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# LIGHTNING PROTECTION OF OVERHEAD POWER DISTRIBUTION LINES

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**Abstract - Distribution lines are often located in areas with high ground flash densities, being therefore subject to lightning-caused power interruptions. This paper presents an overview of the various types of lightning overvoltages that can arise on overhead power distribution networks, as well as typical voltage waveforms. The effectivenesses of the most important methods for mitigating such overvoltages on MV and LV networks are also discussed.**

## 1 INTRODUCTION

In recent years, the growing use of sensitive electronic devices and the increasing demand of utility customers for stability of the power supply have stressed the importance of improving the reliability and power quality levels of electric systems. As lightning is a major source of faults on overhead lines and damages to or malfunction of sensitive electronic equipment, it is essential to evaluate the lightning electromagnetic environment in order to mitigate its effects and improve the power system quality. Many studies have been carried out, especially on medium voltage (MV) lines, aiming at obtaining a better understanding of the characteristics of the lightning overvoltages.

More recently, special attention has been drawn to the transients on low-voltage (LV) systems. As the surge withstand capabilities of LV networks are much lower than those of MV lines, they are more susceptible to lightning-caused disturbances. There are various ways by which lightning can disturb low-voltage lines. Transients may be originated from direct strokes (to the MV or LV networks or to end user installations) or indirect ones (either intracloud or cloud-to-ground flashes).

This paper presents the major mechanisms by which overvoltages are stemmed from lightning in both medium and low-voltage overhead power distribution networks, as well as typical surge waveforms. The effectivenesses of the main protective measures that can be utilized to improve the line lightning performance are also discussed.

## 2 MV NETWORKS

The basic measures that can be applied to improve the lightning performance of MV distribution lines involve the increase of the line insulation withstand capability [1 - 4], the use of periodically grounded shield wires [1, 4 - 8], and the installation of surge arresters along the line [1, 2, 6 - 15]. In this Section, some typical overvoltages are presented and the impacts of the protection alternatives on the reduction of the number of line flashovers, with emphasis on the use of shield wires and surge arresters, are discussed.

### *2.A Lightning Overvoltages*

Lightning can produce overvoltages when it hits either the line conductors (direct strokes) or a point in the vicinity of the distribution network (indirect strokes).

#### *2.A.1. Direct Strokes*

If a flash hits an overhead line, the current injected into the conductor is divided at the strike point, giving rise to two voltage waves that propagate in opposite directions. The prospective magnitude of these voltages can be estimated by multiplying the current that flows in each direction (half of the stroke current) by the characteristic impedance of the line, which is normally in the range of 400 Ω to 500 Ω. Therefore, for a line characteristic impedance of 400 Ω and a stroke current of 10 kA, whose probability of being exceeded is larger than 90 %, the corresponding overvoltage is 2000 kV, which is far beyond the line insulation level. As a consequence, multiple flashovers occur between the conductors and also to earth in different points of the line. Customers around the fault location experience both a voltage sag during the short-circuit and a momentary interruption when the breaker opens to clear the fault.

A typical overvoltage caused by a direct strike to a MV line is illustrated in Figure 1. The voltage, obtained from calculations performed by Mirra *et al.* [16], is characterised by a few short spikes, produced by multiple line insulation breakdowns, followed by a slower front component whose amplitude is somewhat lower than the insulation level of the line.

Direct strikes usually do not cause permanent damages to lines with bare conductors as long as the fault duration is limited by a short-circuit protection device. On the other hand, in the case of lines with covered conductors, the coating prevents the footpoint of the power frequency arcing current from moving along the line, and therefore a flashover between phases for such lines may cause a mechanical breakdown of the conductors [17].

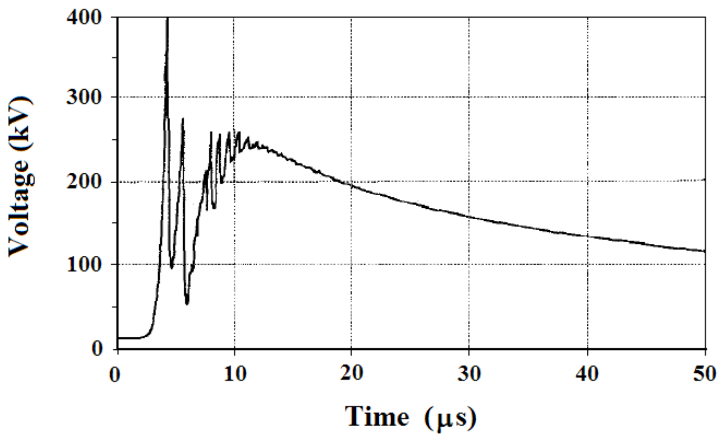



Fig. 1 – Example of a typical overvoltage due to a direct strike to the MV line (adapted from [16]).

### *2.A.2. Indirect Strokes*

Although the overvoltages associated with direct strikes to the line are much more severe, those induced by nearby lightning have a higher frequency of occurrence and are usually responsible for a greater number of line flashovers and supply interruptions on systems with rated voltage 15 kV or less. Due to the impacts of the lightning induced overvoltages on the performance and power quality of distribution systems, several theoretical and experimental studies have been conducted in order to better understand their characteristics or to assess the effectiveness of the methods that can be used for their mitigation [18 - 53].

The induced voltage magnitudes and waveforms depend on many lightning parameters and are substantially affected by the network configuration. The evaluation of such transients entails the calculation of lightning fields, which are defined by the spatial and temporal distribution of the stroke current along the channel, as well as by the earth electrical parameters. A suitable coupling model is required for the analysis of the electromagnetic interaction between the field and the line conductors. In [18] Nucci and Rachidi present different approaches and formulations to describe the coupling between an external electromagnetic field and an overhead line. The effects of a lossy earth and the case of multiconductor lines are also dealt with, and the influences of various parameters on the induced voltages are investigated.

With regard to experimental investigations, Yokoyama *et al.* presented in [45 - 47] simultaneous measurements of induced voltages and the corresponding stroke currents, thus allowing direct comparisons between measured and calculated results.

The appraisal of three different theories for computation of lightning induced voltages on overhead lines presented in [48] concludes that the Rusck model [31] leads to consistent results. However, in its original form the electric field is assumed to be constant in the region between the line and the ground, the lengths of the line and of the stroke channel are assumed to be infinite, only straight lines can be considered and thus realistic configurations cannot be taken into account. These restrictions limit the application of the model and an extension was proposed by Piantini and Janiszewski [49]. The so-called Extended Rusck Model (ERM) overcomes these limitations and enables also to take into account the incidence of lightning flashes to nearby elevated objects, the occurrence of upward leaders, and the presences of a periodically earthed shield wire (or neutral conductor) and equipment such as transformers and surge arresters. Lines with various sections of different directions can be considered through the evaluation of the correct propagation time delays for the elementary voltage components that determine the induced voltage at a given point of the line.

The validity of the ERM has been demonstrated from various comparisons of theoretical and experimental results [49 - 51] for the case of an electromagnetic field radiated by a lightning channel perpendicular to the earth plane. This is indeed the hypothesis under which the Rusck model was developed and Cooray [52] and Michishita and Ishii [53] have shown that, for this condition, it leads to results which are identical to those obtained from the more general coupling model proposed by Agrawal *et al.* [54], whose adequacy has been confirmed in [7, 26, 37, 55].

The calculation of lightning induced voltages on overhead lines through the ERM is based on electric and magnetic potentials due to the charges and currents in the channel. The inducing scalar potential associated with the charges acts as a distributed source and is responsible for the generation of waves that propagate along the conductors. On the other hand, the magnetic potential associated with the currents contributes with its time derivative to the total induced voltage in each point of the line.

In the case of direct strikes to a metallic elevated object, the return stroke starts at the top of the structure. The currents in the object and in the stroke channel are assumed to have equal magnitudes and polarities, but different speeds and directions of propagation, as illustrated in Figure 2 for the case of a downward negative flash. The current through the strike object propagates at a speed very close to that of light in free space, whereas in the channel the speed is a fraction of this value.

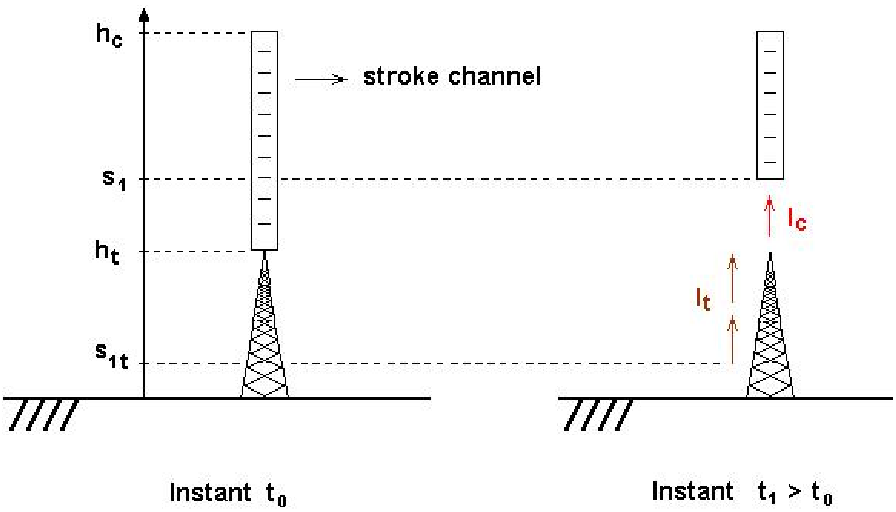



Fig. 2 - Lightning strike to an elevated object. $h_t$: height of the strike object; $h_c$: height of the upper extremity of the stroke channel; $I_c$ and $I_t$: currents in the stroke channel and in the strike object, respectively; $s_1$ and $s_{1t}$: heights, at instant $t_1$, of the current front in the channel and in the strike object, respectively (adapted from [56]).

The voltages *U(x,t)* induced on an overhead line located in the vicinity of the strike object are obtained by adding the component associated with the charges in the stroke channel (electrostatic component) to those associated with the currents that propagate in the lightning channel and in the strike object (magnetic components). Thus,

$$U(x,t) = V(x,t) + \int_0^h \frac{\partial Ai(x,t)}{\partial t}.dz + \int_0^h \frac{\partial Ai_t(x,t)}{\partial t}.dz \qquad (1),$$

where *V(x,t)* is the induced scalar potential, *h* is the height of the line, and *Ai(x,t)* and $Ai_t(x,t)$ are the vector potentials associated with the currents that propagate through the stroke channel and through the strike object, respectively. The procedure for calculating the voltage induced on an overhead line in the presence of a tall strike object, disregarding the reflections at the bottom and top of the structure, is described in [49].

Baba and Rakov, using the finite-difference time-domain (FDTD) method, verified that the ratio between the magnitudes of lightning induced voltages for strikes to a tall object and to flat ground increases with increasing distance from the lightning channel (ranging from 40 m to 200 m), decreasing the current reflection coefficients at the top and at the bottom of the strike object ($\rho_{top}$ and $\rho_{bot}$, respectively), and decreasing return stroke speed [33, 57]. Also, the ratio increases with decreasing the lightning current rise time. Under realistic conditions such as $\rho_{top}$ = -0.5 and $\rho_{bot}$ = 1, the ratio is larger than unity (the tall strike object enhances the induced voltages), but it becomes smaller than unity under some special conditions, such as $\rho_{top}$ = 0 and $\rho_{bot}$ = 1.

The lightning induced voltage waveforms presented by Yokoyama *et al.* in [45 - 47] were measured on an experimental line with two sections, as shown in Figure 3. They were obtained simultaneously with the stroke currents that hit a 200 m high metallic tower situated at a distance of 200 m from the experimental line. Electrical-optical converters were used for transmission of the obtained waveforms by optical cables and, after optical-electrical conversion, the data were stored in magnetic tapes. Due to the characteristics of the converters, the recorded waveforms presented a faster decay than the real ones [46]. The length of the lightning channel was assumed to be equal to 3 km and the stroke current was assumed to propagate through the lightning channel at a constant speed of 30 % of that of light in free space, as these parameters were not measured.

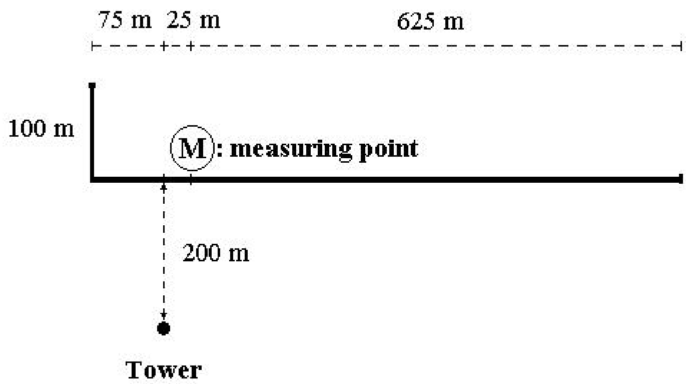
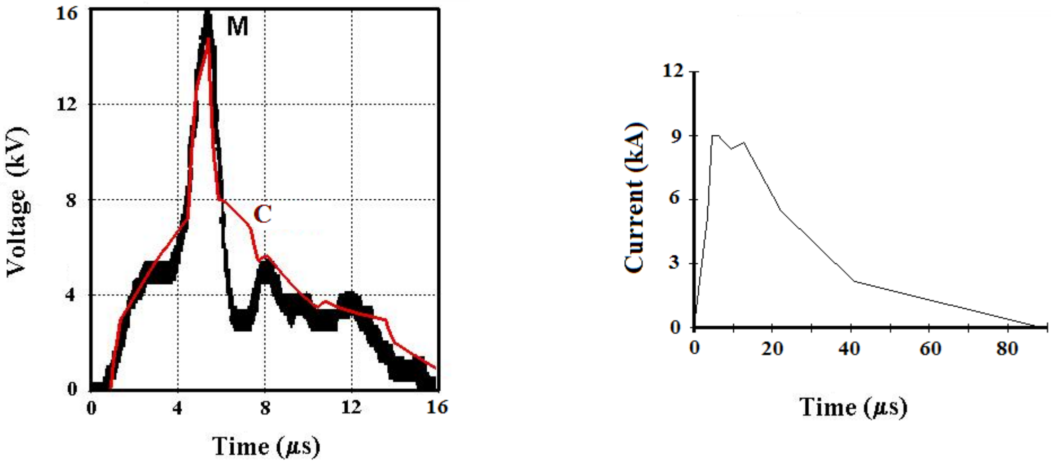



Fig. 3 - Top view of the experimental line for the measurements carried out in [45-47] (adapted from [56]).

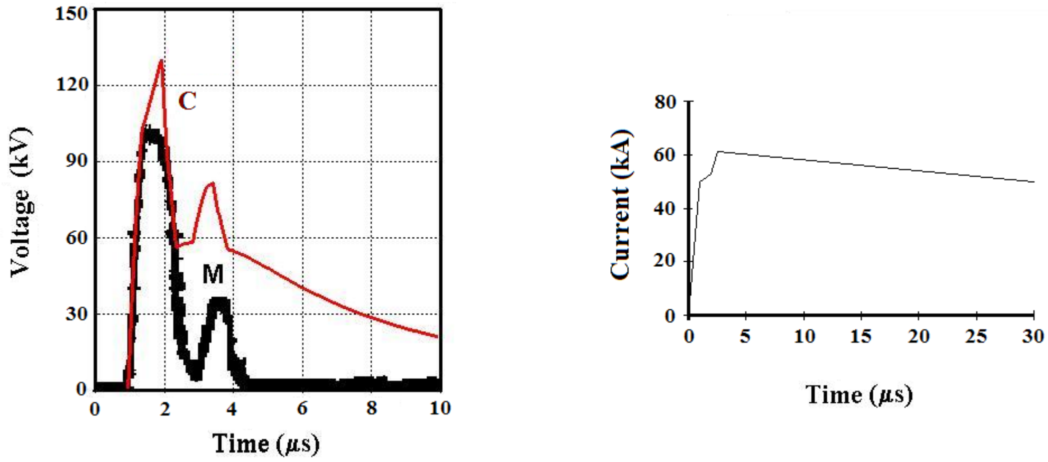
Figure 4 presents measured and calculated voltages induced on the experimental line by downward negative flashes that struck the tower. The corresponding stroke current waveforms are also presented. As shown in [58], the calculations presented in Figure 4, which take into account the effects of the tower, line topology, and finite length of the lightning channel, are in a much better agreement with the measured voltage waveforms than those performed with the original Rusck model. Despite the differences on the wavetails, both the voltage magnitudes and wavefronts are reasonably well reproduced by the ERM.

The observed discrepancies can be attributed partially to the representation of the stroke current waveform, which has a significant influence on the induced voltages especially in the case of strikes to elevated metallic objects. Other reasons for the differences are the features of the electrical-optical converters, as already mentioned, the Transmission Line (TL) model [58] adopted for the determination of the current distribution along the lightning channel, and the fact that no reflections were considered at the top and bottom of the structure. Greater discrepancies would probably be observed in the case of stroke currents with steeper fronts, since in this case the current waveforms along the tower would be affected more significantly by the reflections at the tower extremities. Finally, the assumptions of a constant current propagation velocity of 30 % of that of light in free space *(c)* and of a lightning channel perpendicular to a perfectly conducting ground plane also contribute to the deviations. For these reasons the comparisons can only be made under a qualitative perspective. Even so, the overall agreement between theoretical and experimental results is very reasonable and indicates the adequacy of the ERM, whose validity has also been confirmed from many other comparisons of measured and calculated voltages, using mostly data obtained from scale model experiments.

A comparison using data obtained from the 1:50 scale model described in [26, 30, 55] is presented in Figure 5, where the voltage and time scales are referred to the real system by applying the corresponding scale factors (1:18000 and 1:50, respectively). In this simple configuration, the line was matched at both terminations. A good agreement is observed between the measured and calculated voltages.

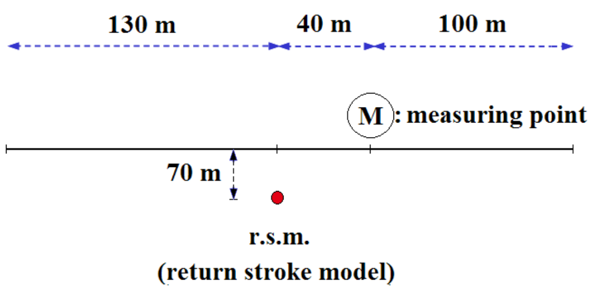



(a)

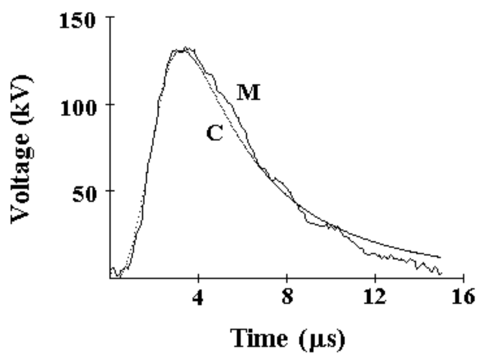



(b)

Fig. 4 - Measured (M) and calculated (C) lightning induced voltages at the observation point indicated in Fig. 3 and corresponding stroke current waveforms (adapted from [56]).
a) Case 81-02 [45]  b) Case 86-03 [47]




(a)




(b)

Fig. 5 - Calculated (C) and measured (M) induced voltages obtained from a 1:50 scale model (all the parameters are referred to the full-scale system). Stroke current with peak value of 34 kA, front time of 2 μs, and propagation velocity of 11 % *c*.
a) line topology (top view)  b) induced voltages

In [26, 55] the experimental facility was used to validate the Agrawal *et al.* coupling model [54] through comparisons with simulations performed using the LIOV-EMTP code [7, 26, 37], considering much more complex network configurations. The LIOV-EMTP allows for the calculation of lightning induced voltages on homogeneous, multiconductor, lossy overhead lines taking also into account the effects of downward leader electric fields and corona [18].

The amplitudes and waveforms of the lightning induced voltages vary widely and are particularly affected by the:
- magnitude, front time and propagation velocity of the stroke current;
- distance between the line and the lightning strike point;
- occurrence of upward leaders;
- position along the line;
- soil resistivity;
- heights of the conductors;
- line configuration (horizontal or vertical, rural or urban);
- presence of a shield wire or neutral conductor;
- earth resistance;
- relative position between the stroke location and surge arresters;
- surge arrester spacing;
- surge arrester V/I characteristic.

In the case of a strike to an elevated object in the vicinity of the line, the induced voltage depends also on the height, surge impedance and earth impedance of the structure and on the equivalent surge impedance of the lightning channel.

An example of a typical lightning induced voltage waveform, recorded by the system described in [11] on a 2.7 km long, unenergized line matched at both terminations, is presented in Figure 6. Despite the large variation of the induced voltage waveforms, they are usually characterised by shorter front times and shorter durations in comparison with overvoltages caused by direct strokes.

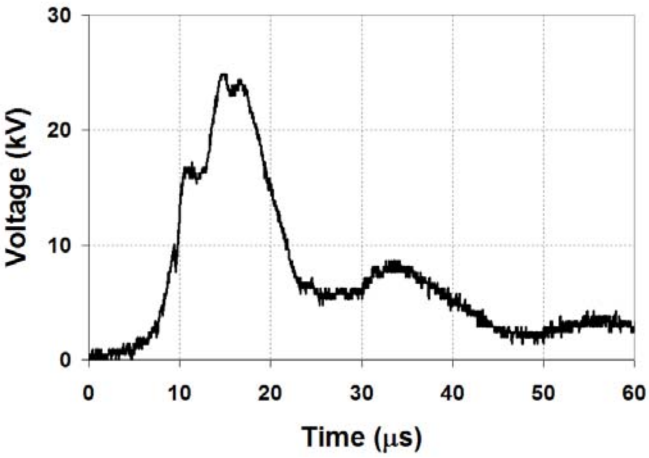



Fig. 6 – Example of a typical lightning induced voltage.

### *2.B Lightning Protection of MV Lines*

The frequency of flashovers associated with indirect strokes decrease substantially as the critical flashover overvoltage (CFO) of the line structures increases, and can be virtually eliminated if the CFO is greater than 300 kV. However, surges with higher magnitudes will then travel over long distances, increasing the stresses on line equipment.

The number of faults caused by direct strokes will remain practically unaltered unless a shield wire earthed at every pole with low earth resistance is used or surge arresters are installed on all phases at very short intervals. A 10 m high distribution line located in open ground in an area with ground flash density of 1/(km$^2$.year) collects on average approximately 11 flashes /(100 km.year). The use of a shield wire in conjunction with arresters on every pole and every phase is effective against direct strokes and theoretically eliminates flashovers. The shield wire protects the arresters from excess energy dissipation, and the arresters prevent back flashovers.

In any case, a cost-benefit analysis of the possible solutions should always be performed.

### *2.B.1. Shield Wires*

Although a shield wire may collect most of the flashes that otherwise would hit the phase conductors, its effectiveness against direct strokes is very limited. The reason is that the potential rise due to the current flow through the pole earth impedance causes a large voltage difference between the earth lead and the phase conductors, which by its turn causes a back flashover in the great majority of the cases. Therefore, in order to mitigate the effects of direct strikes, the shield wire should not only be earthed at every pole, but also the line should have sufficient CFO between the earth lead and the phase conductors, and the earth resistances should be low. Earth resistances must be less than 10 Ω if the CFO is less than 200 kV, whereas for CFO in the range of 300 kV to 350 kV, a ground resistance of 40 Ω will provide similar performance [1].

On the other hand, a shield wire may reduce the magnitudes of the overvoltages associated with nearby strokes. As this effect is due to the coupling between the shield and phases wires, the voltage reduction will occur regardless of the position of the shield wire with respect to the phase conductors. The greater the coupling, the more significant the voltage reduction. The effectiveness of shield wires in improving the indirect lightning performance of distribution lines has been investigated in [5-7, 31, 60-63].

In [5], the mitigation effect of the neutral conductor / shield wire was studied experimentally through the use of a reduced scale model. Several tests were performed in order to investigate the influence, on the induced voltages, of parameters such as the height of the shield wire, the earth resistance, the distance between adjacent earthing points, and the relative position of the stroke channel with respect to the earthing points. The voltages induced on two distribution line models, representing 10 m high, 1.4 km long lines – one with and the other without a shield wire -, both located at a distance of 70 m from the 'lightning' channel, were recorded simultaneously. The voltage measurements were performed at the points closest to the stroke location. The 'stroke' current waveform was representative of first downward negative strokes (the equivalent front time $Td_{30\text{-}90}$ [59], referred to the full-scale system, was about 3.5 µs), and the earth was simulated by interconnected aluminum plates, thus representing a perfectly conducting plane. The current propagation velocity *(v)* along the return stroke model was 11 % of that of light in free space.

As mentioned above, the greater the coupling between the shield wire and the phase conductors and the larger the voltage induced on the former, the greater its influence in terms of reduction of the voltage amplitudes. This is illustrated in Figure 7, which compares the phase-to-earth voltages induced on lines with shield wire heights of 11 m and 7 m with that induced on a line without shield wire or neutral conductor.

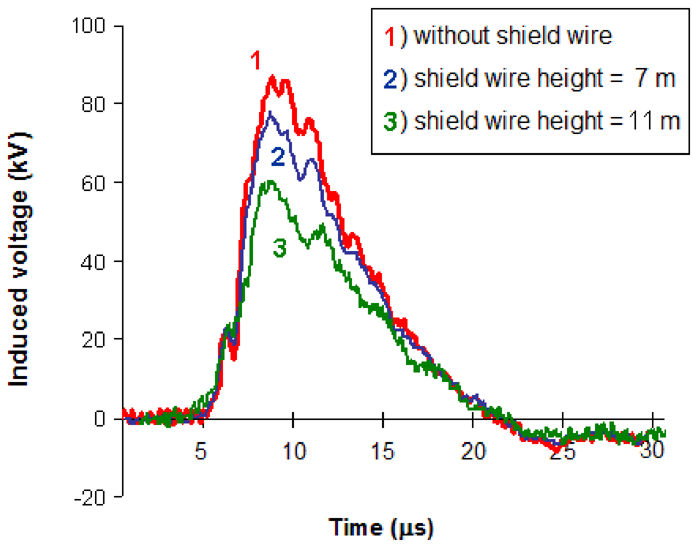



Fig. 7 – Induced voltages (phase-to-earth) at the point closest to the stroke location – influence of the height of the shield wire (adapted from [5]). Lightning current: amplitude 24.9 kA, equivalent front time 3.5 µs; stroke location in front of an earthing point, at a distance of 70 m from the distribution line; earthing spacing: 450 m; earth resistance: 50 Ω; perfectly conducting earth.

The influence of the earth resistance *(Rg)* is illustrated in Figure 8, which presents the induced voltages (phase-to-earth) corresponding to *Rg* = 0 Ω and *Rg* = 1000 Ω for the case of stroke location equidistant from two earthing points. The lower the value of the earth resistance, the lower the induced voltage magnitude, especially if the lightning channel is in front of an earthing point. However, this influence tends to decrease as the distance between adjacent earthing points increases, the stroke current front time becomes shorter or the distance between the stroke location and the closest earthing point increases.

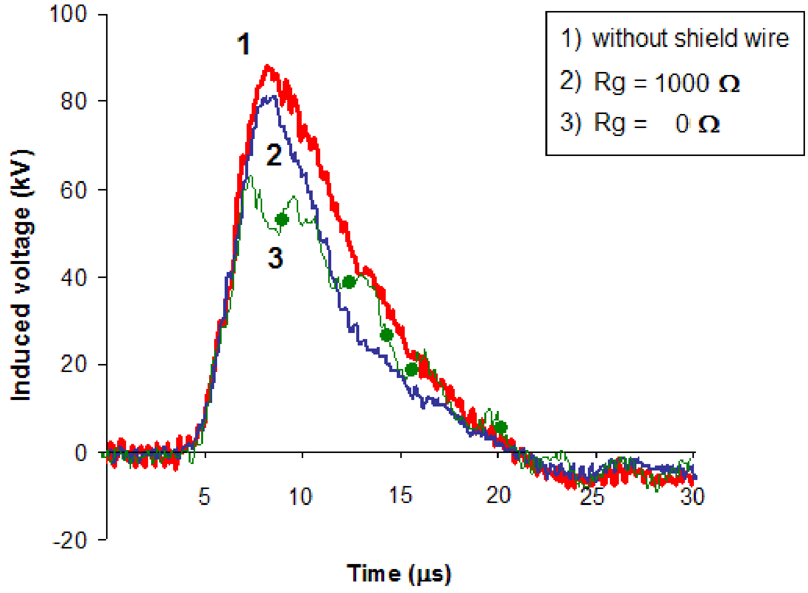



Fig. 8 – Induced voltages (phase-to-earth) at the point closest to the stroke location – influence of the earth resistance (adapted from [5]). Lightning current: amplitude 24.9 kA, equivalent front time 3.5 µs; stroke location equidistant from two earthing points, at a distance of 70 m from the distribution line; distance of 450 m between adjacent earthing points; height of the shield wire: 9 m; perfectly conducting earth.

The relative position between the lightning strike point and the distribution line in general does not influence significantly the induced voltages if the earthing spacing is shorter than about 200 m. The situation changes, however, in the case of larger distances. Figure 9 presents the phase-to-earth induced voltages corresponding to an earthing spacing of 750 m and to the ideal case of earth resistance of 0 Ω. Two stroke locations are considered: in front of an earthing point or equidistant from two adjacent earthing points. The former situation is the most favourable in terms of the attenuation of the voltages induced on the phase conductors.

Figure 10 shows induced voltages on a 3 km long line with horizontal configuration and matched at both ends. The lightning channel is 50 m from the line and equidistant from its terminations. The simulations refer to a subsequent stroke current *(I)* of 24 kA whose waveform is obtained by the sum of two Heidler functions [64] with the following parameters: $I_{01}$ = 21.4 kA, $\tau_{11}$ = 0.25 µs, $\tau 1_2$ = 2.5 µs, $I_{02}$ = 13 kA, $\tau_{12}$ = 2.1 µs, $\tau_{22}$ = 230 µs, and $n_1 = n_2 = 2$. The current propagation velocity is assumed to be 60 % of that of light in free space. The lightning channel is vertical, 4 km long, has no branches, and is modelled according to the Transmission Line (TL) model [58]. The height of the phase conductors is 10 m, earth is a perfectly conducting plane, and the voltages are calculated at the point closest to the stroke location.

In Figure 10a the phase-to-earth voltage corresponding to a neutral conductor placed at the height of 7 m and earthed every 400 m (earth resistance of 20 Ω and lead inductance of 7 µH) is compared with the voltage that would be induced at the same point in the absence of the neutral. As the peak value is reached well before the effect of the neutral earthings is felt at the observation point, only the voltage waveform is changed in this case.

It is interesting to note that in some circumstances a decrease in the earthing spacing *(xg)* may lead to an increase in the phase-to-neutral voltages. This is illustrated in Figure 10b, which depicts the phase-to-neutral voltages for *xg* = 200 m and *xg* =400 m. In both cases the stroke location is equidistant from the neutral earthing points. Before the arrival of the voltages reflected at the neutral earthings, the ratio of the phase-to-earth to the neutral-to-earth voltages is approximately equal to the ratio between their respective heights. However, when the reflections arrive at the observation point, the neutral-to-earth voltage decreases abruptly, causing a sudden increase in the phase-to-neutral voltage. The greater the value of the phase-to-earth voltage at the instant in which the reflections arrive at the observation point is, the greater the phase-to-neutral voltages will be. As the reflections corresponding to the case of *xg* = 200 m arrive earlier than those corresponding to *xg* = 400 m, the phase-to-earth voltage is higher in the former case. Additionally, the reflections are also stronger, as in this case the earthing points are closer to the stroke location than for *xg* = 400 m. The net result will be a larger phase-to-neutral voltage in the case of *xg* = 200 m.

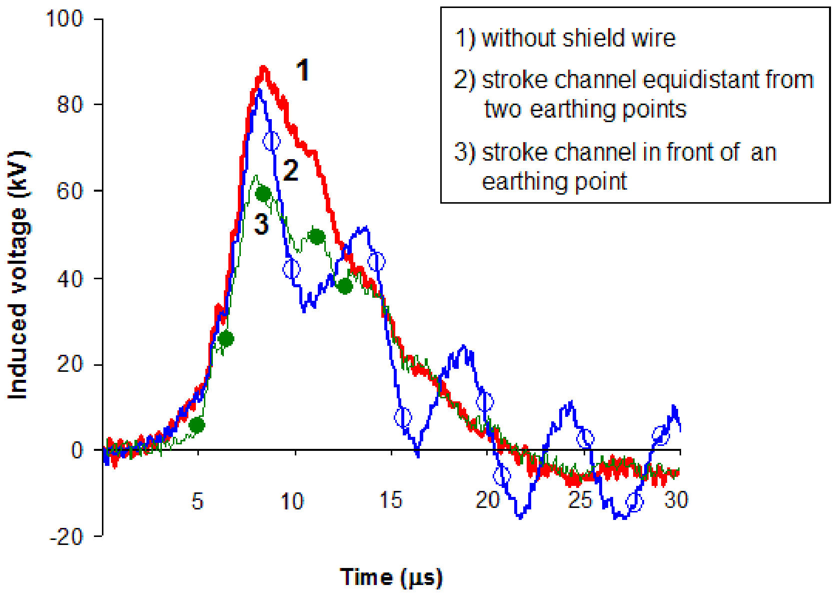



Fig. 9 – Induced voltages (phase-to-ground) - influence of the relative position of the stroke channel with respect to the earthing points (adapted from [5]). Lightning current: amplitude 24.9 kA, equivalent front time 3.5 µs; stroke location at a distance of 70 m from the distribution line; *xg* = 750 m; *Rg* = 0 Ω; height of the shield wire: 9 m; perfectly conducting earth.

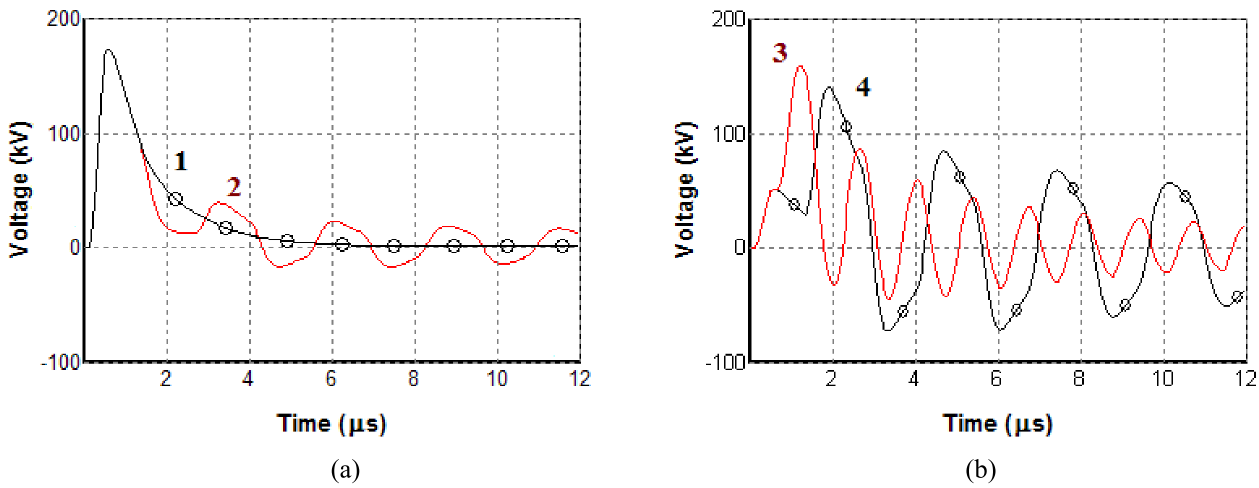



Fig. 10 – Induced voltages by a subsequent stroke of 24 kA at the point closest to the lightning channel. Stroke location is 50 m from the line; *Rg* = 20 Ω.
a) phase-to-earth voltages. Curve 1: neutral not present; curve 2: neutral earthed every 400 m (*xg* = 400 m);
b) phase-to-neutral voltages. Curve 3: *xg* = 200 m; curve 4: *xg* = 400 m

### *2.B.2. Surge Arresters*

In order to protect effectively an unshielded MV line against direct strokes, surge arresters should be installed on all the phases of every pole. According to the analysis performed in [1], in the case of two spans between arresters even a line with CFO of 350 kV and earth resistance of 10 Ω would experience flashovers in about 70 % of the direct strikes.

Such estimate refers to a span length of 75 m and assumes that the neutral is earthed at every pole. For three spans between arresters, the corresponding number is 80 %. However, as pointed out by McDermott *et al.* [13], arresters applied to protect an unshielded line against direct strokes may have a significant failure rate due to excess energy dissipation.

On the other hand, most of the studies agree that the application of surge arresters in MV lines can be effective in reducing the number of flashovers caused by indirect strokes, provided that the arrester spacing is not too large. Some possible measures for improving the reliability of a 83 km long, 13.8 kV distribution line located in a region of ground flash density in the range of 4 to 8 flashes/(km$^2$.year) were investigated by Silva *et al.* [2]. All transformers had surge arresters at the primary side and the neutral was earthed at poles where surge arresters were installed. Distances between arresters varied widely depending on the region crossed by the line, ranging from only 77 m in urban sections to the maximum of 2200 m in some rural areas. Regarding the effectivenesses of the different alternatives considered for improving the lightning performance of this specific line, it was shown that the installation of ZnO surge arresters on all phases with spacing of 300 m, associated with the increase of the insulation level of the rural sections of the feeder (through the installation of 34.5 kV type pin insulators), would reduce the number of lightning outages in approximately 50 %, with a reduction around at least 75 % of the number of faults caused by indirect strokes.

The analysis presented by Paolone *et al.* [7] on the mitigation effect of surge arresters on lightning induced overvoltages was performed with a computer code that consists in an extension of the Agrawal et al coupling model [54]. The authors considered a single conductor, 2 km long line with different arrester spacings: 2 km (only at the line terminals), 1 km, 500 m and 200 m. Information is given about the maximum amplitude of the induced voltage along the line as a function of the spacing between two adjacent surge arresters for the cases of lossy (conductivity of 0.001 S/m) and perfectly conducting earth. The simulations revealed a shortcoming of the effectiveness of surge arresters when they are separated by large distances (e.g., one surge arrester every 1 km). The computed results showed also that an important reduction of the induced overvoltages can be achieved only with a large number of arresters, namely one surge arrester every 200 m.

According to the computer simulations presented by McDermot *et al.* [13], MV lines can be effectively protected against nearby strokes by installing arresters on each phase every 360 m, although surge arresters should be installed on every pole and on every phase to protect an unshielded distribution line against direct strokes. This is in agreement with the conclusions obtained by Geldenhuys and Gaunt [14], from a study performed on a 10 km long rural distribution line of 11 kV in South Africa, that surge arresters installed on the three phases with spacing of 300 m practically eliminate outages caused by indirect discharges. A surge arrester installation interval of 200 m (on all phases) is suggested by Yokoyama [6, 15] to give a fairly good protection for medium voltage distribution lines against overvoltages induced by nearby strokes.

In contrast with these findings, the major conclusion of a project described by Short and Ammon [65] was that there was little evidence that arresters used for overhead distribution line protection would provide significant improvements in reliability. Five feeders were extensively monitored for three years. Three of them had arresters added on all phases with spacing of 40 m (every pole), 200 m and 400 m, while the other two were used as "control circuits" and had no arresters. During the project the circuits with arresters did not show any quantifiable improvement over the circuits without arresters, regardless of spacing. According to the authors, even the circuit with arresters on almost every pole, which was expected to be virtually lightning-proof, had as many lightning-caused faults as the other circuits. This is indeed a surprising result, but the study period was not long enough to allow a definitive conclusion. Moreover, the incidence of lightning flashovers was rather low during the monitoring period and a line survey found that about 10 % of the arresters were missing.

An investigation about the effectiveness of surge arresters in reducing the magnitudes of lightning induced voltages on overhead distribution lines was carried out by Piantini and Janiszewski [9]. Experiments were performed through the use of both a reduced scale model and a full-scale system implemented specifically for this purpose, while the simulations were conducted using the ERM [49 - 51]. 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 can be found in [55]. The results showed that surge arresters can be effectively used for improving the lightning performance of distribution lines even if they are not applied at every pole. However, the influence of the distance between adjacent surge arresters on the induced voltages can be significant, particularly if the lightning strike point is nearly equidistant from two sets of surge arresters. The closer the arresters are, the lower the voltage magnitudes will be. Figure 11 compares the induced voltage on an 1.4 km long straight line without surge arresters with those corresponding to arrester spacings of 300 m and 600 m. The stroke current front time and time to half-value are about 3.2 μs and 58 μs, respectively. All the quantities are referred to the full-scale system by applying the corresponding scale factors.

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 spacings shorter than about 300 m. For larger spacings, the differences between the voltage magnitudes corresponding to the cases of stroke location in front of a set of arresters or equidistant from two sets of arresters tend to increase, especially if the earth resistance is low. For short arrester spacings, 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 is justified because the reflected waves that cause the voltage reduction vary little with the position of the stroke channel with respect to the nearest set of arresters.

On the other hand, for large spacings the induced voltage levels are more sensitive to the distances from the stroke location to the arresters, and the same occurs with the components (henceforth called suppressive components) that, by coupling, cause a reduction of the voltages induced on the phase conductors. The closer the surge arrester is from the lightning strike point, the greatest will its contribution be in reducing 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 are felt almost instantaneously, whereas if the stroke location is equidistant from two sets of arresters the effects of the suppressive components are delayed due to the time needed for their propagation from the arresters to the observation point. The latter situation is illustrated in Figures 11a and 11b, where the delay of the effect of the arresters can be clearly noticed.

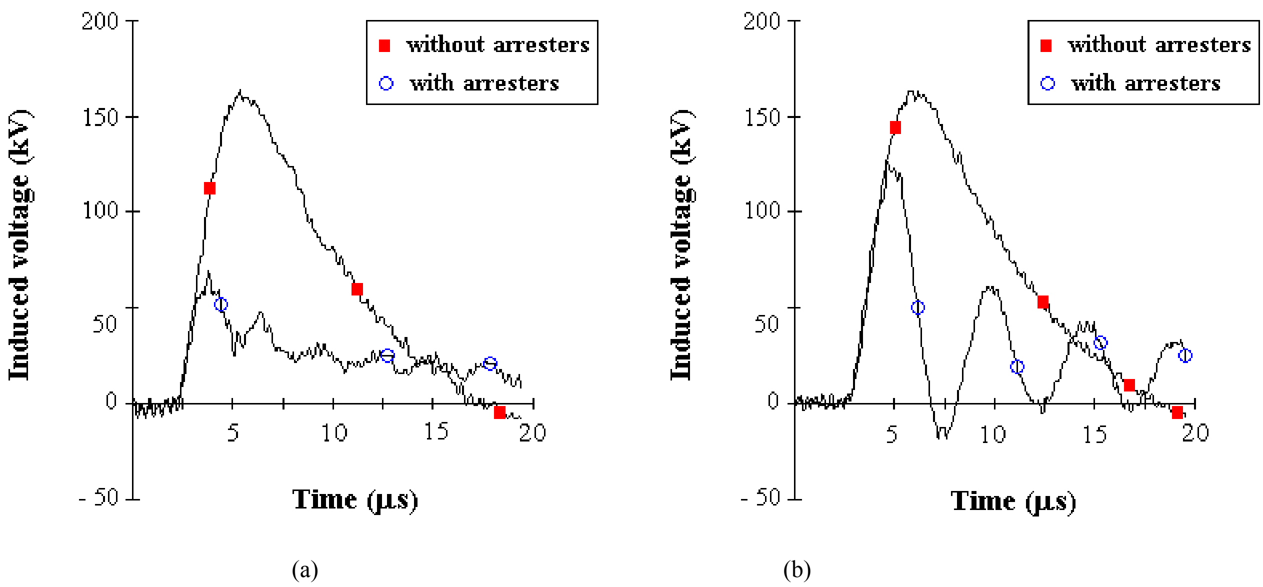
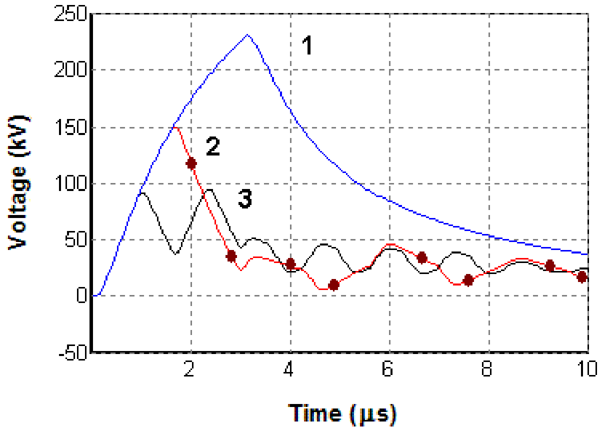


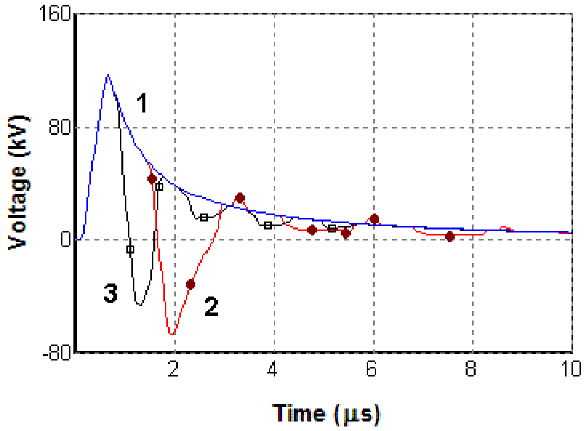

Fig. 11 - Voltages induced on lines with and without surge arresters (s.a.), at the point closest to the stroke location, for arrester spacings of 300 m and 600 m. Lightning strike point 70 m from the line and equidistant from two sets of arresters (adapted from [9]). $I = 38$ kA; $tf = 3.2$ μs; $Rg = 50\ \Omega$.
a) arrester spacing equal to 300 m b) arrester spacing equal to 600 m.

The influence of the distance between adjacent surge arresters on the induced voltages is also illustrated in Figure 12 for the case of strike point 50 m from a 3 km long line and equidistant from its terminations. The line is three-phase, without neutral, and has a horizontal configuration. The conductors are at the height of 10 m above a perfectly conducting earth plane and the stroke current has a triangular waveform with time to half-value of 50 μs. The voltages are calculated at the point closest to the stroke location for distances of 400 m and 200 m between adjacent surge arresters. For comparison purposes, the voltages that would be induced at the observation point in the absence of the arresters are also presented. Figure 12a refers to a current of 50 kA, front time of 3 μs, and propagation velocity of 30 % *c*. These parameters are representative of a first stroke current. Figure 12b refers to a current of 15 kA, front time of 0.5 μs, and propagation velocity of 60 %*c*, which represents a typical subsequent stroke.

As shown in Figure 12a, when the front time is long in comparison with the time required for the reflections at the surge arresters to arrive at the observation point, the voltage magnitudes are significantly reduced. On the other hand, if the voltage peak value is reached before the arrival of the reflections, only the voltage wavetail will be affected, as illustrated in Figure 12b. Therefore, the greater the stroke current steepness, the smaller the effect of the surge arresters.



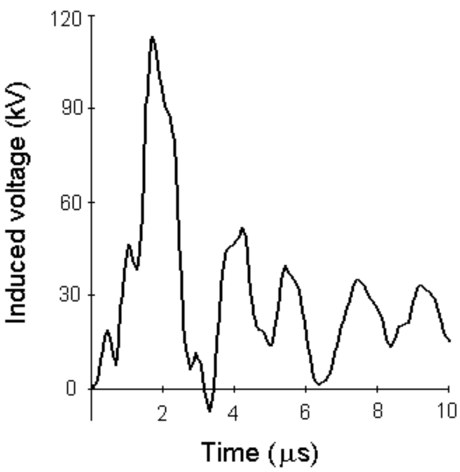

(a)



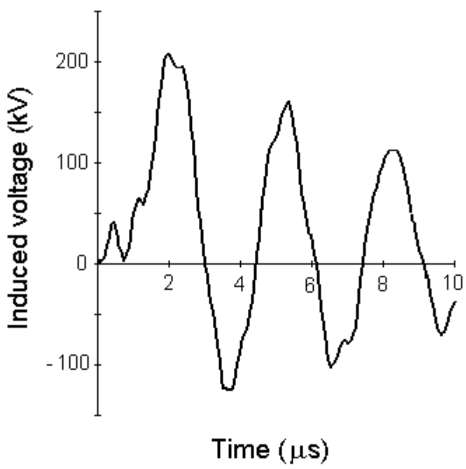

(b)

Fig. 12 – Induced voltages at the point closest to the lightning channel.- influence of the distance between adjacent surge arresters. Stroke location is 50 m from the line, $Rg$ = 50 Ω.
Curve 1: line without surge arresters; curve 2: arresters every 400 m; curve 3: arresters every 200 m.
a) $I$ = 50 kA, $tf$ = 3 μs, $v$ = 30 % $c$  b) $I$ = 15 kA, $tf$ = 0.5 μs, $v$ = 60 % $c$

Figure 13 presents experimental results obtained from measurements carried out on the scale model considering the more complex network configuration indicated in Figure 14. Two values were considered for the distances $s_e$ and $s_d$ between the transformer (measuring point) and the nearest set of arresters: $s_e$ = 75 m and $s_d$ = 75 m, and $s_e$ = 148 m and $s_d$ = 174 m. The line was three-phase and the neutral conductor was earthed at the middle of each lateral and at all points in which transformers or arresters were placed. The stroke current magnitude and front time were, respectively, 34 kA and 2 μs. The value of the earth resistance was 50 Ω except at the measuring point, where $Rg$ = 0 Ω. As expected, a significant difference is observed between the voltage amplitudes relative to the two situations.




(a)




(b)

Fig. 13 - Measured phase-to-earth induced voltages considering different distances between surge arresters and measuring point.
Stroke current: amplitude 34 kA, front time $tf$ = 2 μs. Test configuration shown in Figure 14.
a) $s_e$ = 75 m; $s_d$ = 75 m  b) $s_e$ = 148 m; $s_d$ = 174 m

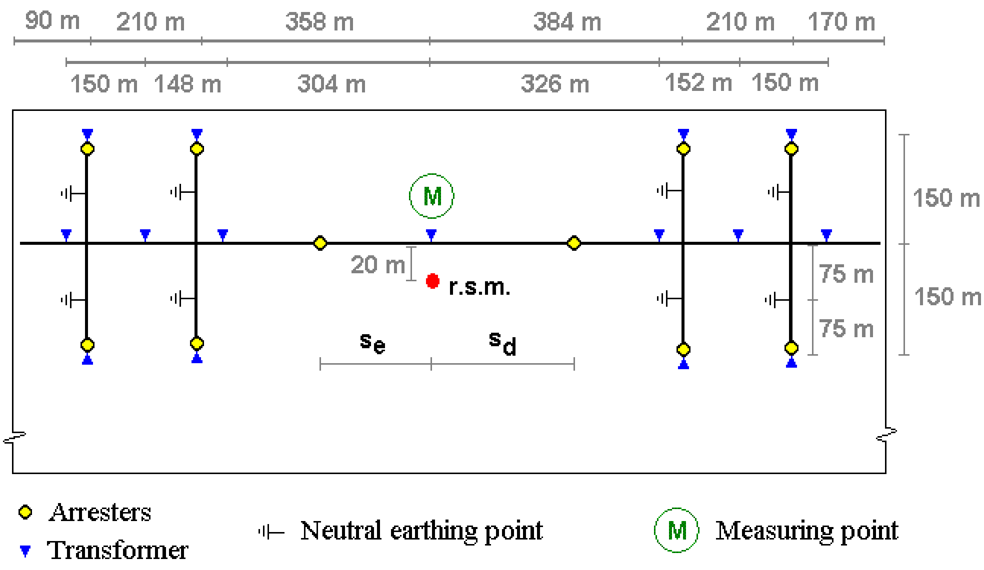


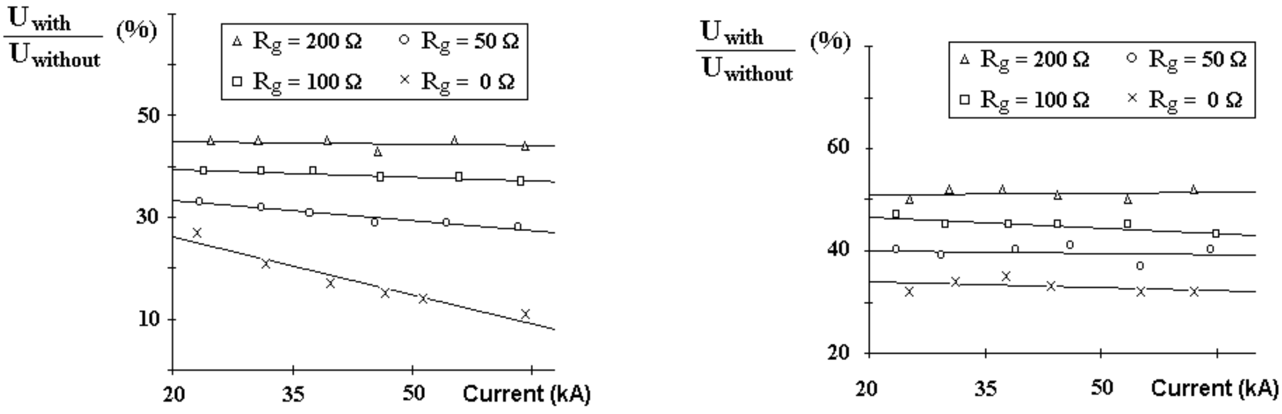

Fig. 14 – Test configuration related to the voltage waveforms presented in Figure 13. Neutral conductor grounded at the middle of each lateral and at all installation points of transformers and surge arresters; r.s.m.: stroke location.

Figure 15a illustrates the influence of the return stroke current magnitude on the ratio of the peak values of the induced voltages measured simultaneously on two distribution lines located at the same distance (70 m) from the strike point. One of the lines has no surge arresters, while the other has MO arresters added on the three phases every 300 m. The stroke current front time is about 3.2 µs and the voltages are measured, on each line, at the closest point to the stroke location. The results were obtained from the scale model [9], and the ratio between the peak values of the voltages induced on the lines with and without arresters $(U_{with}/U_{without})$ is presented for different values of *Rg*.

When the lightning strike point is located in front of a set of surge arresters, the ratio $U_{with}/U_{without}$ tends to decrease with the return-stroke current magnitude. This behaviour is more evident for low values of earth resistance, as for in these cases the voltage on the protected line (at the point closest to the stroke location) is very close to the voltage at the surge arrester terminals and varies little with the return stroke current peak, while the voltage on the line without arresters is directly proportional to the current. Figure 15a shows that, for *Rg* greater than 50 Ω, the influence of the return stroke current peak is not significant, i.e., the ratio between the peak values of the voltages induced on the lines with and without surge arresters practically does not depend on the current peak for currents with the same front time.

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 (i.e., the ratio $U_{with}/U_{without}$) in general does not depend significantly upon the return stroke current amplitude, as shown in Figure 15b. On the other hand, for currents with the same time variation rate *(dI/dt),* the front time increases with the current peak *I*, resulting in a larger reduction of the induced voltage amplitude, with respect to that of the unprotected line, as *I* increases.

The earth resistance may have a significant influence on the induced voltage amplitude, especially when the lightning strike point is in front of a set of arresters. This is due to the fact that, for lower values of *Rg*, the current that flows to 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, Figure 16 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 earth resistances of 0 Ω and 200 Ω.




(a) (b)

Fig. 15 - Ratio of the voltages induced on lines with and without MO surge arresters *($U_{with}/U_{without}$)* as a function of the stroke current magnitude (adapted from [9]). Stroke location is 70 m from the lines; *tf* = 3.2 µs; 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

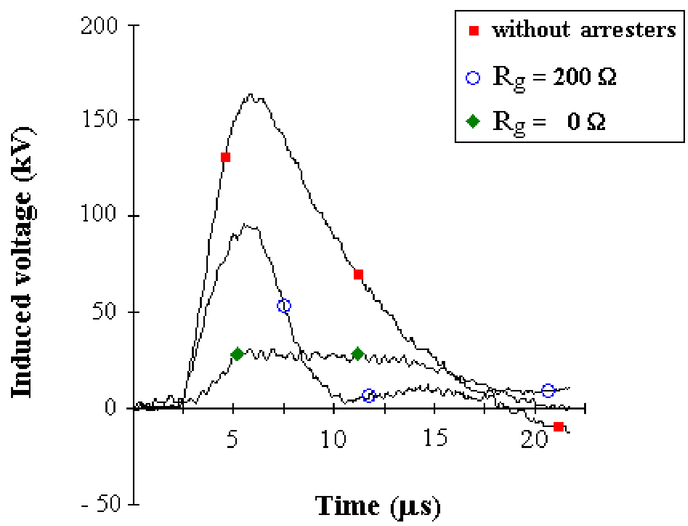



Fig. 16 - Voltages induced on lines with and without surge arresters. Lightning strike point is in front of a set of arresters, at a distance of 70 m from the line (adapted from [9]). *I* = 38 kA; *tf* = 3.2 µs; arrester spacing = 600 m.

In [9] the lightning performances of distribution lines with and without surge arresters are compared in terms of the average annual number of lightning induced voltages with magnitudes exceeding a given insulation level. The results refer to lines in open ground, and indicate clearly that the installation of surge arresters may improve the distribution line performance with respect to indirect strokes. Both for the first and subsequent strokes the time to crest was determined, in each event, from the ratio between the current magnitude and its rate of rise $TV_{5\%}$, which is defined as the current rate of rise between the instants corresponding to 30 % and 90 % of the first peak value whose probability of being exceeded is 5 %. This approach leads to conservative results. The current propagation velocity was assumed current dependent, although the existence of a relationship between these two parameters is not generally supported by experimental data, as pointed out by Rakov [66]. Regarding the relative position of the line and the lightning channel, the most critical situation, i.e., lightning strike point equidistant from two sets of surge arresters, was considered in the simulations, and this leads also to conservative results. On the other hand, earth was assumed as a perfectly conducting plane, an assumption that may lead to induced voltage magnitudes lower than those corresponding to situations where the finite ground conductivity is taken into account, as demonstrated by Borghetti *et al.* [67].

## 3 LV NETWORKS

The increasing application of sensitive electronic equipment and the increased awareness of issues concerning power quality have highlighted the importance of improving the lightning performance of LV networks, which are much more susceptible to lightning-caused disturbances than MV lines because of their lower withstand capability.

### *3.A Lightning Overvoltages*

Lightning transients on low-voltage networks can be produced by several mechanisms, which can be classified into the following categories:

- direct strikes to the LV system;
- cloud flashes;
- indirect strikes;
- transference from the medium voltage system.

#### *3.A.1. Direct Strokes*

If a flash hits a LV line, multiple flashovers occur and a rough estimation of the overvoltage can be obtained, if the propagation effects are disregarded, by multiplying the stroke current by the equivalent earth impedance. However, even in the case of a low value for the effective impedance, voltages much larger then the line lightning impulse withstand level would result, which would lead to further flashovers.

In general, low-voltage networks are not that prone to direct strikes due to their relatively short lengths and to the shielding provided by the MV line, trees and nearby structures. However, in some rural and semi-urban areas, exposed LV lines longer than 1000 m do exist, and in case of direct lightning hits, the resulting overvoltages can damage unprotected connected equipment.

A direct strike to the lightning protection system or to other parts of an end-user building causes an earth potential rise that may lead to the operation of surge protective devices or to flashovers between the structure and the line conductors. In both situations a portion of the stroke current is injected into the power line, producing overvoltages that propagate along the network. This portion depends mainly on the relative impedance of the line with respect to the impedances of all the other possible current paths (local earth, metallic pipes and other services such as telecommunications lines). Figure 17 illustrates the situation, showing a case in which 50 % of the stroke current enters the earth termination system and 50 % is distributed evenly among the services entering the structure.

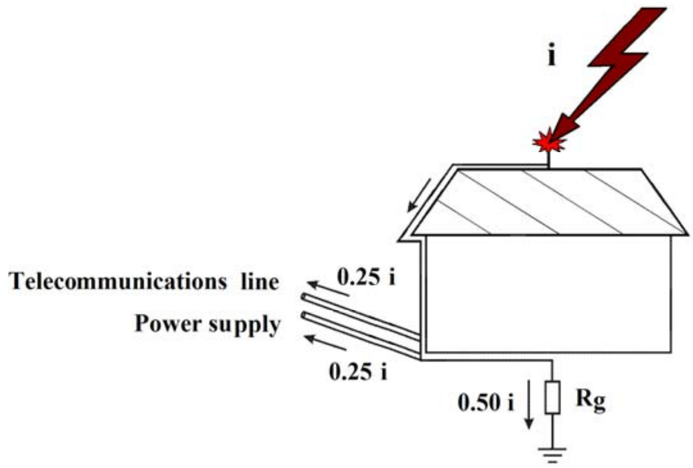



Fig. 17 - Injection of surges into the low-voltage power line due to a direct strike to an end-user installation. The current division depends on the relative impedances of the all possible current paths.

#### *3.A.2. Cloud Flashes*

Cloud discharges, which include intracloud, cloud-to-cloud, and cloud-to-air flashes, last typically between 200 ms and 500 ms [68] and are the most frequent type of discharges, representing about 75 % of the global lightning activity [66, 69]. Nevertheless, the number of studies conducted about this phenomenon is relatively scarce in comparison with that bearing on cloud-to-ground flashes, which have a much greater impact in terms of deleterious effects. The main practical interest in cloud flashes lies in the protection of aircraft and space craft, although the short interval between the associated induced voltage pulses may cause degradation, damage, and failure of electronic components of sensitive apparatus connected to the low-voltage power supply.

The voltages induced on complex low-voltage power installations by cloud (IC) and cloud-to-ground (CG) discharges have been studied in [70 - 73]. The investigation carried out by Galván *et al.* [70] refers to two small networks isolated from the power supply. Simultaneous measurements of the incident vertical lightning electromagnetic fields and the corresponding induced voltages across a 50 Ω resistor connected between one of the phase conductors and earth were performed. The technique proposed by the authors uses these measurements to extract the transient response of the power installation, irrespective of its complexity. The peak-to-peak values of the four voltages induced by cloud flashes shown in the paper are below 2 V, and in all cases a relatively good agreement was found between measured and calculated results.

The experimental study conducted by Silfverskiöld et al. [71] compares the amplitudes of the common-mode voltages induced on a residential installation in the complete duration of typical CG (negative and positive) and IC flashes. The installation was disconnected from the power distribution line. The measurements of the vertical component of the electric field and the corresponding induced voltages on the power installation showed that the discharge events that take place inside the cloud, preceding CG and IC flashes, give rise to bipolar pulses with very fast rise time. The pulse trains associated with such processes may induce voltages with magnitudes of the same order of (and even higher than) those induced by the return stroke itself. These events are therefore important and should be taken into account in the evaluation of the interference problems caused by lightning electromagnetic pulses (LEMP). From the analysis of the obtained results the authors estimate, from a typical lightning within a distance of a few kilometers from the low-voltage power installation network, a few tens of induced voltage pulses exceeding 400 V peak-to-peak.

A further investigation of the transient response of low-voltage power installations to lightning electric fields was performed by Galván and Cooray in [72], where comparisons between measured and calculated induced voltages using the measured lightning electric field (both inside and outside the installation) as the driving source are also presented. The amplitudes and waveforms of the induced voltages were found to be highly dependent on the soil resistivity and on the loads connected to the low-voltage power installation. In [73] Galván *et al.* apply the technique proposed in [70] to a simple circuit and to a complex wiring system. Comparisons between measured and simulated induced voltages, presented for both systems, are in good agreement. Discussions are provided on the advantages and limitations of the method, which represents an useful tool for evaluating induced voltages in electrical installations with linear behaviour.

Voltages induced by cloud discharges at both open-circuited terminations of an unenergized 460 m long distribution line, together with the corresponding electric fields, are reported by Rubinstein and Uman [74]. The line consisted of two conductors arranged in a vertical configuration, and the peak-to-peak voltages induced at the top conductor by a flash at an altitude greater than about 5 km were around 140 V.

Even though further investigations are necessary to better characterise the voltages induced by cloud discharges as well as the significance of their effects on sensitive loads, protection measures against the more severe types of lightning surges are likely to be effective against such transients.

### *3.A.3. Indirect Strikes*

When lightning strikes the earth or an object in the vicinity of a distribution network, the voltages that arise on the low-voltage conductors may be subdivided as follows:

- voltages induced "directly", due to the electromagnetic coupling between the line and the stroke channel;
- voltages associated with the part of the stroke current that is intercepted by the earthing points of the neutral conductor;
- voltages transferred from the MV line.

From experiments performed at Camp Blanding using the rocket-and-wire technique to trigger lightning, Rakov and Uman [75] and Fernandez *et al.* [76] showed that when the strike point is at tens of meters from the line, an appreciable fraction of the total current enters the system from the neutral earth connections. In three cases reported in [75], in which the distances between the line and the strike point were 60 m, 40 m and 19 m, the observed peak values of the currents entering the system from its earth connections were, respectively, 10 %, 5 %, and 18 % of the stroke current peak.

The voltages "directly" induced are in general the most important on account of their severity and frequency of occurrence. However, although the number of studies conducted in this field has been increasing consistently [16, 56, 77 - 84], there is still a stark contrast to that of MV lines, to which much more attention has been given in the past.

The analysis carried out by Hoidalen in [78] made use of the Agrawal et al. coupling model [54] for the calculation of lightning induced voltages on low-voltage systems. From frequency response measurements, simple models were proposed for the input impedances of typical distribution transformers and low-voltage power installations, and their influences upon the lightning induced voltages on simple TN and IT systems were investigated. The line considered in the simulations was 500 m long and the phase conductors were simulated by a single wire with characteristic impedance of 300 Ω. In one end there was a transformer, modelled as an inductance of 10 μH, while an impedance representing the power installation was connected at the other termination. The voltage magnitudes were found to have a high dependence on the load, the lowest values being associated with larger installations. A comprehensive investigation was conducted by Hoidalen in [77], where the effect of the finite earth conductivity on the induced voltages on TN and IT systems is thoroughly discussed.

In [16, 80] the authors concluded that the induced voltages are characterised by a high frequency damped oscillation with a period equal to twice the travel time of a span (portion of the line between two adjacent neutral earthings). The simulations were done with the LIOV-EMTP code [7, 26, 37], which is based upon the Agrawal et al. coupling model, and considered overhead cables with two or four twisted conductors, with neutral earthing spacing in the range of 250 m to 400 m. Due to the high transient electromagnetic coupling between the conductors, for the configuration examined the wire-to-wire voltages were disregarded and line-to-earth voltages, assumed to be the same on the different conductors, were presented.

The influences of various parameters on the lightning induced voltages were evaluated by Piantini and Janiszewski [81] for the case of a 300 m long, single-phase line. In [82], a line with twisted conductors was considered. The main difference between the bunched cable and the open wire configuration is that the former is characterised by a stronger coupling between the wires, that are much closer. The greater the mutual surge impedance between the neutral and phase conductors, the smaller the induced voltage magnitudes. If the conductors are twisted, this impedance varies along the line. However, as the distance between the wires is much smaller than their heights above ground, the variation is small and for practical cases it can be neglected. The simulations, performed using the ERM [49 - 51], showed that the induced voltages have a great impact on the lightning performance of low-voltage distribution lines.

Measurements performed by Hoidalen [83] in Norway, where the ground flash density is mostly below 1 / (km$^2$.year), show that more than 1000 voltages above 500 V should be expected per year in a typical rural low-voltage overhead line with isolated neutral. Voltages up to 5 kV were recorded, and according to the study, overvoltages can be induced by strokes more than 20 km away from the line.

Rocket triggered lightning experiments with simultaneous measurements of induced voltages on a 210 m long overhead LV line with twisted conductors are reported by Clement and Michaud [84]. The line was connected to a transformer at one of the ends, and to a 60 m long underground cable, terminated by LV arresters, at the other. The stroke location was either on a tower close to the underground cable termination or on the firing area, 50 m away from this point. The induced voltages were measured at the low-voltage transformer terminals for a total of 12 launchings. The stroke currents varied in amplitude from 4 kA to 50 kA, and the corresponding phase-to-earth and neutral-to-earth voltages reached maximum values in the range of 2 kV to 12 kV.

The analysis of the characteristics of such surges is of great importance, since they have a high frequency of occurrence and can often reach large magnitudes. The severity of the induced voltages depends on many lightning parameters and is also substantially affected by the network configuration.

### *3.A.4. Transference from the MV system*

Lightning overvoltages on the low-voltage network can be originated from the primary circuit either in the case of a direct hit or a nearby stroke. In both situations the transformer plays an important role in the transference mechanism.

Direct strikes to the primary circuit produce overvoltages on the LV network due to transference from the distribution transformer and to injection of current into the neutral conductor. The latter is a consequence of the earth potential rise caused by the flow of current through the earth resistance following the operation of MV surge arresters and the occurrence of flashovers across the MV insulators. The transferred voltages may vary widely depending on the strike and observation points, stroke current magnitude and waveform, and line configuration.

The overvoltages that result on a typical low-voltage distribution network in the case of direct lightning hits on the primary line were studied in [16, 85 - 88]. A typical distribution network was considered in [85] and the voltages at different points of the LV line were calculated in order to study the basic characteristics of the transferred surges for the case of direct strokes to the MV line. The simulations were performed with the Alternative Transients Program (ATP) [89], and flashovers across the MV and LV insulators were taken into account according to the "Disruptive Index Model" [90]. It was shown that a correct representation of the distribution transformer is essential and that the well-known purely capacitive PI-circuit is generally not adequate for the evaluation of transferred surges. The simulations showed also that voltage magnitudes of some tens of kilovolts may occur at the transformer LV terminals and at the consumers' entrances in the absence of surge protective devices.

The influences of the stroke current magnitude and front time, earth resistance and number of low-voltage power installations on the voltages transferred to the LV network were discussed in [86]. The results showed that the flashovers that take place across medium and low-voltage insulators affect significantly the magnitudes and waveforms of the transferred voltages and thus should always be taken into account. In most of the cases the larger phase-to-neutral voltages occur at the transformer terminals. The voltages are characterised by oscillations originated from the various reflections throughout the secondary network and therefore are strongly affected by the spacing between adjacent earthing points. The effect of the earth resistance of the neutral conductor on the phase-to-neutral voltages is greater than that of the earth resistance at the consumers' entrances. For a given line, the general trend of the phase-to-neutral voltage magnitudes is to decrease with the number of consumers.

In general, the shorter the distance between the transformer and the lightning strike point, the higher the transferred voltages. However, the insulator flashovers tend to diminish this effect. In [87], the low-voltage power installations were represented as pure inductances, resistances or capacitances, and were connected to the LV network through 20 m long service drops. The reflections that occur at both terminations of the service drops led, in the situations considered, to a decrease of the phase-to-neutral voltages at the transformer terminals when the values of the load impedance increased. At intermediate points and at the line terminations the voltage amplitudes may increase or decrease with the load impedance, depending on the magnitudes of the reflected waves at the various discontinuity points. Concerning the line configuration, the results obtained in [91] showed that the overvoltages are usually much larger in the open wire line in comparison with the bunched cable, and that the energy dissipated in the power installations may be, in some cases, ten times higher.

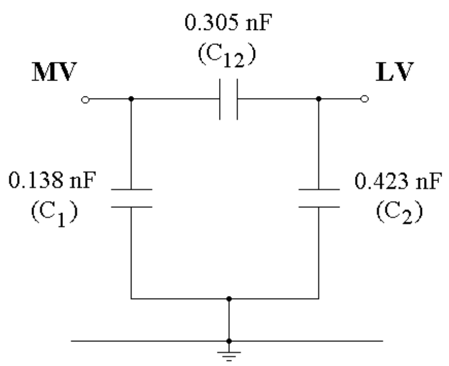
The assessment of the voltages transferred from the MV line due to lightning strikes in the vicinity of the distribution network requires the knowledge of the transformer high frequency behaviour, as well as the voltages induced at the primary side. This subject is discussed in [92 - 94] for the case of unloaded transformers, while the presence of the low-voltage line is considered in [56, 95].

A suitable transformer model is essential for the evaluation of transferred surges. In the well-known purely capacitive PI-circuit, the transformer is represented by the capacitances C1 (between primary and earth), C2 (between secondary and earth), and C12 (between primary and secondary). This circuit, however, is not adequate for evaluating transferred surges, as it greatly overestimates the overvoltages. This is illustrated in Figure 18, which presents the measured and calculated voltages transferred to the secondary (in open circuit) of a typical distribution transformer (rated power 30 kVA, 13.8 kV – 220 / 127 V, delta - earthed wye connected) when a standard 1.2/50 μs impulse voltage of 1.7 kV is applied to the primary terminals short-circuited. The measured values corresponding to the 30 kVA transformer are C1 = 0.138 nF, C2 = 0.423 nF, and C12 = 0.305 nF, and its equivalent PI-circuit is depicted in Figure 18a. For comparison purposes, the voltage calculated using the model presented in [96] is also shown. The absolute value of the ratio between the peak values of the measured and calculated - using the PI-circuit - voltages is 17.5 (40 V against 700 V). It can be readily seen that not only the magnitudes, but also the voltage waveforms differ considerably.

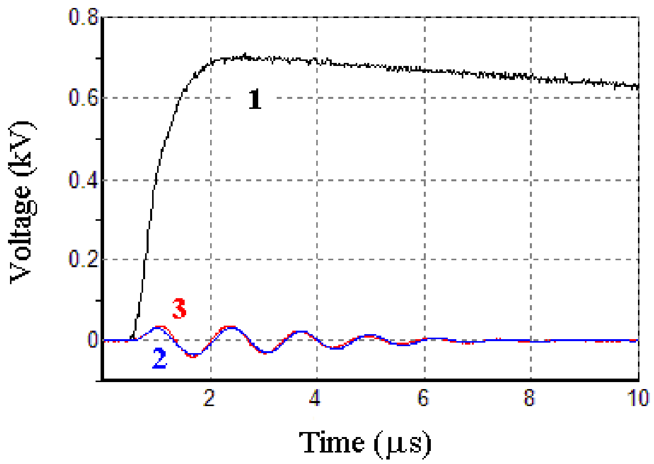
In realistic situations, the voltages transferred to the secondary terminals oscillate with a frequency governed by the transformer transient response and by the configuration of the LV network, with the distance between adjacent loads playing a major role. Even though on the primary side voltages of higher magnitudes may be induced by first strokes, the larger transferred voltages are usually associated with the subsequent strokes. The reason is that the voltages induced by the subsequent strokes have steeper fronts and, thus, broader frequency spectra. The difference between the magnitudes of the voltages at the LV transformer terminals is much less than that at the primary side.

As an example, Figure 19 presents the phase-to-neutral voltages at the transformer terminals, both with and without surge arresters at the MV side, considering a typical subsequent stroke current of 12 kA whose waveform is obtained by the sum of two Heidler functions [64] with the following parameters: $I_{01}$ = 10.7 kA, $\tau_{11}$ = 0.25 μs, $\tau_{12}$ = 2.5 μs, $I_{02}$ = 6.5 kA, $\tau_{12}$ = 2.1 μs, $\tau_{22}$ = 230 μs, and $n_1 = n_2 = 2$. The lightning channel is vertical, 4 km long, has no branches and is modelled according to the Transmission Line (TL) model [58]. The current propagation velocity is assumed to be 60 % of that of light in free space and the stroke location is in front of the transformer, 50 m from the LV line. The LV line is three-phase, lossless, 1000 m long, and the heights of the phase and neutral conductors are, respectively, 6.5 m and 6.48 m. Its configuration is depicted in Figure 20. No coupling is considered between the primary and secondary circuits, and earth is assumed as a perfectly conducting plane.

The transformer is represented by the model developed in [96], while the input impedance of the power installations seen from the line are simulated according to the circuit obtained in [78] for a typical installation in the TN system. The distance between adjacent neutral earthings is 200 m. The low-voltage power installations are close to the line and, thus, in Figure 20b each impedance formed by an inductance of 7 µH in series with a resistance of 20 Ω corresponds to the equivalent impedance of the earth connections of the neutral and of the closest consumer's installation. In this way, each equivalent impedance takes into account the inductances of the earth lead and of the service drop, as well as the earth resistances at that neutral earthing point and at the closest service entrance.

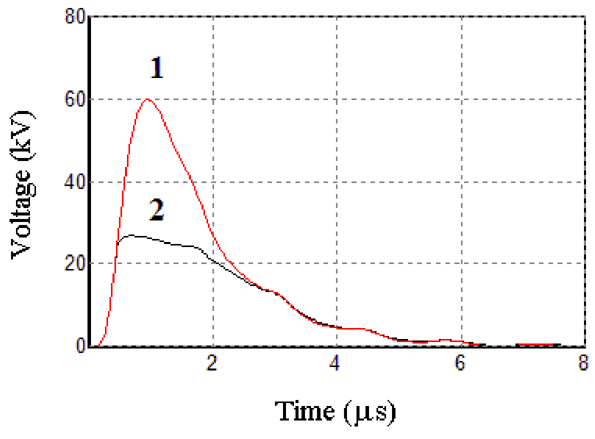



(a)

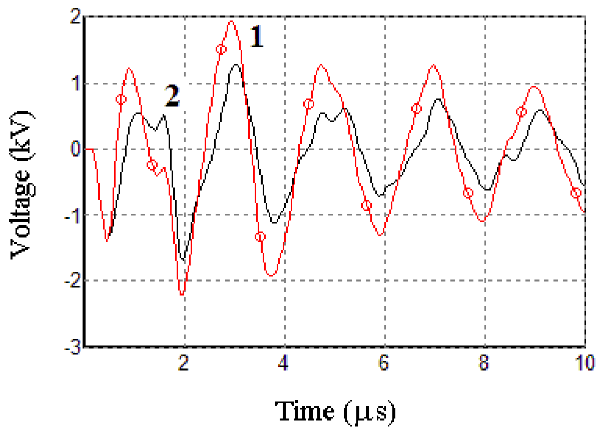



(b)

Fig. 18 - Equivalent capacitive PI-circuit and comparison of measured and calculated phase-to-neutral voltages transferred to the secondary of a 30 kVA distribution transformer, in the no-load condition, for a standard 1.2/50 µs impulse voltage of 1.7 kV applied to the primary terminals short-circuited.
a) equivalent capacitive PI-circuit
b) transferred voltages (curve 1: capacitive PI-circuit; curve 2: model presented in [96]; curve 3: measured)

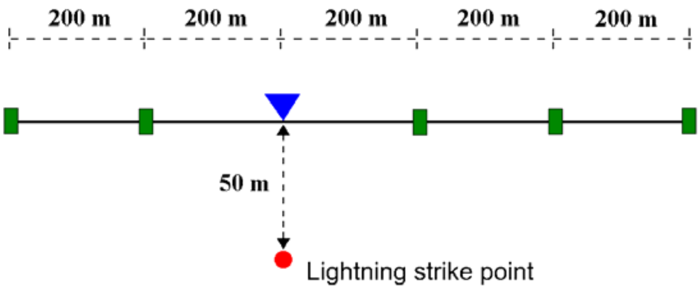



(a)

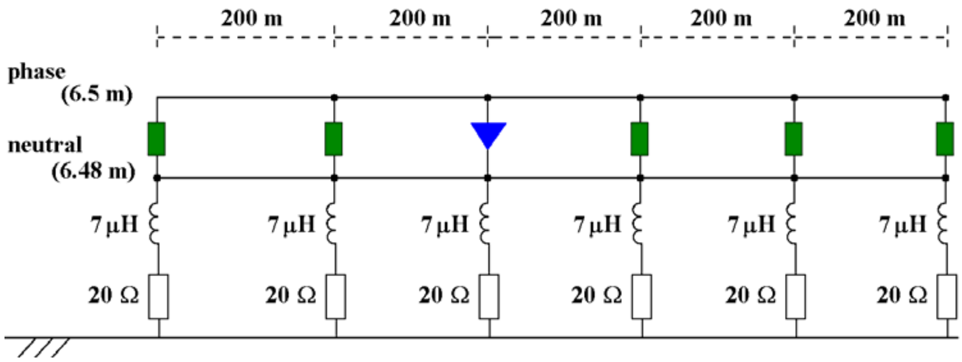



(b)

Fig. 19 - Phase-to-neutral voltages at the transformer terminals considering a typical subsequent stroke current of 12 kA. Stroke location in front of the transformer, at a distance of 50 m from the LV line (configuration depicted in Figure 20).
Curve 1: without MV surge arresters; curve 2: with MV surge arresters.
a) induced voltages at the MV side
b) transferred voltages to the LV side




(a)




(b)

Fig. 20 - Low-voltage line configuration considered in the simulations presented in Figure 19. The triangles and the rectangles denote, respectively, the distribution transformer and the low-voltage power installations.
a) top view b) side view

### *3.B Lightning Protection of LV Networks*

The overvoltages stemmed from lightning have often high magnitudes and are usually the major cause of failures or damage to transformers and consumers' electric appliances, especially in the case of lines characterised by poor pole earthing conditions and located in regions with high lightning incidence.

A fault on a transformer is always sustained and the corresponding costs are related to the repair or replacement of the equipment and to the service interruption. Protection measures such as the application of secondary arresters and the reduction of the earth resistance at the transformer pole can improve the lightning performance of LV networks. However, although there has been an increasing awareness of the effectiveness of the application of low-voltage arresters, this practice has not been widespread among electric utilities. With a few exceptions, e.g. [97], this measure is usually taken only to meet cases where the action – mainly for improving the earth connections - did not give satisfactory results [84] or to solve recurrent problems. This is in fact an economic issue, a trade-off between the lightning costs and the investment in the protection scheme. The failure rate of the surge protective devices has also to be considered in the cost-benefit analysis. However, even without taking into account the costs of damages to consumers' equipment, their application to transformer secondaries can be justified in areas with high lightning damage rates, as pointed out by Darveniza [98] and by Dugan *et al.* [99].

Gapless secondary arresters of the metal oxide varistor (MOV) type are the most appropriate to protect the LV network. The impact, on the lightning overvoltages, of the application of such devices to the transformer and service entrances will be discussed in this Section.

#### *3.B.1. Distribution Transformers*

Although several factors can cause distribution transformers to fail, in lightning-prone regions failure rates can be more than twice the norm, which is typically between 0.8 % to 1.5 % for non-interlaced and 0.4 % to 0.7 % for interlaced transformers [100]. Most of the additional failures may be due to current surges in the low-voltage windings [101]. These surges can be created whenever a significant portion of the stroke current is injected into the neutral between the transformer and the power installations. The problems related to the so called "low-voltage side surges" or "secondary side surges" have been discussed in [99 – 104].

Let us consider the case of a direct strike to the primary line, as illustrated in Figure 21. The MV arrester discharge current splits so that one portion flows through the pole earth lead and another is injected into the neutral conductor. The division of the bulk of the stroke current is determined by the earth resistances, but in the beginning of the transient it is highly dependent on the ratio between the inductances of the two paths. Therefore, as the path to the pole earth is shorter and the corresponding inductance is lower, initially a greater portion of the current flows through the transformer earth lead. After a few microseconds, when the current time derivative becomes smaller, the influence of the inductances decreases and the division is controlled by the resistances. The lower the earth resistance of the service entrance in comparison with that of the transformer pole, the larger the magnitude of the surge current that enters the neutral and the worse the problem.

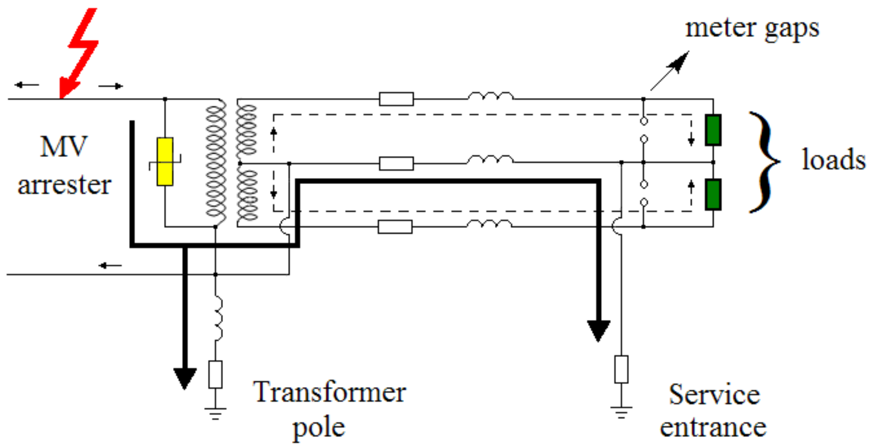



Fig. 21 - Injection of current into the neutral due to a direct strike to the MV line.

The voltage drop across the neutral, produced by the surge current, gives rise to equal currents in the two phase conductors - if the configuration is symmetric -, which can damage loads and cause meter gaps to flash over. These currents flow through the transformer secondary, as indicated in Figure 21, and induce a surge voltage in the primary which can cause part of the winding to short out. This would change the transformer ratio and subject the load to sustained overvoltages, resulting in damage to consumers' equipment. The surge voltage can also cause a layer-to-layer insulation breakdown and a subsequent transformer failure and power outage. As pointed out by Dugan *et al.* [99], the surge voltage distribution inside the transformer is such that the primary arrester has little effect on the prevention of this failure.

Although for the symmetric configuration the surge current divides equally into the secondary windings, there is a significant, equal and opposite voltage induced in each half of the MV winding so that the net voltage across the primary terminals is nearly zero. The magnitude of this induced voltage is approximately proportional to the voltage across the secondary windings, and it can be estimated reasonably well by considering only the inductances [99]. Hence, transformers with lower secondary impedances have a better performance against this type of surge. This is the case when the secondary windings are interlaced, as in this condition the impedance at surge frequencies is about a tenth that of non-interlaced transformers [100].

On the other hand, interlacing the secondary windings is not effective to solve the problem in the case of unbalanced surges, i.e., when the currents through the secondary windings are not equal. This situation happens, for instance, if flashover or arrester operation occurs on only one side of a service. According to Marz and Mendis [100], up to half of all interlaced transformer failures may be due to secondary side surges. A better solution involves the application of low-voltage arresters to the transformers, as in this case protection is provided against both balanced and unbalanced surges, regardless of winding connection.

The situation illustrated in Figure 21 refers to just one power installation connected to the LV line. In the case of multiple services from the transformer, a lower voltage drop will develop across the neutral and therefore less current will be forced into the secondary transformer terminals. The stresses on both the transformer and the consumers' loads will then be reduced in comparison with the single service case. On the other hand, multiple services mean higher line lightning exposure and a possible increase in the number of surges may counteract this effect.

Longer lengths of the LV circuit lead to greater voltage drops and consequently to current surges of higher magnitudes impressed on the transformer secondaries. This voltage increase is however not linear, as the ratio of resistance to inductance of the entire circuit generally increases, changing the dynamic response of the circuit and reducing the rate of rise of the surge currents [101].

Comparisons between surge currents in secondary windings for three types of cable, namely the open wire, triplex, and shielded, are presented in [104]. The best results, i.e., the lower currents, are obtained with the shielded cable. Due to the greater spacing between conductors and lower mutual coupling between wires, an open wire line has higher inductance than a triplex cable of the same length, and therefore a larger net voltage develops across the neutral, causing a surge current of higher magnitude to flow in the transformer and consumers' loads.

Long-term studies performed by Darveniza and Mercer [97] led to an improved lightning protection scheme for exposed pole mounted transformers in Australia. The protection measures consisted in the relocation of primary surge arresters close to the terminals and in the fitting of secondary arresters. The lightning damage rates decreased from about 2 to 0.3 per 100 transformers per year after the implementation of the protection system [98], and the authors attribute this reduction mainly to the installation of secondary arresters.

It is important to note that protecting the transformer by means of interlaced secondaries or low-voltage arresters results in larger surge currents, as both measures provide a low impedance for the surge. As a consequence, customers' devices may be subjected to higher voltage stresses.

Concerning the transformer LV arrester, discharge levels of 2 kV to 5 kV are considered adequate. Although the lightning impulse withstand level of a transformer secondary is typically in the range of 20 kV to 30 kV, insulation degradation may be caused by overloading, so that lower protective levels may be beneficial. Secondary arrester classes between 175 V and 650 V are in principle suitable, but 440 V or 480 V arresters have some advantages over both the limits. They have better coordination with the primary arrester than 175 V arresters, which are susceptible to thermal failures caused by switching events [100, 101, 103], and have a lower discharge voltage than a 650 V arrester, thus reducing the risk of damage to sensitive consumers' devices.

As pointed up by Dugan *et al.* [99], the LV transformer arresters must not substitute one type of failure for another and should be designed so that the possibility of failure is remote. Although the magnitude of a typical secondary current surge may be less than 1 kA, the arresters should have a current discharge capability of at least half of that for a standard distribution class arrester, i.e., in the range of 20 kA to 40 kA.

In the simulations performed in the next section, the transformer is protected with 440 V secondary gapless MOV arresters, whose equivalent circuit is a capacitance of 780 pF in parallel with a non-linear resistor with the V/I characteristic depicted in Figure 22. The inductance of the connecting leads is disregarded.

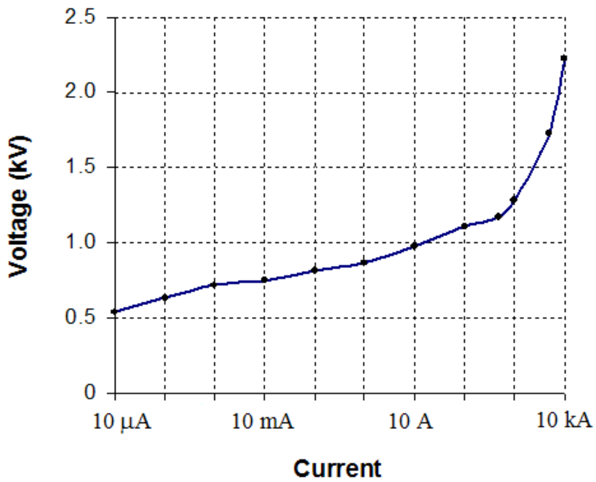



Fig. 22 - V/I characteristic of the secondary MOV arresters.

### *3.B.2. Low-voltage Power Installations*

The characteristics of the lightning overvoltages on the secondary network depend on a number of parameters, but in general those induced by nearby strokes or transferred from the medium voltage line due to direct strikes to the primary conductors play a more significant role in the network performance. These overvoltages may have a damaging effect on the customers' loads, and the use of properly coordinated surge protective devices at the service entrance and at susceptible equipment is recommended especially in regions with high lightning incidence.

The arresters applied at the service entrance should be similar in rating to the transformer arrester and have a discharge voltage of less than 2 kV. This level, which is already too high for sensitive electronic equipment, may be much higher within the installation due to voltage oscillations caused by reflections at various points. Therefore, local protection is required for such loads.

The arresters at the service entrance should have higher energy handling capability than those placed at internal parts of the premises - sometimes referred to as "suppressors" - and divert the bulk of the surge current. None of the protective devices should be overloaded, and this is the concept of arrester coordination. Besides the energy absorption capability, the clamping voltages and the distances between the secondary arresters and the suppressors should also be considered for achieving a successful coordination. This topic is specifically addressed in [105 – 109], and guidelines for installing surge protective devices are given in [110].

In order to evaluate how the overvoltages induced at the service entrances by indirect strokes are affected by the application of secondary arresters, the following line configurations, indicated in Figure 23, will be considered:

1) arresters not installed (configuration 1);
2) arresters only at the transformer terminals (configuration 2);
3) arresters at the transformer terminals and at all service entrances, excepting at Point 4 (configuration 3).

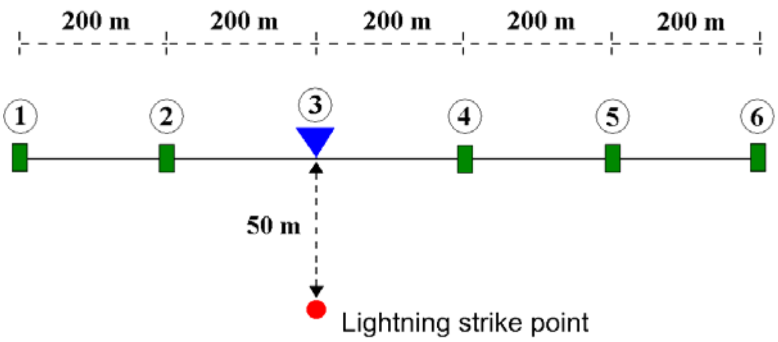



Fig. 23 - Low-voltage line configurations. The triangle and the rectangles denote, respectively, the distribution transformer and the low-voltage power installations. Configuration 1: line without arresters; configuration 2: arresters only at Point 3; configuration 3: arresters at points 1, 2, 3, 5, and 6.

The arresters at the service entrances and at the transformer are assumed to have the same characteristics. The three-phase line is represented by an equivalent single conductor, so that the corresponding arrester capacitance to be considered in the simulations is 2.34 nF. Likewise, the values of currents in the horizontal axis of Figure 22 should be multiplied by 3. The transformer input impedance is simulated by a simple inductance of 16 μH, which corresponds to the inductance of the equivalent single-phase model of the 30 kVA transformer considered in [96]. Due to the presence of the secondary arresters at its LV terminals, the transformer model does not drastically influence the results.

The circuit adopted in Section 3.A.4 to represent the impedance seen by the power line at the service entrances is typical of a relatively large power installation [78]. The equivalent load impedance has been shown to significantly affect the induced voltages, larger impedances leading to higher voltages. A more conservative condition is considered henceforth, and the loads, in the TN system, are simulated by just an inductance of 10 μH, which is representative of smaller installations [77]. The other parameters remain the same as in Section 3.A.4.

The most critical situation, from the point of view of a power installation, is that in which the stroke location is in front of it. This case is illustrated in Figure 24, in which the phase-to-neutral induced voltages at Point 4, relative to the line configurations 1 and 2, are compared. The results refer to the subsequent stroke, which induces considerably higher voltages than the first stroke for typical secondary line configurations. If the stroke location is in front of an unprotected service entrance, the presence of arresters at other points of the line will not be effective in reducing the induced voltage magnitude at that point. For the situation considered, the induced voltage peak value is about twice the recommended protective level of 2 kV.

A more favourable situation occurs when the lightning strike point is in front of the transformer, as indicated in Figure 23. The phase-to-neutral voltages induced by the subsequent stroke at points 2, 3, 4, and 5 are presented in Figure 25 for the line configuration 2, which corresponds to arresters installed only at the transformer terminals. In this case all the voltage magnitudes are lower than 2 kV.

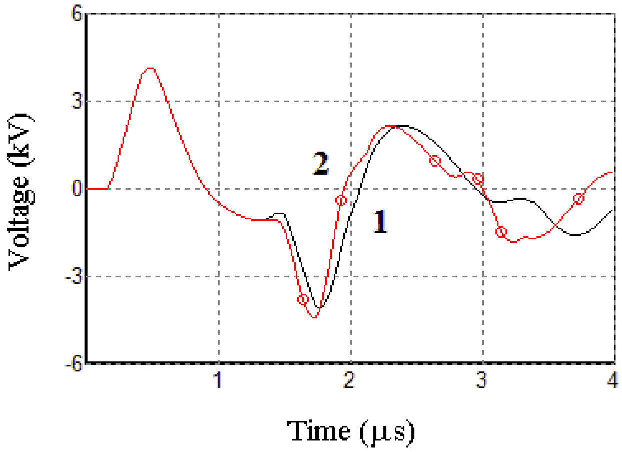
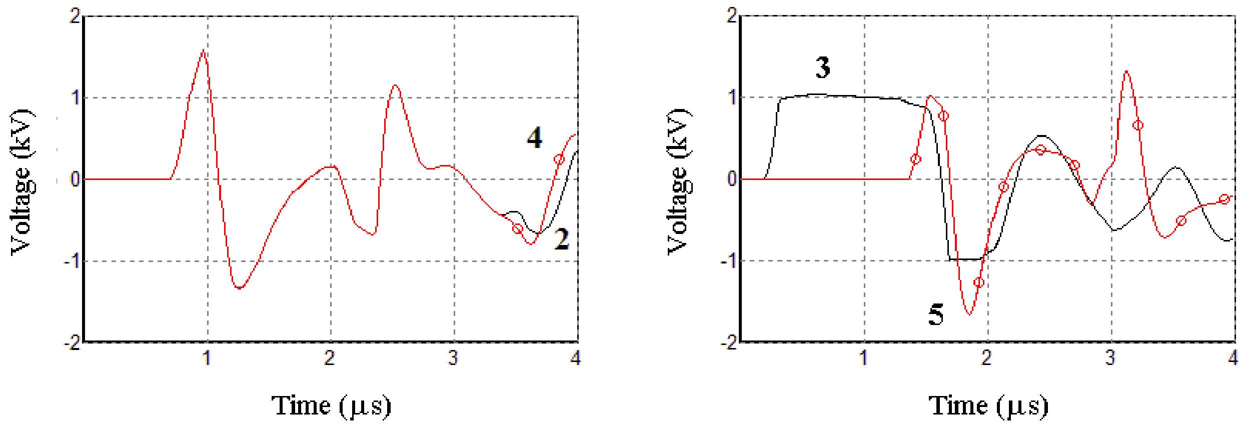



Fig. 24 - Phase-to-neutral induced voltages at Point 4 of Figure 23 when the stroke location is in front of it, at a distance of 50 m. $I$ = 12 kA. Curve 1: configuration 1; curve 2: configuration 2.



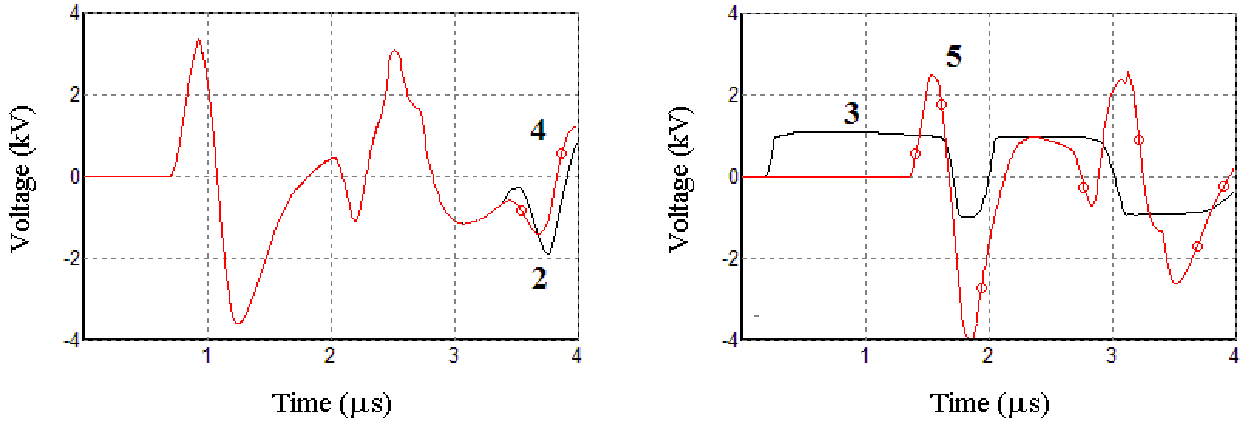

(a) (b)

Fig. 25 - Phase-to-neutral induced voltages at points 2, 3, 4, and 5 of Figure 23 considering a typical subsequent stroke current ($I$ = 12 kA). Configuration 2 (arresters only at the transformer terminals).
a) Points 2 (curve 2) and 4 (curve 4) b) Points 3 (curve 3) and 5 (curve 5)

Let us now consider a more severe condition, in which the subsequent stroke current has the same waveform, but its magnitude is 29.2 kA. This value has a probability of only 5 % of being exceeded [59], and the corresponding maximum time derivative is about 120 kA/µs. Figure 26 shows the voltages induced at points 2, 3, 4, and 5. In this case, the level of 2 kV is exceeded at all the service entrances.

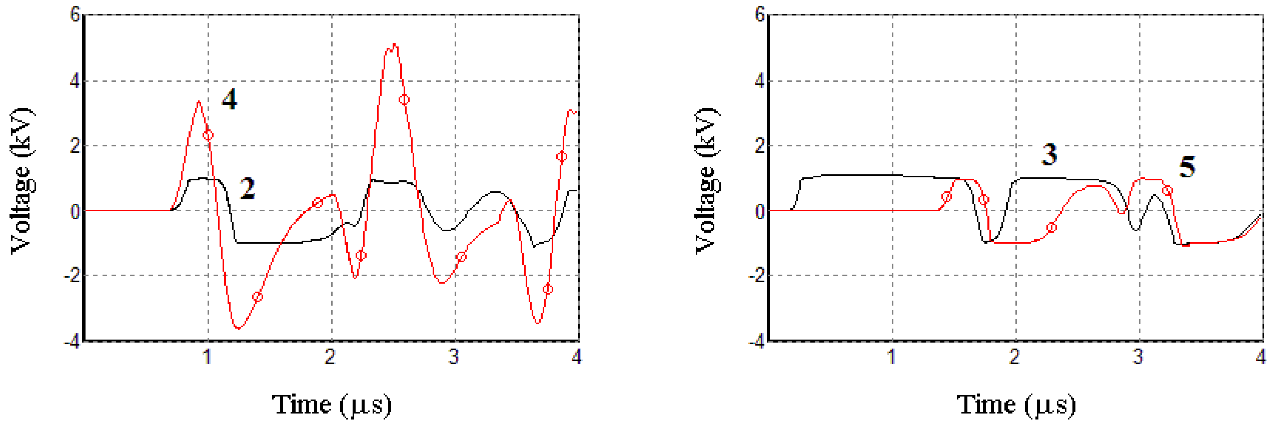
The application of secondary arresters to a power installation can effectively reduce the local overvoltages to acceptable limits. However, in some circumstances this may result in higher voltage stresses at unprotected premises. This situation is illustrated in Figure 27, which depicts the phase-to-neutral induced voltages corresponding to the line configuration 3. At all service entrances, with the exception of the unprotected one (Point 4), the voltages are kept below approximately 1.1 kV. A comparison of Figures 27a and 26a shows that the voltage magnitude at Point 4 is indeed larger than that relative to configuration 2 (5 kV against 3.5 kV), in which the arresters were placed just at the transformer terminals. For the network configuration 3 and the "severe" subsequent stroke current considered, only when the distance between the line and the stroke location is greater than 200 m the peak voltage at Point 4 will be lower than 2 kV. Thus, in order to protect low-voltage power installations against lightning overvoltages, properly rated and coordinated surge protective devices should be installed at all service entrances.

In comparison with TN systems, IT systems are in general subject to much larger induced voltages and are also far more affected by the finite earth conductivity. A meticulous analysis of this topic is presented by Hoidalen in [77]. Higher values of the soil resistivity usually lead to larger voltage magnitudes, particularly in the case of IT systems. On the other hand, as the voltage front time, which has a remarkable influence on the effectiveness of the surge protective devices, also increases, the net result may be, in some cases, a decrease of the voltage magnitude.




(a) (b)

Fig. 26 - Phase-to-neutral induced voltages at points 2, 3, 4, and 5 of Figure 23 considering a subsequent stroke current with amplitude $I = 29.2$ kA. Configuration 2 (arresters only at the transformer terminals).
a) Points 2 (curve 2) and 4 (curve 4) b) Points 3 (curve 3) and 5 (curve 5)




(a) (b)

Fig. 27 - Phase-to-neutral induced voltages at points 2, 3, 4, and 5 of Figure 23 considering a subsequent stroke current with amplitude $I = 29.2$ kA. Configuration 3 (arresters at points 1, 2, 3, 5, and 6).
a) Points 2 (curve 2) and 4 (curve 4) b) Points 3 (curve 3) and 5 (curve 5)

When lightning strikes the MV network, short duration pulses of several tens of kilovolts may be transferred to the secondary circuit either by the first and subsequent strokes. As in the case of nearby lightning, higher voltage amplitudes are usually related to the subsequent stroke. The presence of arresters at various places of the LV line does not prevent high voltages from arising at unprotected points.

## 4 CONCLUSIONS

The magnitudes and waveforms of the lightning overvoltages depend considerably on many line and stroke parameters, which may combine in an infinite variety of ways.

The basic measures that can be applied to improve the lightning performance of MV distribution lines involve the increase of the line insulation withstand capability, the use of periodically grounded shield wires, and the installation of surge arresters along the line.

The frequency of flashovers associated with indirect strokes decrease substantially as the critical flashover overvoltage of the line structures increases, and can be virtually eliminated if the CFO is greater than 300 kV. However, the number of line faults caused by direct strokes will remain practically the same and surges with higher magnitudes will travel over long distances, increasing the stresses on line equipment.

A shield wire may reduce the amplitudes of the overvoltages associated with nearby strokes regardless of its position with respect to the phase conductors. However, the closer it is to the phase conductors, the greater the voltage reduction will be. Its effectiveness decreases with the increase of both the earthing spacing and the earth resistance.

The application of line arresters can be effective in reducing the number of flashovers caused by indirect strokes, provided that the arrester spacing is not too large.

In order to mitigate the effects of direct strokes, the shield wire should not only be earthed at every pole, but also the line should have sufficient CFO between the earth lead and the phase conductors, and the earth resistances should be low. Alternatively, surge arresters should be installed on all phases at very short intervals, but if the line is unshielded the arresters may have a significant failure rate due to excess energy dissipation. Undoubtedly the best solution consists in the use of a shield wire in conjunction with arresters on every pole and every phase. This solution is effective against direct strokes and theoretically eliminates flashovers, but a cost-benefit analysis should always be performed.

Secondary systems are much more susceptible to lightning-caused disturbances than MV lines because of their lower withstand capability. Larger overvoltages are usually associated with subsequent strokes, although severe surges can also be produced by the first stroke.

Phase-to-ground voltages induced by nearby lightning can reach some tens of kilovolts in various points along the network, especially if the stroke location is not in front of a neutral earthing point. Lower magnitudes are observed at the transformer and customers’ entrances, but the value of 10 kV may often be exceeded in the case of strikes closer than about 50 m. Phase-to-neutral voltages of some kilovolts are common if surge protective devices are not applied. In the case of direct strikes to the MV line, short duration pulses of several tens of kilovolts are transferred to the secondary circuit.

In regions of high lightning activity, surges originated in the low-voltage side can be responsible for a great number of transformer failures or damages, even if arresters are placed close to the primary terminals. The application of arresters on transformer secondaries can significantly reduce the lightning damage rates of exposed transformers, but it does not prevent overvoltages from arising at the service entrances.

Similarly, the application of secondary arresters to a power installation can effectively reduce the local overvoltages to acceptable limits, but in some circumstances this may result in higher voltage stresses at unprotected premises. Therefore, unless they are applied at every service entrance, exposed sensitive electronic equipment can be damaged. In fact, voltage oscillations caused by reflections at various points within the installation can give rise to internal overvoltages with higher magnitudes than that limited by the arresters placed at the service entrance. Therefore, local protection is required for such susceptible loads.

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