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Analysis of the effectiveness of shield wires in mitigating lightning-induced voltages on power distribution lines

Alexandre Piantini

University of São Paulo, Institute of Energy and Environment, Lightning and High Voltage Research Center – CENDAT/USP, Av. Prof. Luciano Gualberto, 1289, 05508-010, São Paulo, Brazil

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ABSTRACT

The use of multi-grounded shield wires constitutes one of the methods that can be applied to improve the lightning performance of overhead power distribution lines. Although the effectiveness of this measure against direct strokes is quite limited, the line performance against indirect strokes can be greatly improved. However, the degree of improvement varies from case to case, as the magnitudes of the induced surges are significantly affected by many lightning and network parameters, as well as by the soil resistivity. In addition, the presence of a shield wire or a neutral conductor has different effects on the phase-to-ground and phase-to-shield wire (or phase-to-neutral) voltages. In this paper, an analysis is presented of the effectiveness of shield wires in reducing the magnitudes of lightning-induced voltages on medium-voltage power distribution lines considering various realistic situations. A discussion is provided on the influence of the most important parameters on the effectiveness of the shield wire in terms of both phase-to-ground and phase-to-shield wire voltages.

1. Introduction

Lightning is one of the most important sources of disturbances on overhead power systems and many studies have been undertaken on the effectiveness of the different alternatives that can be applied to mitigate its effects. Regarding power distribution networks, the main methods to improve their lightning performance are the increase of the critical impulse flashover voltage (CFO) of the line structures, the installation of surge arresters, and the use of shield wires. A grounded conductor – either a shield wire or a neutral – reduces the amplitudes of lightning-induced surges because of its electromagnetic coupling with the phase conductors [1].

Shield wires are used on transmission and subtransmission lines in order to intercept (ideally all) lightning strokes with currents larger than the critical current, i.e., the current that produces an overvoltage equal to the critical impulse flashover voltage (CFO). They are much less frequently used on distribution lines, although some utilities have been using them with great success [2].

The direct stroke performance of a distribution line is usually not much affected by a shield wire because of the ground potential rise caused by the flow of the stroke current through the pole ground impedance, which generally causes voltage differences between the ground lead and the phase conductors larger than the line CFO. Therefore, grounding at every pole, low values for the ground resistances, and a sufficient CFO between the ground lead and the phase conductors are required for the shield wire to be effective [2,3].

On the other hand, due to its coupling with the phase conductors, a periodically grounded wire reduces the magnitude of surges induced by nearby strokes and may improve the lightning performance of a distribution line. Its effectiveness depends on the combination of the values of several parameters as, for example, the relative position of the shield wire with respect with the phase conductors, the grounding spacing, the ground resistance, the soil resistivity, the stroke current waveshape, etc [4].

A number of theoretical and experimental studies, involving different assumptions and conditions, have been conducted on the effect of a grounded conductor on lightning-induced voltages. Both in Refs. [5] and [6] the shield wire is assumed to be at zero potential at any time and it is concluded that it reduces the induced voltages on the phase conductors. The amount of reduction is dependent on the position of the shield wire in relation to the ungrounded conductors [5] and the adoption of the shield wires is an effective means of reducing the yearly line outage rate [6]. In Ref. [7], assuming just one connection of the shield wire to ground, a simple expression is derived for the calculation of the ratio between the voltages induced on a phase conductor with and without the presence of the shield wire. Although such expression can be used

E-mail address: piantini@iee.usp.br

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to evaluate the shielding factor of typical distribution lines with acceptable accuracy, as demonstrated in Ref. [8], its validity is restricted, in principle, to the case of only one connection to ground.

The case of a multi-grounded shield wire has been treated, e.g., in Refs. [1,3,4,9–21]. In the analysis carried out in Ref. [15], using the model presented in Refs. [13,22–24], the evaluation of the shielding effect of the ground wire considered only the case of a perfectly conducting ground. Using an improved version of the Extended Rusck Model (ERM) [25], which allows for the calculation of lightning transients taking into account the soil electrical characteristics, the influence of some of the most important parameters on the lightning-induced voltages on a line with a shield wire was studied in Ref. [1]. In Ref. [4] the ERM was used to investigate the shielding factors considering some realistic situations. Such analysis is extended in this paper, which aims at discussing the effectiveness of a shield wire in reducing the magnitudes of lightning-induced voltages on medium-voltage power lines and the way the most important parameters influence the shielding factors in terms of both phase-to-ground and phase-to-shield wire voltages.

The methodology adopted for the analysis is presented in Section 2. The obtained results, which include a parametric analysis, are discussed in Section 3. The main conclusions are presented in Section 4.

2. Methodology

If we consider an infinite line with a phase conductor and a shield wire (or a neutral) grounded at a single point x_1, the following relationship exists between the current $I_g\ (x_1,t)$ which will flow to ground in the event of a nearby lightning strike and the voltage $U_g\ (x_1,t)$ that would be induced at point x_1 in the absence of the connection to ground [26]:

$$U_g(x_1, t) = (0.5Z_g + R_g)I_g(x_1, t) + L dI_g(x_1, t)/dt \quad (1)$$

where Z_g is the surge impedance of the shield wire, R_g represents the ground resistance, and L is the ground lead inductance. Although, strictly speaking, the term “ground impedance” is more appropriate than “ground resistance”, in this paper the ground impedance is represented by the d.c. resistance of the shield wire, i.e., by the ground resistance. This is a reasonable approximation in the case of grounding systems of small dimensions – which is typically the case of power distribution networks –, for which the inductive and capacitive components of the ground impedance can be neglected in comparison with the resistive component.

The induced voltage $U_p(x_2,t)$ at point x_2 on the phase conductor is given by [26]:

$$U_p(x_2, t) = U_p'(x_2, t) - 0.5Z_m I_g(x_1, t - |x_2 - x_1|/c) \quad (2)$$

where $U_p'(x_2,t)$ is the voltage that would be induced at point x_2 of the phase conductor in the absence of the shield wire grounding and Z_m is the mutual impedance between the conductors. Eq. (2) shows that, due to the electromagnetic coupling between the shield wire and the phase conductor, the induced voltage on the latter will be reduced regardless of the relative position of the wires.

The induced voltages on the line conductors in the absence of the connection to ground are calculated using the ERM [25], which can take into account realistic situations such as, e.g., a multi-conductor line with a multi-grounded neutral or shield wire over a finitely conducting ground. The incidence of lightning flashes to nearby elevated objects and the occurrence of upward leaders can also be considered, as well as the presence of equipment such as transformers and surge arresters [13]. The effect of a multi-grounded conductor is evaluated by calculating the currents that flow to ground at the various grounding points taking into account the multiple reflections and, then, the voltages associated with these

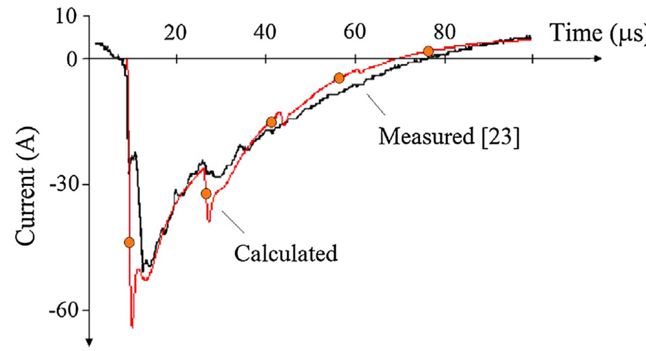

Fig. 1. Measured and calculated induced currents at one of the shield terminations of a 5 m high telecommunications cable by a rocket-triggered lightning.
Adapted from Ref. [25].

currents that, due to the coupling between the wires, are induced on the phase conductors [15]. The ERM has been validated with experimental data obtained using different techniques: rocket-triggered lightning, lightning flashes to instrumented towers, and scale models.

Fig. 1 presents a comparison between measured and calculated currents induced at one of the shield terminations of a 2600 m long, 5 m high telecommunications cable by a rocket-triggered lightning experiment carried out by Paulino et al. [27]. The stroke current magnitude and propagation velocity were about 16 kA and 130 m/µs respectively, and the average soil resistivity of the area was 400 Ωm. The stroke location was 350 m from the line and about 2520 m from the measuring point. The shield was grounded at both ends and the ground resistances were 40 Ω and 228 Ω. The induced current was measured at the termination with the higher ground resistance value. Further details of the experiment can be found in Ref. [27]. A good agreement is found between measured and calculated results. Possible reasons for the differences are discussed in Ref. [25], and involve the facts that in the simulations the line was considered straight and that neither attenuation nor distortion of the waves along it were taken into account, the fact that the soil was considered homogeneous, and the uncertainty in the estimation of the stroke current propagation velocity.

In Ref. [28] Yokoyama et al. present measurements of lightning currents at the top of a 200 m high tower and the corresponding induced voltages on a 820 m long experimental line located 200 m from the tower. The heights of the shield wire and the conductor where the voltage was measured were 10.5 m and 10 m, respectively, with a horizontal distance of 2.4 m between them. Fig. 2 shows a comparison between measured and calculated induced voltages relevant to Case (82-06) [28]. In this case the shield wire was connected to ground at only one point, about 300 m from the measuring point, and the value of the ground resistance was 12 Ω. Possible reasons for the observed deviations between calculated results and measurements performed in the system described in Ref. [28] involve, among others, slight imprecisions in the representation of the stroke current, the characteristics of the optical-electrical converter used for the voltage measurements, the fact that the simulated return stroke current was assumed to propagate along the lightning channel with neither attenuation nor distortion, and the assumptions of a constant current propagation velocity of 30% of that of light in free space and of a lightning channel perpendicular to a perfectly conducting ground plane. Current reflections at the top and bottom of the tower and the possible occurrence of upward leaders, not considered in the calculations, also contribute to the deviations.

Another comparison, now involving scale model experiments performed under controlled conditions, is presented in Fig. 3, where