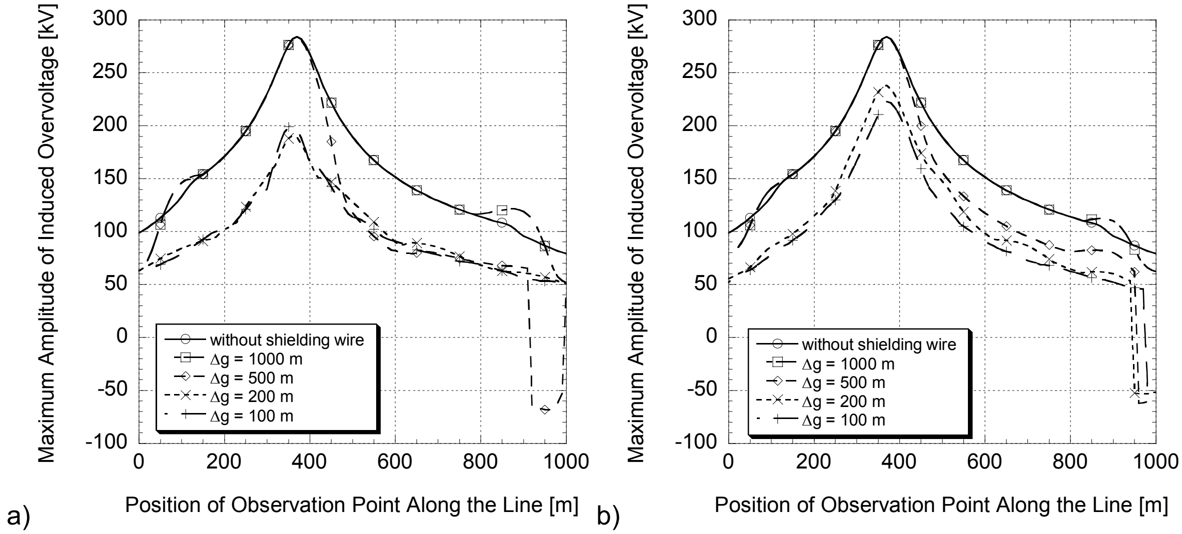

Fig. 11 – *Maximum amplitude of the induced voltage along the line of Fig. 9 as function of the spacing (Δg) between two adjacent groundings of the shield wire. Lossy ground (σ_g = 0.001 S/m). Fig. 11a: grounding resistance equal to 10 Ω. Fig. 11b: grounding resistance equal to 300 Ω. Adapted from [19].*

4.2.3 Impact of MO surge arresters on the mitigation of lightning-induced voltages

In [21] the influence of some line and lightning parameters on the effectiveness of surge arresters in terms of the reduction of the induced voltage magnitude is analyzed by means of scale model experiments. The scale model was used to simulate a typical 15 kV distribution line (horizontal configuration, height above ground of 10 m, and separation between phase conductors of 0.75 m). The MO surge arrester protective level was about 34 kV (for an impulse current of 5 kA, 8/20 μs waveform). For the validation of the arrester model, comparisons were performed with test results corresponding to actual SiC and ZnO distribution arresters, all with rated voltage and current of 12 kV and 5 kA, respectively. Details about the modelling of the various system components are presented in [22].

All the following results refer to the full-scale system. The experiments consisted of simultaneous measurements of the voltages induced on two distribution lines due to the propagation of a current pulse of magnitude I_o along the lightning path. The lines, one without MO surge arresters and the other with arresters added on all the three phases, were located at the same distance (d = 70 m) from the lightning strike point. The voltages were measured, on each line, at the point closest to the stroke location. The front time (t_f) of the currents injected into the stroke channel was about 3.2 μs.

4.2.3.1 Stroke Current Magnitude

Fig. 12a illustrates the influence of the return-stroke current peak on the ratio of the peak values of the voltages induced on the lines with and without MO surge arresters ($U_{\text{with}}/U_{\text{without}}$) for the case of an arrester spacing of 300 m and lightning strike point in front of a set of arresters, and considering different values of grounding resistance R_g. The results shown in Fig. 12b refer to the case of a lightning strike point equidistant from two sets of arresters.

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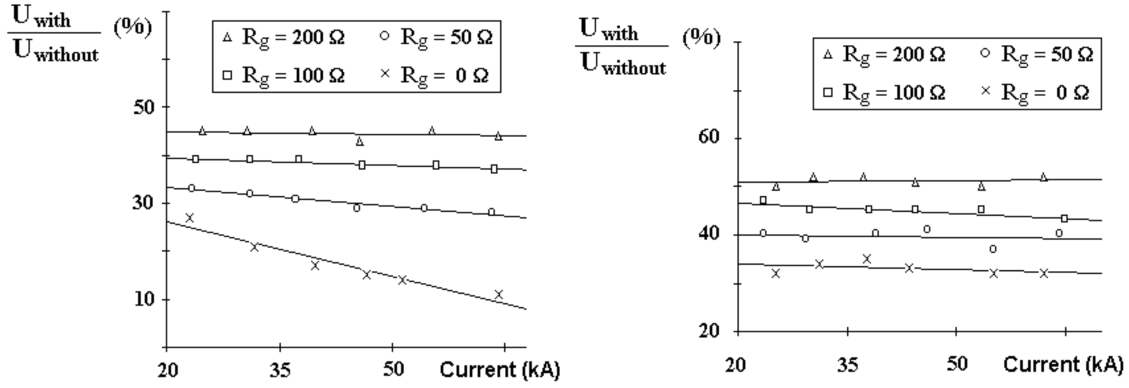
[5] This differs from the case of direct stroke for which the effectiveness of the shield wire depends strongly on the grounding resistance.

When the lightning strike point is located in front of a set of MO surge arresters, the ratio $U_{with}/U_{without}$ tends to decrease with increasing return-stroke current peak. This behaviour is more evident for low values of grounding resistance where the voltage on the protected line (at the point closest to the stroke location) varies very little with the return stroke current peak (it is very close to the voltage at the surge arrester terminals), while the voltage on the line without arresters is directly proportional to this current. Fig. 12a shows that the influence of the return-stroke current peak is not significant for grounding resistances greater than 50 Ω, i.e., the ratio between the peak values of the voltages induced on the lines with and without MO surge arresters does practically not depend on the current peak as long as the current rise time is kept constant.

In the case of strokes equidistant from two sets of arresters and currents with a fixed front time, the degree of reduction of the induced voltage (ratio $U_{with}/U_{without}$) does not in general depend significantly upon the return-stroke current peak, as shown in Fig. 12b. On the other hand, for currents with the same steepness (dI/dt), the front time t_f increases with the current peak I_p, which results in a larger reduction of the induced voltage amplitude (with respect to that of the unprotected line) as I_p increases.



(a) (b)

Fig. 12 - *Ratio of the voltages induced on lines with and without MO surge arresters ($U_{with}/U_{without}$) as function of the stroke current amplitude. tf = 3.2 μs; d = 70 m, arrester spacing = 300 m. (a) lightning strike point in front of a set of arresters, (b) lightning strike point equidistant from two sets of arresters. Adapted from [21].*

4.2.3.2 Grounding resistance

As shown in Fig. 12, the grounding resistance has a significant influence on the reduction of the induced voltage amplitude, especially when the lightning strike point is in front a set of arresters. This is due to the fact that, for lower grounding resistances, the current that flows to the earth (through the surge arresters) increases, thus increasing the value of the voltage component that, by coupling, reduces the voltages induced on the phase conductors. For illustration purposes, Fig. 13 compares the voltage induced on a line without arresters with those corresponding to the case of arrester spacing of 600 m, lightning strike point in front of a set of arresters and different values of the grounding resistance.

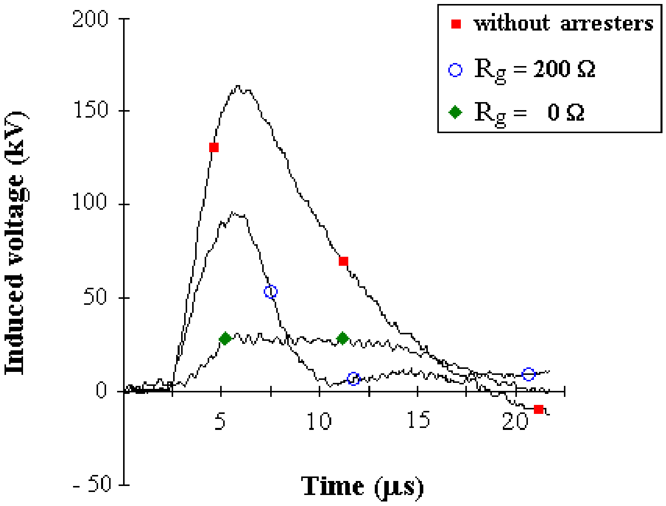


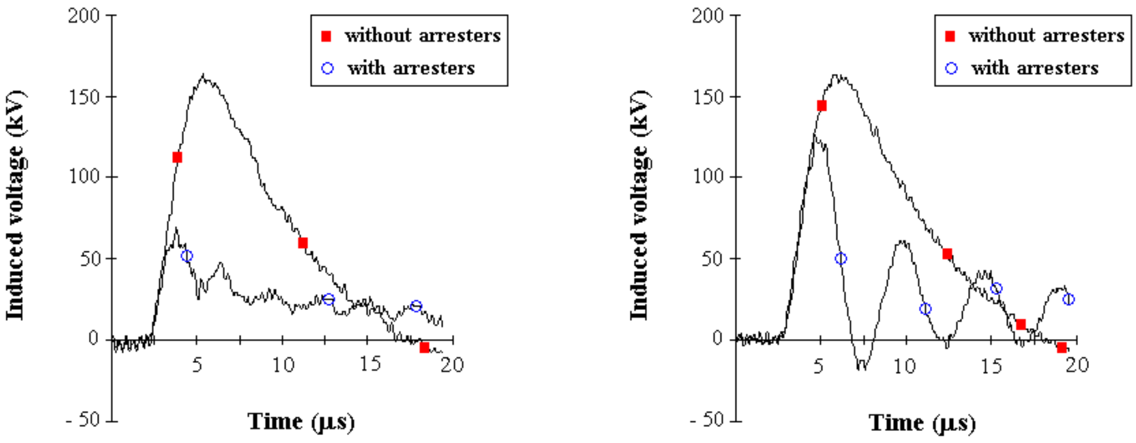
Fig. 13 - *Voltages induced on lines with and without surge arresters. Lightning strike point in front of a set of arresters. I_p = 38 kA; t_f = 3.2 μs; d = 70 m, arrester spacing = 600 m. Adapted from [21].*

C. Arrester Spacing and Relative Position between Lightning Strike Point and Surge Arresters

The influence of the distance between adjacent surge arrester sets on the induced voltages is significant, particularly if the lightning strike point is nearly equidistant from two sets of surge arresters. Fig. 14 compares the induced voltage on a line without surge arresters with those corresponding to arrester spacing of 300 m and 600 m. The greater the arrester spacing, the larger the induced voltage magnitude.

The induced voltages are in general not much affected by the relative position between the lightning strike point and the surge arresters in case of arrester spacing distances shorter than about 300 m. For larger spacing distances, the differences between the voltage magnitudes corresponding to the cases of a stroke location in front of a set of arresters and equidistant from two sets of arresters tend to increase, especially if the grounding resistance is low. For short arrester spacing distances, i.e., when the time for propagation of the reflected waves between two adjacent arresters is much smaller than the induced voltage rise time, this behaviour can be explained considering that the components responsible for the voltage reduction vary little with the position of the stroke channel in relation to the nearest set of arresters.

On the other hand, for large spacing distances, the induced voltage levels are more sensitive to the distances between the stroke location and the arresters. The same occurs with the components (henceforth called suppressive components) that, by coupling, cause a reduction in the voltages induced on the phase conductors. The closer the surge arrester is from the lightning strike point, the greatest will its contribution be to reduce the voltage, so that the most favourable situation corresponds to stroke locations nearly in front of a set of arresters. Besides, in this case the contributions of these arresters occur almost instantaneously, whereas if the stroke location is equidistant from two sets of arresters the effects of their contributions are delayed due to the time needed for the propagation of the suppressive components from the arresters to mid-span. The latter situation is illustrated in Figs. 14a and 14b, where the delay of the effect of the arresters can be clearly noticed.



(a) **(b)**

Fig. 14 - *Voltages induced on lines with and without surge arresters (s.a.) for arrester spacing of 300 m and 600 m. Lightning strike point equidistant from two sets of arresters.* I_p *= 38 kA;* t_f *= 3.2 μs; d = 70 m;* R_g *= 50 Ω. (a) arrester spacing equal to 300 m, (b) arrester spacing equal to 600 m. Adapted from [21].*

The presence of MO surge arresters may also be studied by numerical simulation. The surge arresters along the line represent a transverse discontinuity that can be treated in a similar way as done for the groundings of the shield wire [19]. Fig. 15 shows the line configuration used for analyzing the effect of surge arresters. The chosen configuration is a single-conductor line with surge arresters placed at regular (equidistant) intervals along the line. Moreover, in order to provide a sensitivity analysis relevant to the effects of the number of surge arresters placed along the line on the induced voltages, the following cases are considered: 2 surge arresters at the line terminal only; 3 surge arresters located every 500 m; 5 surge arresters located every 200 m and 11 surge arresters located every 100 m.

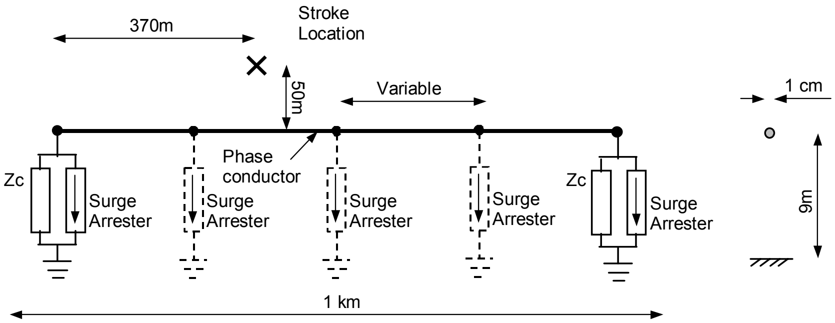
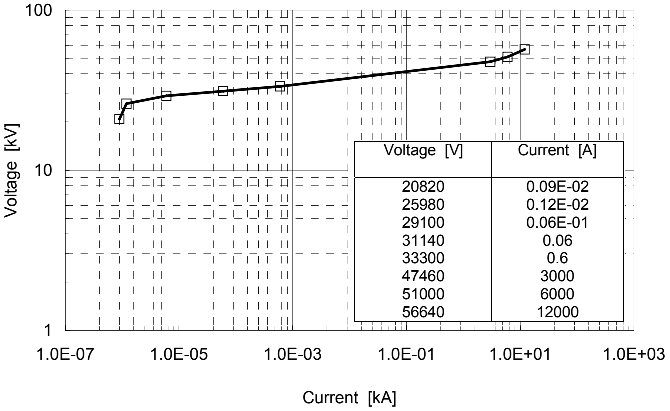


Fig. 15 – *Simple line configuration with surge arresters with VI characteristic of Fig. 16. The lightning data are as in Fig. 9. Adopted from [19].*

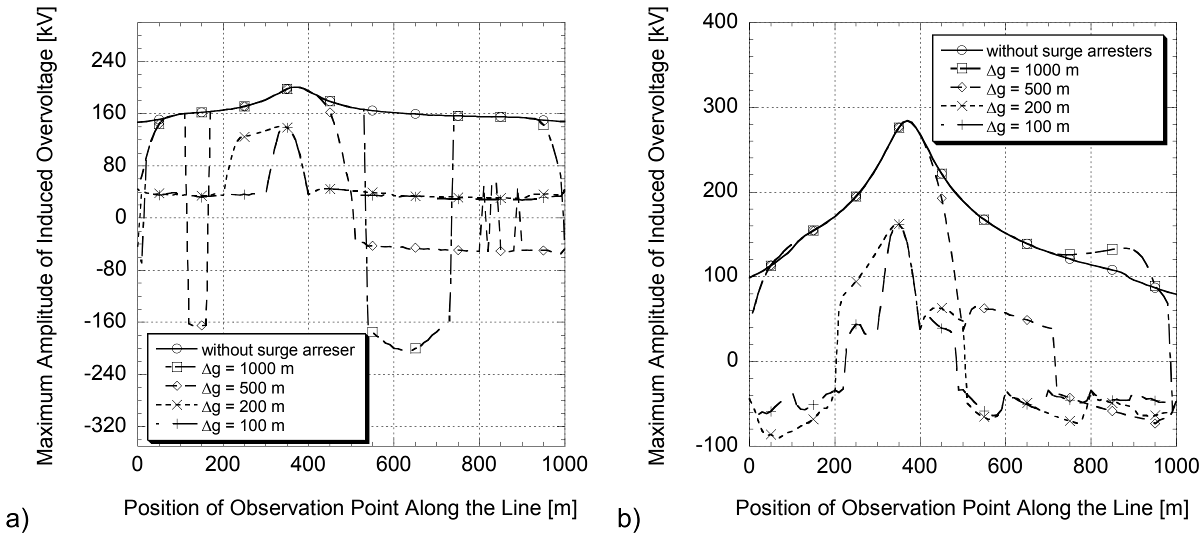
The surge arresters are modeled using a V-I non-linear characteristics [23], which, for lightning-induced transients, is typically obtained by using the standard 1.2/50 μs pulse test. An example of V-I characteristic is shown in Fig. 16. The selected arrester is suitable for 15 kV system voltage and the surge arrester protective level is 55 kV.



Voltage [V]	Current [A]
20820	0.09E-02
25980	0.12E-02
29100	0.06E-01
31140	0.06
33300	0.6
47460	3000
51000	6000
56640	12000

Fig. 16 – *Surge arrester non-linear V-I characteristic considered in the simulations.*

The peak value of the induced overvoltages along the line, calculated by using the procedure proposed in [19], are shown in Fig. 17 for a perfectly-conducting ground (Fig. 17a) and for a lossy ground (Fig. 17b). The value of the earthing resistance in the simulations was 0 Ω.



a) b)

Fig. 17 – Peak value of the induced voltage along the line of Fig. 15, as function of the spacing (Δg) between two adjacent surge arresters. *(*a) Perfectly conducting ground. (b) Lossy ground (σ_g = 0.001 S/m). Adapted from [19].

Similar to the experimental results obtained using a scale model, the results of Fig. 17 show that a significant reduction of the induced overvoltages can be achieved only with a large number of surge arresters. With a large number of surge arresters, the maximum amplitude of the induced overvoltage tends to be confined within the range defined by the threshold voltage of the surge arrester. On the other hand, a low number of surge arresters (e.g. located every at both ends only) may result in important negative peaks of the induced voltage along the line, which are due to surge reflections occurring at the location of the surge arresters that are in operation.

4.3 Cables

Cables are very commonly used in MV networks and they must be protected against lightning overvoltages. They may constitute a section of an overhead line (e.g. to cross a road or a densely constructed area) or may be used to connect equipments to the overhead line. The protective device (arrester or spark gap) is normally connected between conductor and cable sheath and the sheath is connected to ground. Usually there is no need for lightning protection of power cable networks completely without overhead lines.

4.3.1 Protection of cables at both terminals

A cable is normally well protected against lightning overvoltages if surge arresters protect both ends of the cable. It should, however, be noted that the maximum overvoltage along the cable may exceed the maximum voltage at the two ends of the cable.

The expected maximum lightning overvoltages along a cable inserted in an overhead network and protected by surge arresters at both ends have been analyzed by CIGRE WG B1-05 [23] for system voltage 145 kV and higher. Some of the results from [23] are relevant for lower voltage levels as well. As was mentioned, the arresters limit the overvoltages at the ends of the cable but the maximum voltage along the cable may significantly exceed (e.g. by 30 % [24] – see also the earlier publications [31] and [32]) the maximum overvoltage at the ends of the cable. It is, therefore, in some cases, important to minimize the residual voltage of the arrester and to minimize the leads connecting the arrester to the cable and ground. The arrester protects also closely connected equipment (if any), provided that the cable shield and the equipment are connected to the same grounding system.

4.3.2 Protection of cables at one terminal only

One or both ends of a cable may be exposed to lightning. If both ends are exposed to lightning, protection installed at one end is sufficient for very short cables only. Longer cables where both ends are exposed to lightning must be protected at both ends. If cables are protected on one end only, one must be aware that there is a certain risk of insulation breakdown due to the stochastic nature of the lightning discharge and it has to be considered that at the unprotected end of the cable, traveling wave reflections will occur, which may increase overvoltages to levels exceeding the withstand voltage of the cable or its termination.

A rough estimation of the average number of insulation breakdown expected in one year is given by the following expression [9]

$$N_{ib} = 2 \times \frac{U_l - U_p}{U_{ca} - U_{pl}} \times \beta \times L_c \times N_d \times 10^{-5} \qquad (5)$$

where:

N_{ib}	is the expected number of cable insulation flashovers in one year;
U_l	is the rated lightning impulse withstand voltage of the line;
U_{ca}	is the rated lightning impulse withstand voltage of the cable;
U_{pl}	is the protective level of the overvoltage protective device;
β	is the transmission coefficient of the line-to-cable connection ($\beta = 2\, Z_c/(Z_l + Z_c)$, where Z_l and Z_c are the surge impedances of the line and of the cable respectively; β ranges from 0.1 to 0.2 in practical cases);
L_c	is the length of the cable in meters;
N_d	is the expected number of direct lightning strokes to the connected overhead line per 100 km per year (evaluated according to indications given in section 6.1.1 of the Part 1 [2]).

EXAMPLE

U_l =350 kV U_{ca} = 125 kV U_{pl} = 70 kV β = 0.15 L_c = 100 m

Case A: The line is 10 m high, and crosses an irregular ground, in an area characterized by 4 flashes per square kilometer per year, then N_d = 40 (number of direct strokes in one year per 100 km of line) and N_{ib} = 0.06. This means that for every 100 installations of this type, protected at only one terminal of the cable, one should expect on average 6 breakdowns every year, which could be considered as unacceptable.

Case B: N_d = 4 (that is for a line in an area characterized by a low ground flash density or effectively screened against direct lightning by a forest). Then, N_{ib} = 0.006. In this, second case one should expect on average 6 breakdowns a year for every 1000 installations that could be deemed acceptable.

The example given above shows that the protection of a cable at only one terminal can be adopted only in areas with low keraunic level or when the overhead lines are well shielded against direct lightning.

Formula (5) is valid only if the loop connecting the protective device between conductor and cable shield is very short (< 2 m in total). For larger loops the formula gives an underestimation of N_{ib}.

4.3.3 Non protected cables

In some countries characterized by very low keraunic levels, this possibility (non protected cables) can be considered as acceptable.
It is to be noted that this practice implies a non-zero risk of insulation flashover. In fact direct lightning strokes to the MV line in the vicinity of the cable can easily cause overvoltages higher than the insulation level of the cable. The risk of such an event shall, thus, be carefully evaluated by considering the following essential elements:

- ground flash density;
- rated lightning impulse withstand voltage of the line and rated lightning impulse withstand voltage of the cable;
- cable length;
- shielding of the line by surroundings.

4.3.4 Cable sheath protection

Due to thermal reasons, and to reduce the losses in the cable sheath, the sheath of single line cables in distribution systems is often earthed at one side only. The sheath in the unearthed side of the cable must then be protected with a MO surge arrester. The voltage induced along the cable sheath during a short circuit is decisive for the dimensioning of the surge arrester. The induced voltage depends on the short circuit current itself, the cable length and the inductive coupling factor between the cable conductor and the cable sheath. It is recommended to use for the cable sheath protection MO surge arresters with line discharge class 2 according to IEC 60099-4. Cables for higher voltage systems than 36 kV may require higher ratings for the MO surge arresters for cable sheath protection.

4.4 Protection of transformers

Besides the application of the two general rules illustrated above (§3.2.1), attention shall be paid to the protection of transformers connected via a cable, and the protection of the insulation of the low voltage winding and terminals.

4.4.1 Protection of transformers connected via a cable

A cable connecting an overhead line to a substation or a cable section between two overhead lines has normally to be protected with arresters at both ends. Protection at one end only may be sufficient for relatively short cables. Although the main overvoltage stress in distribution systems is originated by lightning, yet switching overvoltages should not be neglected.

Figure 18 shows typical arrangements of a substation, which is fed by the overhead line via a cable. An arrester has to be placed at the junction between the overhead line and the cable (case a), or directly at the connection of the cable to the transformer (case b). If the cable is longer than the values indicated in Table 2, a second arrester is necessary at the other end of the cable. The calculated figures in Table 2 apply for a specific MO surge arresters with I_n = 10 kA and line discharge class 2. Further, the steepness of the incoming voltage was set to S = 1550 kV/μs for wooden poles and S = 800 kV/μs for earthed cross arms. Please note that the results in Table 2 and 3 are obtained by time domain simulations since the formulae in §3.2.1 are not valid for the actual cases.

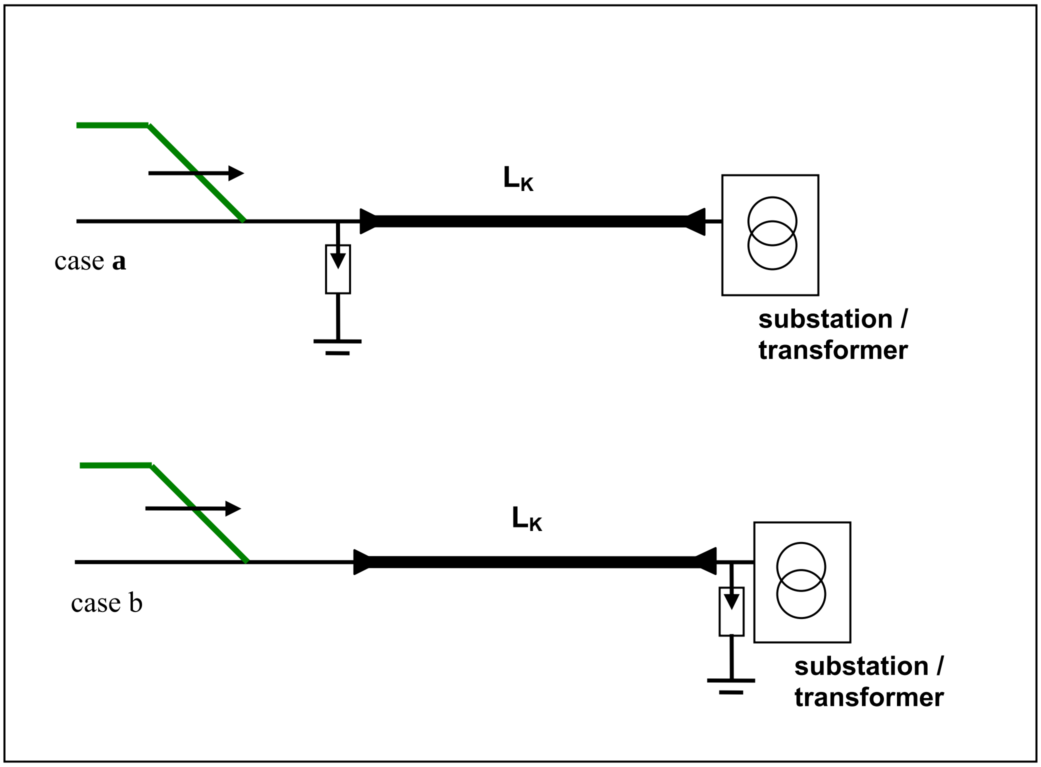


Fig. 18 – *Substation connected via a cable to the overhead line. Cable and transformer protected by one MO surge arrester only. Case a: MO surge arrester at the junction between overhead line and cable; case b: MO surge arrester installed directly at the transformer.*

Table 2 - *Maximum length L_K for cables, protected by one arrester only. Z is the surge impedance of the cable* [3].

	Case a: MO surge arrester at the junction of overhead line and cable				Case b: MO surge arrester directly at transformer terminals			
	Wooden pole		Earthed cross arm		Wooden pole		Earthed cross arm	
	Z = 30 Ω	Z = 60 Ω	Z = 30 Ω	Z = 60 Ω	Z = 30 Ω	Z = 60 Ω	Z = 30 Ω	Z = 60 Ω
U_m in kV	L_K in m		L_K in m		L_K in m		L_K in m	
3.6	∞	∞	∞	∞	8	4	19	13
7.2	85	75	110	100	11	5	27	17
12	45	33	50	39	8	4	22	16
17.5	35	27	36	30	6	3	19	15
24	34	27	36	30	9	4	21	17
36	30	24	30	26	7	4	19	17

It has to be noted that the case *a* arrangement is the more common one and gives better overall protection for the cable and the transformer.

If the length of the cable exceeds the values given in Table 2 for an arrangement according the case *a*, a second MO-arrester is needed at the other end of the cable. The question is, now, under which circumstances the second arrester protects both the cable and the transformer sufficiently. Figure 19 and Table 3 show the arrangement and the resulting acceptable distance *a* between cable and transformer. The cable is connected directly to the arrester A2 in Fig.19 and bare conductors are used to connect the transformer to the cable/arrester.

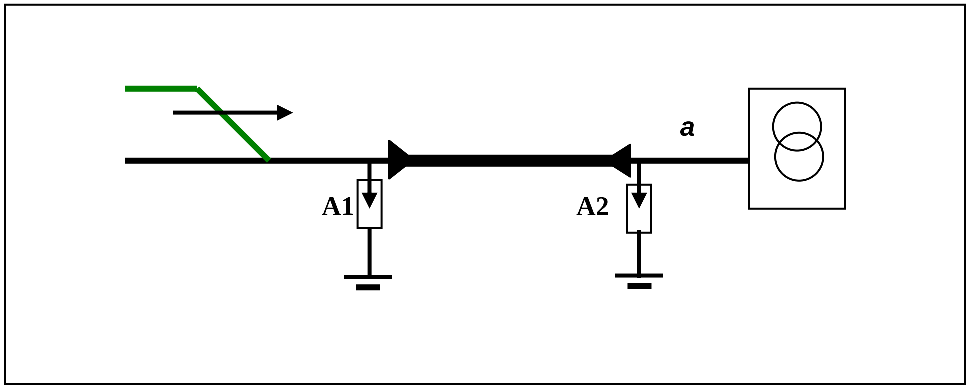


Fig. 19 - *Cable and transformer protected by two arresters..* **a** *is the distance between cable end and transformer.*

Table 3 - *Maximum permissible distance* **a** *between cable and transformer when the second arrester A2 is installed at the cable end* [3].

	Wooden pole	Wooden pole	Earthed cross arm	Earthed cross arm
	Z = 30 Ω	Z = 60 Ω	Z = 30 Ω	Z = 60 Ω
U_m in kV	*a* in m	*a* in m	*a* in m	*a* in m
3.6	100	100	500	500
7.2	45	40	60	55
12	17	12	22	15
17.5	15	9	20	13
24	13	9	18	11
36	7	6	18	11

The cable lengths in Tables 2 and 3 have been obtained for a selected MO surge arrester with I_n = 10 kA and line discharge class 2 according IEC. The LIWV of the equipment and the U_{pl} of the arrester are according the values given in Table 1. Other arresters with deviating characteristics and other values for the LIWV may result in other lengths. The values in Tables 2 and 3 should therefore be considered as **indicative examples** only.

4.4.2 Protection of the low-voltage side of distribution transformers

This problem will be treated in part 3 dealing with lightning protection of low voltage networks. Just as a rough indication, it may be said that capacitive and resistive couplings of overvoltages through the transformer and the station earth may lead to failures on the low voltage side.

If on the low voltage side, overhead lines are used, protection with additional low voltage arresters may be necessary.

4.4.3 Protection of transformers by integrated surge arresters

Surge arresters directly attached to high-voltage windings immersed in oil in a pole transformer are quite effective in preventing lightning faults due to the closeness of their positions to the vulnerable part of the transformer [25-26]. Careful consideration on the deterioration of the ZnO element immersed in oil is necessary in designing the equipment. Oil is beneficial as surface insulation and cooling of the ZnO elements. Note that there are high requirements on the quality of the oil used. Especially the possibility of ageing and deterioration of the oil after some years has to be considered.

4.5 Other equipment

Gapless arresters incorporated in a cutout switch for the primary side of a pole transformer is effective in protecting the switch from lightning overvoltages [26]. This switch is also useful in reducing lightning fault of pole transformers as the switch is installed close to a transformer.
Equipment installed in buildings and integrated in structures do not need additional special measures for the protection against overvoltages. However, rotating machines, transformers and parallel line traps may need additional overvoltage protection at the terminals. The reason is that due to traveling wave phenomena, the incoming overvoltages are reflected (by the inductive impedance of the apparatus) and this leads to an increased overvoltage at the terminals.

5. BENEFITS OF THE APPLICATION OF LIGHTNING PROTECTION FOR POWER QUALITY

5.1 Voltage disturbances due to lightning

Lightning strikes to or near distribution lines are responsible for a considerable number of line faults. The corresponding outages are either transient or permanent.
During transient outages, the fault is cleared by interrupting the supply and reclosing within some tenths of seconds to a few seconds. Generally, the line reclosure is successful if the delay time between tripping and reclosing is sufficiently long compared to the total duration of multiple stroke flashes (the large majority of flashes show a total duration of less than 1 s).
Transient faults are now difficult to accept by consumers, as the loads such as electronic equipment become very sensitive to short duration voltage disturbances.
In general, a permanent fault makes the automatic reclosing unsuccessful, and the interruption may last for several hours. These fault conditions are not acceptable by the majority of the consumers, what requires an adequate management of the network neutral grounding.
Generally, the consequences of outages depend on the sensitivity of the loads to interruptions of supply and voltage dips.
Flashovers and outages due to lightning can be minimized by a proper design of the distribution lines including their lightning protection.
A method to estimate the outage rate of a line due to lightning and to compare it with a specified interruption rate is described in the following paragraphs.
Furthermore, some measures intending to improve lightning performance of a distribution line are reported.

5.2 Considerations for the protection design of distribution lines

The lightning protection design of distribution lines requires the determination of the following parameters:

- the number of line flashovers due to direct strikes;
- the number of flashovers due to nearby lightning strikes;
- the desired line flashover performance.

5.3 Aspects to consider when comparing estimated or actual and desired line lightning performance

When determining the desired total outage rate, several parameters must be taken into account. The most important of these parameters are the sensitivity of loads to interruption of supply, and the cost caused by interruptions to the customers and to the electric utility.
Furthermore, a distinction should be made between non-permanent and permanent interruptions. This means that the two types of interruption should be taken into account by different weighting factors. The ratio between non-permanent and permanent faults due to lightning should be evaluated from collected data deriving from the electric utility field experience. Then, a cost-benefit analysis should be performed in order to compare the benefit resulting from the improvement of the line's lightning performance to the cost of modifying the line in order to reduce lightning outage rate. The cost-benefit analysis should also include the possibility of making sensitive apparatus of the users immune to the short interruptions or voltage dips.

5.4 Design aspects intended to improve lightning performance of distribution lines

An effective reduction of the lightning fault rate of a MV line can only be achieved with very expensive measures, such as converting the overhead line into an underground cable or installing surge arresters at every pole and every phase.

Other measures, such as upgrading the line insulation or adding a shielding wire, can in practice reduce only the number of faults due to induced overvoltages, but they have no noticeable influence on the number of faults due to direct strikes. The cost effectiveness of these solutions should always be evaluated.

The following specific notes about these solutions should be taken into account.

- Over-insulation of a line

A line with wooden poles without earthing of the cross-arms has an impulse withstand voltage in the range of 1-2 MV. No faults due to induced overvoltages will occur for such lines. However, in case of direct strikes, the probability of flashover between phases and to earth will not be significantly reduced. Sometimes, in areas with high lightning activity, it may be beneficial to increase the lightning impulse insulation level of the lines to reduce the line faults due to induced overvoltages [2].The incoming lightning overvoltages occurring at the end of a line due to a stroke at some distance from the end are more or less limited to the flashover voltage to ground. Increasing the withstand voltage of the line gives thus increased stresses on the installation connected to the end of the line. More attention should then be paid to the protection of all equipments by surge arresters or by other specific measures. Additional arresters may be needed.

- Addition of shielding wires

Shielding is used successfully for transmission lines, but it is not effective enough when applied to distribution lines. It cannot prevent faults due to direct lightning, but can reduce the number of faults due to induced overvoltages. For points located in the immediate vicinity of a grounding connection, the induced overvoltage is reduced by a factor given approximately by Equation (4).

- Application of surge arresters on every pole (line arresters) [27]

Line surge arresters can be effective against direct strikes if they are installed on every pole and on every phase. The surge arrester should have an adequate energy adsorption capability. The arresters could also be installed at every two poles, but the impulse insulation level at the non-protected poles and the grounding resistance at the protected poles should be coordinated in order to avoid flashover at the non-protected poles due to the ground potential rise at the protected pole (The ground potential rise increases the voltage to ground on the phase conductors since the arresters limit the potential between the phase conductors and the cross-arm).
A solution of equivalent nature is to install arresters only on the upper phase of a vertical configuration, but it has also to be coordinated with pole grounding resistances and the impulse insulation level of other phases in order not to increase the back-flashover rate of non-protected phases.

- Combined measures

When low pole grounding resistance (less than 10 Ohms) is difficult to achieve, the line design could include both arresters and shield wire. In this case, the surge arresters protect the line from back-flashovers, while the overhead shield wire protects the surge arresters from excess energy discharge [27-28].

5.5 Aspects for automatic reclosure protection

As already mentioned, if a lightning overvoltage does not cause a permanent failure, the fault can be cleared by the automatic reclosing circuit breakers or line reclosures and the supply can be restored after a short time.

The selection of delay time between tripping and reclosing should take into account the duration of multiple stroke flashes and the lightning return stroke amplitude.

For example, lines with high-speed automatic reclosing circuit breakers may suffer unsuccessful reclosure for a non-permanent fault if reclosing is attempted within the duration of multiple stroke flashes.

It is worth mentioning that the typical number of strokes per flash is 3 to 5 and the interstroke time interval is in the order of 60 ms [29].

5.6 Self-extinction characteristic of air insulation

The capability of a spark gap to extinguish an arc between its electrodes is a very important feature. In fact, whenever it can extinguish the arc in a time sufficiently short, it prevents the operation of the protection system and thus the opening of the line circuit breaker. There is a report on an operating ungrounded 6.6 kV line where the probability of occurrence of flashovers for direct lightning strikes to the line was 50% [30]. According to this report, even at about 1/3 of double phase or triple phase flashovers, phase-to-phase arc extinguished and did not lead to trip out of the lines.

A spark gap is able to extinguish the arc without the interruption of the power supply, provided that the arc current is sufficiently low. For this reason, spark gaps can extinguish the arc currents only in MV networks with isolated neutral, or where the single phase-to-ground current is limited by resistors or where the neutral is connected to ground with an arc suppression coil. For networks with resonant neutral grounding, which are becoming more and more popular, it has to be realized that the quenching current is not more than few amps.

Another important parameter, which influences the self-extinction capability of a spark gap, is the shape of the recovery voltage across the electrodes immediately after the extinction. If there is a restrike then the final arc extinction may take a much longer time.

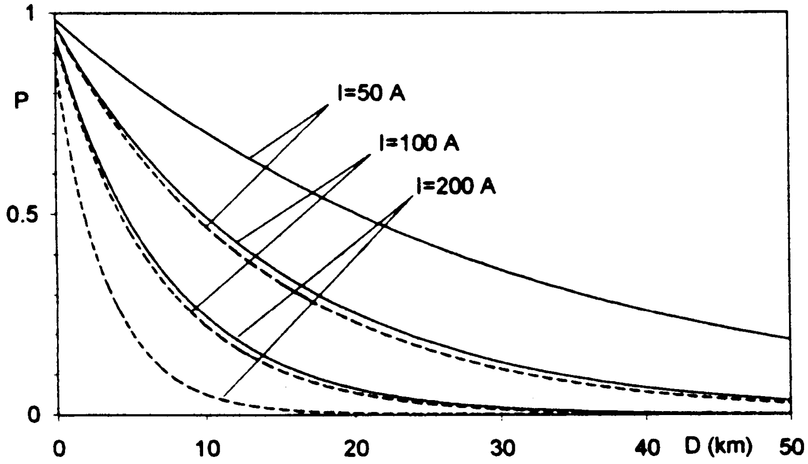


Fig. 20 - *Probability P of self-extinction of spark gaps in a time shorter than 0.5 s. P is given as function of the arc current I and of the distance D from the primary substation.*
—— spark gaps having an arcing distance of 5.6 cm installed in 20 kV networks
– – – spark gaps having an arcing distance of 3 cm installed in 10 kV networks

An Italian study [30] provides some results showing that the distance from the primary transformer station to a radial MV line may have an influence on the self-extinction characteristics of spark gaps [31], most probably due to the shape of the recovery voltage.

Figure 20 summarizes the experimental results, in terms of self-extinction probability within a time shorter than 0.5 s as function of the arc current and of the distance from the primary substation, for spark gaps having an arcing distance of 5.6 cm and 3 cm installed in 20 kV and 10 kV networks with isolated neutral, respectively.

Appendix I

The effect of the length of conductors between arrester and apparatus to be protected

Fig. A1 shows a transformer that is connected to an overhead line and protected against lightning overvoltages by an arrester. The maximum overvoltage at the transformer will be higher than the protective level of the arrester. This appendix analyzes the effect of the length of conductor between the arrester and the transformer as well as the conductor from the arrester to the common grounding point of the arrester and the transformer. All conductors are assumed to be overhead lines with the same characteristic impedance.

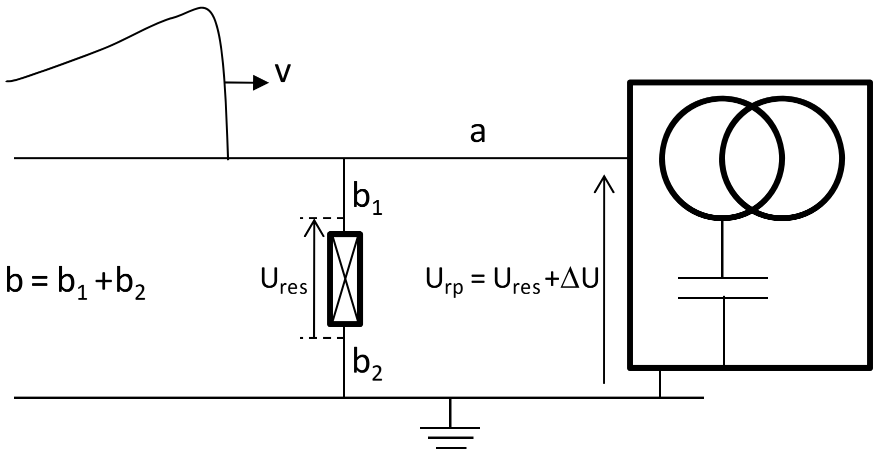


Fig. A1 - *Transformer connected to an overhead line and an arrester*

It is possible to obtain an analytical expression for the transformer voltage based on the following assumptions:

- the arrester is ideal (with residual voltage U_{res});
- the lines are lossless and have the same characteristic impedance;
- *b* is equal zero;
- the steepness of the incoming lightning voltage is constant;
- there is no ground potential rise;
- the transformer impedance is infinite, i.e. the transformer represents an open circuit.

The analytical expression becomes:

$$U_{rp} = U_{res} + \frac{2 \times S \times a}{\nu} \qquad (A.1)$$

where S is the steepness of the incoming wave and ν is the speed of light (300 μs/m).

The voltage across the arrester is not influenced by the arrester itself when the voltage is less than U_{res}. This means that under this condition, the arrester does not cause any reflection of the incoming voltage wave. A reflected wave equal the incoming wave is generated at the transformer. That wave will reach the arrester after a time delay equal $2 \bullet \tau$ where τ is the travel time for line segment *a*. The derivative of the arrester voltage increases from S to $2 \bullet S$ when the reflected wave reaches the arrester. The arrester voltage will increase with this rate of rise until it reaches U_{res} and the voltage remains constant after that instant.

The transformer voltage can be determined based on a lattice diagram when the arrester voltage is known. An ideal voltage source equal the known arrester voltage may then be connected to the arrester end of line segment *a* while the other end is open. This means that the corresponding reflection coefficients become respectively -1 and +1. The ideal voltage source causes a voltage wave that propagates to the transformer end where a reflected wave propagating towards the arrester is generated. The reflected wave is equal to the incoming one. The reflected wave becomes after a time delay an incoming wave at the arrester where a reflected wave equal minus the incoming one is generated. That wave generates an additional incoming wave at the transformer and new waves are generated at the ends of the line segment. The voltage at the transformer becomes:

$$u_{pr}(t)=2\cdot[e(t-\tau) - e(t-3\cdot\tau) + e(t-5\cdot\tau) - e(t-7\cdot\tau) + e(t-9\cdot\tau) - e(t-11\cdot\tau) + e(t-13\cdot\tau) \cdot\cdot\cdot\cdot\ \cdot\cdot\cdot\cdot] \qquad (A.2)$$

where *e(t)* is the voltage source, i.e. the arrester voltage.

The travel time τ is equal to *a/v* where *v* is the speed of light (300 m/μs).

Fig. A2 shows the contribution to $u_{rp}(t)$ from each component in (A.2) and the resulting $u_{rp}(t)$. It is possible based on Fig. A2 to derive the analytical expression (A.1) for the maximum value of $u_{rp}(t)$. The expression is equal to formula (1) in section 3.2.1 when *b*=0. Note that the formula is valid only when the maximum value becomes less than $2\bullet U_{resl}$.

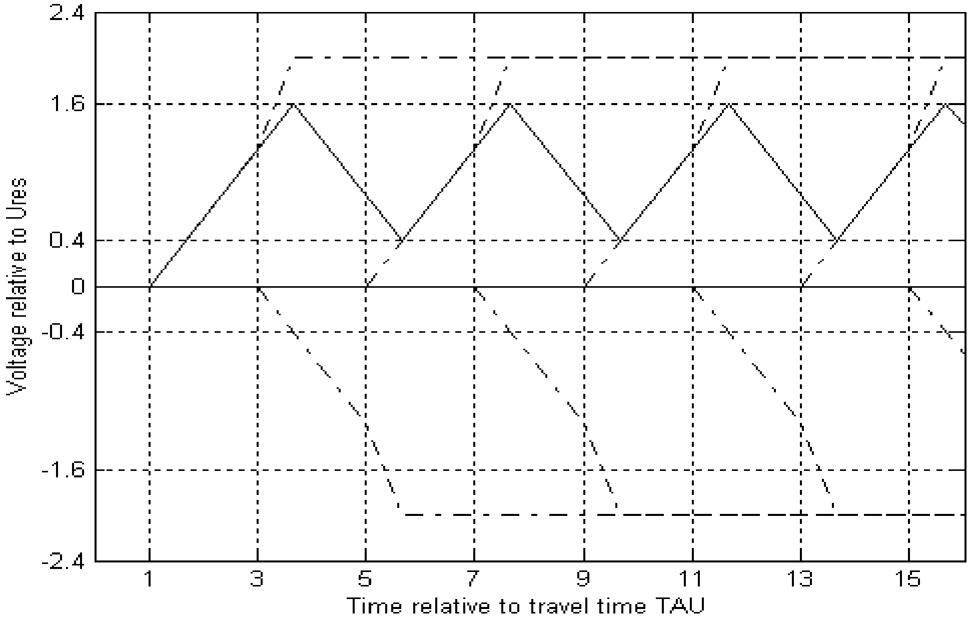
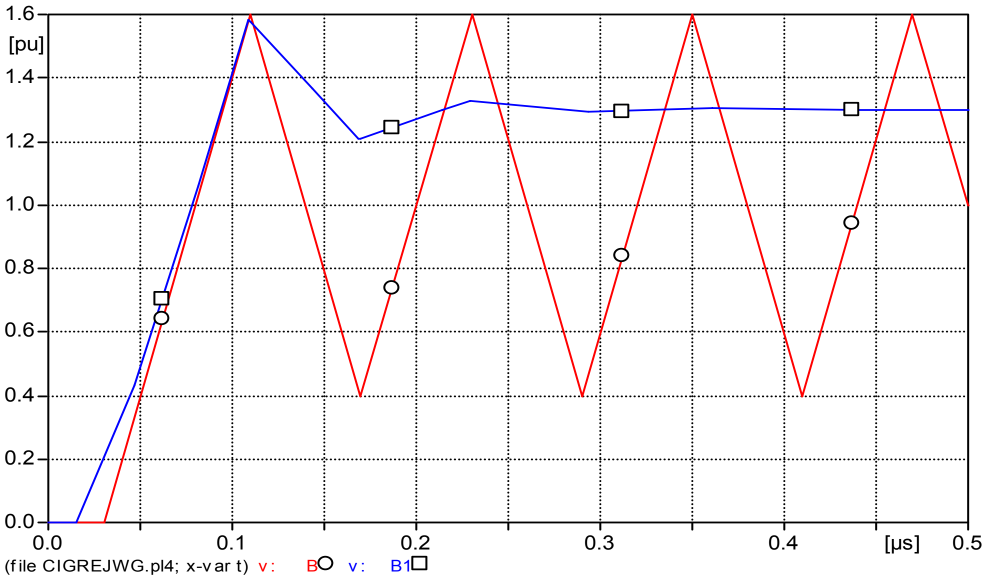


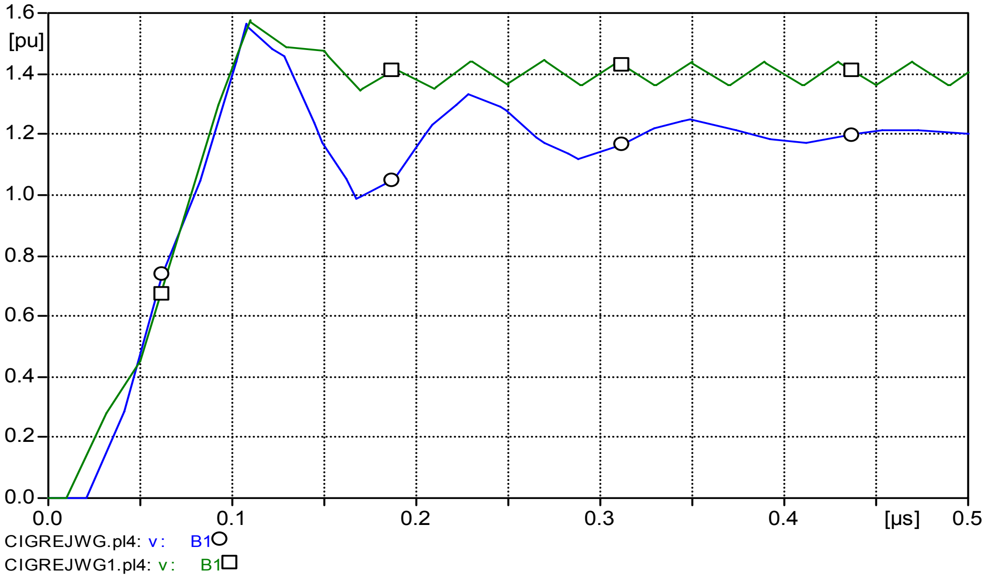
Fig. A2 - *Voltage at transformer (solid line) based on the contribution from each component in (A.1) (dashed-dotted lines)*

It is not possible to find a simple formula for the maximum transformer voltage when *b*≠0. Some specific computations were therefore made in order to see if formula (1) still can be used as a reasonable approximation. The computation was made by EMTP and Fig. A3 shows the transformer voltage when varying b_1 with b_2 equal zero. The sum $a+b_1$ was kept constant (equal 9 m). The steepness S of the incoming wave was 800 kV/μs and U_{res} was 80 kV. The voltage in Fig. A3 is in p.u. of U_{res}.

The maximum voltage is 1.6 p.u. when $b_1=0$. This value agrees with formula (1). The maximum value is somewhat reduced when $b_1 \neq 0$ and lowest obtained maximum value was 1.56 p.u..



Curve ○ : b_1=0 and a=9 m   Curve □ : b_1= 4.5 m and a=4.5 m



Curve ○ : b_1=3 m and a=6 m   Curve □ : b_1= 6 m and a= 3 m

Fig. A3 - *Transformer voltage for various values of b_1 when keeping b_1+a constant* (b_2=0)

It is seen that the oscillating part of the transformer voltage is reduced when b_1 increases.

The voltage approaches after some time to a constant value that increases when b_1 increases. The constant value is higher than the arrester voltage and the increase is due to the inductive voltage drop along the line segment b_1. It can be shown that the increase is proportional to the length of b_1.

There is no oscillation when *a* =0 and the maximum transformer voltage becomes in that case 1.6 p.u., which is the same value as from (1).

Fig. A3 assumes that b_2=0 and $b_1 \neq 0$. Some computations were made interchanging the values for b_1 and b_2, i.e. with b_1=0 and b_2 equal to the values used in Fig. A3. There was a rather minor influence from the interchange. The maximum transformer voltage was somewhat reduced, e.g. from 1.56 p.u. to 1.53 p.u.

The computed results obtained here show that replacing *a* in the analytical formula (A.1) by *a+b* gives a conservative but reasonably accurate estimate for the maximum transformer voltage. It should in this respect be kept in mind that the results are based on several simplifications and it is recommended to perform a more detailed analysis when considering a specific case.

The results shown in Fig. A3 are all based on the same steepness *S*. Some additional computations were made varying the steepness and the overall results were not altered, i.e. formula (1) gave still a conservative but reasonably accurate result. Varying the total length (a+b) for a given steepness is equivalent to varying the steepness while keeping the length constant. It is, therefore, reasonable to assume that formula (1) gives an acceptable estimate for all cases where the maximum transformer voltage does not exceed 2 p.u. Those cases have most probably very limited practical interest since the lightning withstand voltage of the transformer is normally less than twice the residual voltage of the arrester.

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