Lightning Overvoltages on Rural Distribution Lines

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Abstract: This paper presents information concerning the characteristics of lightning overvoltages on overhead power distribution lines. Discussion on the protection measures against transients caused by both direct and indirect strokes is also presented.

Key words: electromagnetic induction; finitely conducting ground; lightning overvoltages; lightning protection; power distribution lines
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0 Introduction

The reliability of a power system bears on its ability to supply continuous and uninterrupted energy without significant momentary disturbances. However, power distribution lines are often placed in areas of high keraunic levels, being therefore prone to lightning-caused faults. Failures of network equipment, especially distribution transformers and pin insulators, have been observed frequently, particularly when lines cross rural areas and are consequently more exposed to direct strikes.

Lightning overvoltages on distribution lines may be originated either by direct hits or induction due to nearby discharges. The former present larger amplitudes and are the main sources of disturbances on transmission lines. On the other hand, voltages induced by indirect strokes are often of greater importance in the case of overhead distribution systems with rated voltage 15 kV and less, due to their higher frequency of occurrence and to the lower line insulation withstand capability. The induction mechanisms of these two kinds of overvoltages are completely different and both of them must be correctly computed for the evaluation of the lightning performance of a given distribution network.

Some means that can be applied to improve the lightning performance of overhead distribution lines involve the augmentation of the insulation capability[1-4], the use of shield wires periodically grounded[1,5-7], and the increase of the number of surge arresters per kilometer of the line[1-3, 6-8]. This paper presents the characteristics of the lightning overvoltages on rural lines and discusses the effectiveness of some measures to mitigate them. The voltages induced on urban distribution networks are treated in [8, 9].

1 Direct Strokes

In the case of a direct hit to a line conductor, the stroke current is divided at the strike point and gives rise to 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 by the characteristic impedance of the line. If a lightning current of 5 kA, which is exceeded in more than 99 % of the cases, is injected into a conductor with characteristic impedance of 450 Ω, the corresponding overvoltage is 1125 kV, which is far beyond typical MV line insulation levels. As a consequence, multiple flashovers occur in various points of the line.

1.1 Overvoltages

An example of a typical overvoltage caused by a direct strike to a primary line without a shield wire or surge arresters is illustrated in Fig. 1. The short spikes in the wavefront are associated with insulation flashovers, and they are followed by a slower component whose amplitude is somewhat lower than the line insulation level.

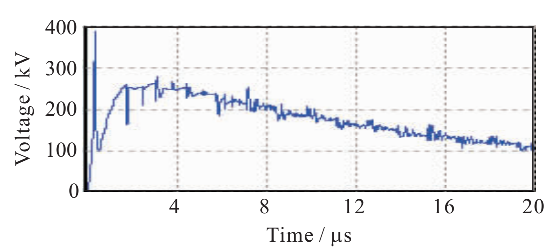


Fig. 1 Example of a typical overvoltage due to a direct strike to the primary network

1.2 Lightning protection

The line performance against direct strokes will practically not change unless a shield wire grounded at every pole with low ground resistance is used or surge arresters are installed on all phases at very short intervals. A shield wire will prevent most of the flashes from striking the phase conductors, but the ground potential rise caused by the current flow through the pole ground impedance will lead to backflashovers in most of the cases. In order to mitigate the effects of direct strikes, the shield wire should not only be grounded at every pole, but the ground resistances should be less than 10 Ω if the critical flashover overvoltage (CFO) is less than 200 kV[2].

In the case of an unshielded overhead line, an effective protection against direct strokes can be achieved only with the installation of surge arresters on all the phases of every pole. However, as pointed out in [10], arresters applied to protect an unshielded line against direct strokes may have a significant failure rate due to excess energy dissipation. 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. In this case the arresters, which prevent the occurrence of backflashovers, are protected from excess energy dissipation by the shield wire.

In mountainous regions, where the soil resistivity is usually high, a great percentage of the stroke current is injected into the distribution line in the case of a direct hit to a tall structure. This problem is particularly important in Japan, where the duration of stroke current is extremely long in winter lightning. Numerous cases of charges exceeding 300 C have been observed in winter lightning, leading to frequent arrester failures. As shown in [11], this problem can be significantly reduced by the use of more than one shield wire.

According to [12, 13], the problem of the limited energy handling capability of metal oxide arresters may be overcome by the use of the so-called Long Flashover Arresters (LFAs), which have been developed and used successfully for this purpose.

2 Indirect Strokes

The voltages induced on an overhead power distribution line in the case of a nearby strike depend on many lightning parameters and are substantially affected also by the line configuration. These voltages may frequently cause short interruptions and usually have an important impact on the line lightning performance.

2.1 Overvoltages

An important characteristic of the overvoltages induced by nearby strokes is that they have much shorter durations in comparison with the surges associated with direct strokes. Parameters such as the distance of the stroke location to the line and the amplitude and front time of the stroke current influence the induced voltages significantly, as illustrated in Figs. 2 and 3.

The calculations refer to a 10 m high, 2 km long, three-phase line, matched at both ends. It has no surge arresters, shield wire, or neutral conductor, and the soil is assumed to be a perfectly conducting plane. The stroke current has a triangular waveform with front time t_f, time-to-zero equal to 150 μs and amplitude (I) equal to 50 kA. It propagates along the lightning channel with speed (v) equal to 90 m/μs (30% of that of light in free space), and the Transmission Line model[14] is used for the calculation of its distribution along the channel. The strike point is equidistant from the line terminations and the distance between the line and the stroke location (d) is equal to 50 m. Unless otherwise indicated, all the simulations presented henceforth refer to these conditions.

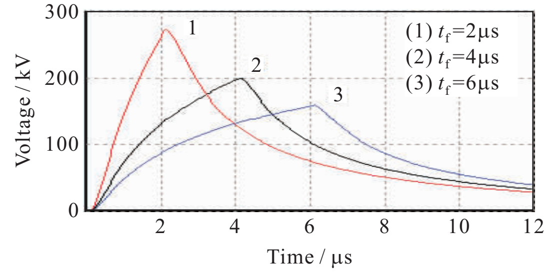


Fig. 2 Lightning induced voltages at the point closest to the stroke location (d=50 m) for different values of the stroke current front time (t_f)

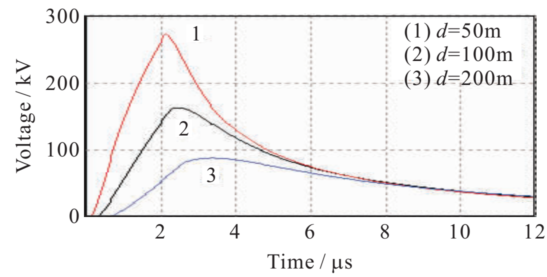


Fig. 3 Lightning induced voltages at the point closest to the stroke location for different distances between the line and lightning channel (d). Stroke current front time t_f=2 μs

The influence of the stroke current front time is illustrated in Fig. 2 for the cases of t_f equal to 2 μs, 4 μs, and 6 μs. The induced voltage is directly proportional to the current time-variation rate. Therefore, for a constant current amplitude, the voltage peak value increases when t_f diminishes.

Fig. 3 shows that the distance d has a substantial influence on the induced voltages. The shorter this distance, the larger the magnitudes of the electromagnetic fields and consequently the larger the induced voltages.

The voltage amplitude practically does not depend on the tail of the stroke current. On the other hand, a variation in the current peak value causes a proportional variation in the induced voltage as long as the other parameters are kept constant.

Other parameters may also have an important influence on the induced voltages. A sensitivity analysis is presented in [15], where the voltages are shown to be particularly affected by the soil resistivity.

The voltages depend on the lightning radiated electromagnetic fields, which by their turn are affected by the soil parameters. For both the magnetic field and the vertical component of the electric field, for distances not exceeding some few kilometers from the stroke location and soil resistivities varying between 100 Ωm to 1000 Ωm the propagation effects will not cause any significant changes, except for a slight change in the peak and rise-time[16, 17]. Therefore, in these cases the fields can be computed with the assumption of the soil as a perfectly conducting plane. On the other hand, the horizontal component of the electric field may be substantially affected by the soil resistivity even for relatively close distances from the stroke location[18, 19]. As a consequence, the soil resistivity may have a remarkable effect on the lightning induced voltages[15, 20, 21].

Fig. 4 illustrates the influence of the soil parameters on the horizontal component of the electric field considering three distances (d) between the observation point and the stroke location, namely 100 m, 200 m and 400 m. The calculations refer to a height (h) of 10 m above ground and comparisons are presented for the case of a perfectly conducting soil and two combinations of its resistivity (ρ_g) and relative permittivity (ε_{rg}): $\rho_g=50$ Ωm and $\varepsilon_{rg}=30$ (good conductive ground), and $\rho_g=500$ Ωm and $\varepsilon_{rg}=15$ (poorly conductive ground). The horizontal electric field over a perfectly conducting plane is calculated using the Master and Uman equation[22] while in the case of finite soil conductivity the calculation is done using the Cooray-Rubinstein approach[23].

As shown in Fig. 4(a), for short distances from the lightning strike point the electric fields associated with the three soil types are relatively close. As the distance increases, the difference between the fields also increases, and it becomes clear that the assumption of a perfectly conducting ground is no longer applicable. Evidently, the higher the soil resistivity, the shorter the distance for which the assumption loses its validity.

The effect of the soil resistivity is more pronounced in the case of steeper currents. This can be readily observed if the waveforms depicted in Fig. 4 are compared with those shown in [19]. The results presented in [19] consider distances from 100 m to 10 km, soil resistivities from 50 m to 5000 Ωm, and typical subsequent stroke currents, which are characterized by shorter front times. It is shown that, for short distances from the lightning channel, the field amplitude tends to decrease

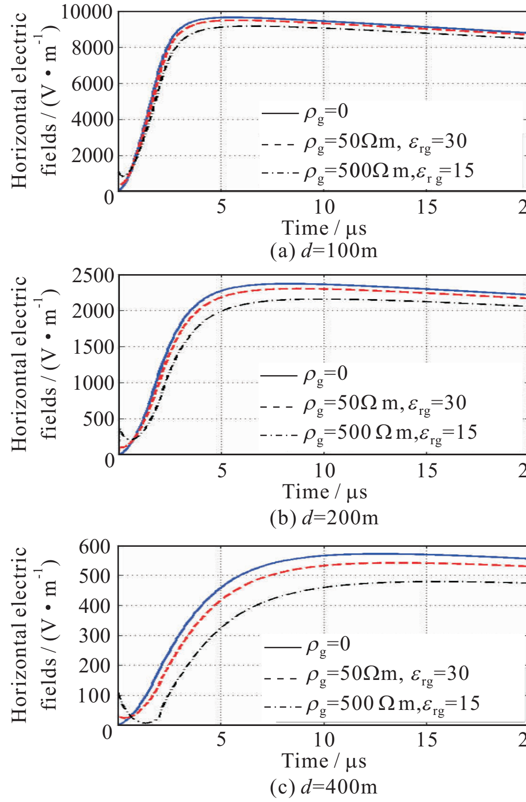


Fig. 4 Horizontal electric field for three soil types at different distances from the stroke location. I=50 kA; t_f=2 μs; h=10 m; v=90 m/μs

as the ground resistivity increases. This is the same result observed in Fig. 4(a), which refers to a stroke current with $t_f=2$ μs.

However, for distances of a few hundred meters from the stroke location, the absolute value of the horizontal electric field magnitude tends to increase with the increase of the ground resistivity. As shown in Fig. 4(b) and in Fig. 4(c), this is not the case when $t_f=2$ μs. For this front time, the same behavior of the horizontal electric field will be observed for longer distances from the strike point.

In terms of lightning induced voltages, the calculations should not, in general, adopt the assumption of a perfectly conducting ground, unless the soil resistivity is lower than about 100 Ωm[24].

2.2 Lightning protection

Lightning induced overvoltages can be mitigated by the use of shield wire(s) and/or surge arresters.

Due to the coupling with the phase wires, either a shield wire or a neutral conductor may reduce the induced voltages. The greater the coupling and the lower the value of the ground resistance (R_g), the lower the magnitude of the phase-to-ground induced voltages. The influence of the ground resistance is particularly important when the lightning channel is in front of a grounding point, and it tends to decrease as the grounding spacing increases, the stroke current front time becomes shorter or the distance between the stroke location and the closest grounding point increases[1].

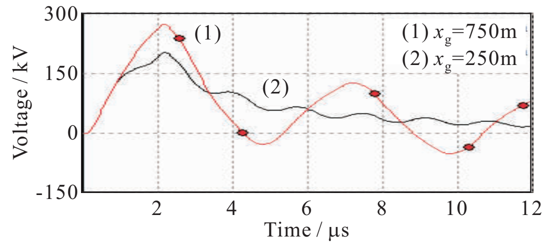
The effectiveness of the shield wire / neutral in improving the line performance against indirect strokes is highly dependent on the distance between adjacent grounding points (x_g). Fig. 5 presents phase-to-ground and phase-to-neutral induced voltages at the point closest to the lightning channel considering grounding spacings of 250 m and 750 m. The height of the neutral conductor is 9 m, the ground resistance is 25 Ω, the inductance of the ground lead is equal to 9 μH, and the stroke location is equidistant from two grounding points. Not only the voltage magnitudes but also their waveforms are strongly affected by the multiple reflections that occur at the grounding points. The effect of the neutral conductor can be evaluated by comparing the voltages shown in Fig. 5(a) with that indicated by curve 1 in Fig. 3, which corresponds to the voltage that would be induced at the same point of the line in the absence of the neutral.

The effectiveness of surge arresters in reducing the magnitudes of the lightning induced voltages on a typical 15 kV overhead line was investigated in [8]. Experiments were performed through the use of a reduced scale model and of a full-scale system, while the simulations were conducted using the Extended Rusck Model (ERM)[25]. The results showed that 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 arresters on the induced voltages can be significant, mainly if the stroke location is nearly equidistant from two sets of arresters.

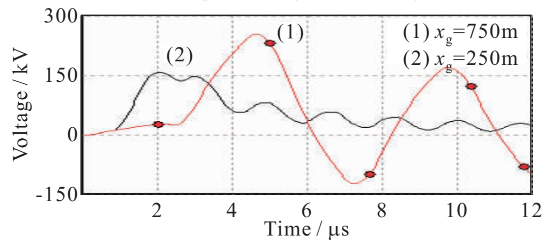
The analysis presented in [5] shows that an important reduction of the induced overvoltages can be achieved only with a large number of arresters, namely one surge arrester every 200 m, the same interval suggested in [11]. According to [10], an effective protection can be obtained by installing arresters on each phase every 360 m.

In [3], 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·a) were investigated. All transformers had surge arresters at the MV side and the neutral was grounded at poles where arresters were installed. The distances between arresters varied widely depending on the region crossed by the line, ranging from only 77 m in urban sections to 2200 m in some rural areas.

The results of the simulations show that the



(a) phase-to-ground voltages



(b) phase-to-neutral voltages

Fig. 5 Induced voltages at the point closest to the lightning channel for different grounding spacings (x_g). I=50 kA; t_f=2 μs; d=50 m; R_g=25 Ω

installation of surge arresters on all phases every 300 m, associated with the increase of the insulation level of the rural sections of the feeder (through the installation of 34.5 kV insulators), would reduce the number of lightning outages in approximately 50%, with a reduction around at least 75% in the number of faults caused by indirect strokes.

The effect of the surge arresters is illustrated in Fig. 6, in which the phase-to-ground induced voltages are presented for different arrester spacings (x_g). The heights of the phase and neutral conductors are, respectively, 10 m and 8 m, and the inductance of the ground lead is 8 μH, as shown in Fig. 7. The U-I curve of the surge arresters, which are installed on all phases, is presented in Fig. 8. The neutral is grounded at the poles where arresters are applied.

The distance between adjacent arresters has a major influence on the line performance against indirect strokes. When the front time of the induced voltage is long in comparison with the time required for the reflections (caused by the surge arresters) to arrive at the observation point, the voltage magnitudes are significantly reduced, as can be observed by comparing curves 1 and 3 in Fig. 6. On the other hand, if the voltage peak value is reached before the arrival of the reflections, only the voltage wavetail will be affected. This is the case of curve 2 in Fig. 6. Therefore, the larger the arrester spacing or the greater the stroke current steepness, the smaller the effect of the arresters.

The influence of the ground resistance may be important if the lightning strike point is close to a set of arresters[1], and the magnitudes of the over-

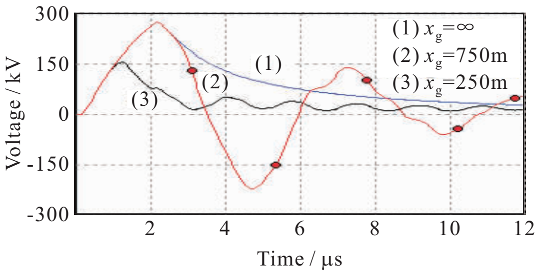


Fig. 6 Induced voltages (phase-to-ground) at the point closest to the lightning channel for different arrester spacings (x_g). I=50 kA; t_f=2 μs; d=50 m; R_g=25 Ω

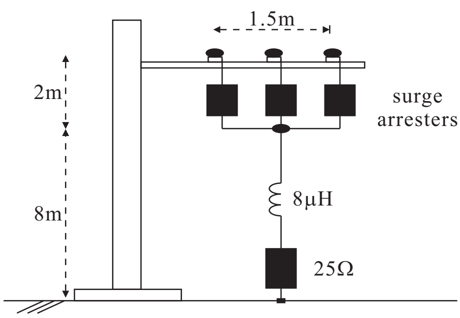


Fig. 7 Line configuration for the simulations presented in Fig. 5

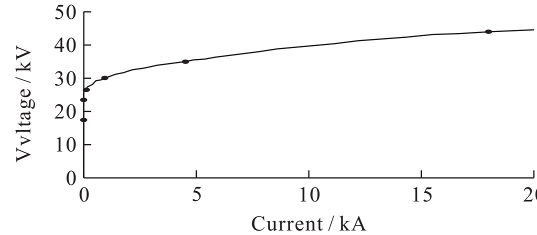
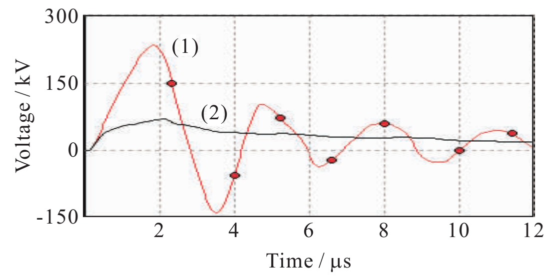


Fig. 8 U/I characteristic of the surge arresters



Curve 1: stroke location equidistant from two sets of arresters;
Curve 2: stroke location in front of a set of arresters.

Fig. 9 Induced voltages (phase-to-ground) at the point closest to the lightning channel for different positions of the stroke location with respect of the surge arresters. I=50 kA; t_f=2 μs; d=50 m; x_g=450 m; R_g=25 Ω

voltages tend to increase in the case of high values of the soil resistivity, as shown in [5].

In the case of short arrester spacing, the induced voltages are in general not much affected by the relative position between the stroke location and the arresters. On the other hand, the difference between the voltages corresponding to stroke location in front of or equidistant from two sets of arresters tends to increase with xg, as shown in Fig. 9. The heights of the phase and neutral wires are 10 m and 8 m, and the neutral is grounded where the arresters are applied.

3 Conclusions

The overvoltages caused by direct and indirect strokes depend on many parameters and have distinct characteristics.

Either a shield wire or a neutral conductor may reduce the amplitudes of the lightning induced overvoltages.

The application of surge arresters at distances shorter than about 400 m can be effective in reducing the number of flashovers caused by indirect strokes. However, a shorter spacing may be necessary in the case of soils with high resistivity.

The best protection measure against lightning overvoltages consists in the use of a shield wire in conjunction with arresters on every pole and every phase, but a cost-benefit analysis should always be performed.

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