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The use of shield wires for reducing induced voltages from lightning electromagnetic fields

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ABSTRACT

The mechanisms from which lightning overvoltages can be produced on a power line depend on the system voltage. In medium voltage (MV) overhead distribution systems, lightning transients can be originated from either direct or indirect strokes. The main methods that can be adopted to improve the line lightning performance concern the increase of the critical impulse flashover voltage (CFO) of the line structures, the installation of surge arresters, and the use of one or more shield wires. This paper deals with the evaluation of the effectiveness of shield wires in reducing the magnitudes of the surges induced by nearby strokes on MV distribution lines. Such effectiveness depends on the combination of several parameters such as the relative position of the shield wire with respect to the phase conductors, the grounding interval, the ground resistance, the stroke current steepness, and the relative position of the stroke channel with respect to the grounding points. Realistic situations corresponding to typical configurations of a rural distribution line with either an overhead ground wire or a neutral conductor are considered. The analysis is carried out based on both computer simulations and test results obtained from scale model experiments, under controlled conditions.

1. Introduction

The main function of a shield wire is to intercept direct lightning strokes that would otherwise hit the phase conductors producing overvoltages higher than the line lightning impulse withstand level. For this purpose, the shield wire must be installed above the phase conductors, and its proper placement is one important task of transmission-line designers. Other functions involve the lowering of the self-surge impedance of an overhead ground wire system and the raising of the mutual surge impedance of an overhead ground wire system to the protected phase conductors [1]. Direct stroke protection with shield wires can be effective on transmission lines, which are characterized by relatively high values of critical impulse flashover voltage (CFO).

On the other hand, the direct stroke performance of distribution lines is generally not much affected by the presence of a shield wire. Because of the low lightning impulse withstand capability of the line poles, even if the shield wire is grounded at every structure the ground potential rise caused by the flow of the stroke current through the pole ground impedance causes, in most of the cases, voltage differences between the ground lead and the phase conductors larger than the line CFO. The greater the value of the ground impedance, the greater these voltage differences and hence the greater the probability of backflashover occurrence [2–4]. Therefore, for the shield wire to be effective against direct strokes it must be not only grounded at every pole but also the ground resistances must be low – less than 10 Ω if the insulator CFO is less than 200 kV [2]. However, due to its coupling with the phase conductors, a shield wire can also be used with the purpose of reducing induced voltages from external electromagnetic fields. This reduction occurs even if it is beneath the phase conductors, so that a grounded neutral has the same effect.

Investigations on the effectiveness of shield wires in terms of decreasing the magnitudes of lightning induced voltages on medium voltage overhead distribution lines have been conducted, e.g., in [4–20]. In [5] the shield wire is assumed to be at zero potential at any time, even during the transient. A simple expression is presented in [6] for the calculation of the ratio between the voltages induced on a phase conductor with and without the presence of a shield wire for the case of a perfectly conducting ground. The formula was derived assuming just one connection of the shield wire or neutral conductor to ground and applies only for points situated close to the grounding point, although results with reasonable accuracy are obtained for the case of multiple groundings as long as the distance between adjacent groundings is short (e.g. 30 m [2]). In [7,8] the shield wire is considered to be a conductor belonging to a multi conductor transmission line and grounded

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at both line terminations. In [9] the model presented in [7,8] is extended and generalized in order to evaluate the effect of periodically grounded shield wires on the attenuation of lightning induced voltages. A procedure for the estimation of the annual number of lightning-induced flashovers on distribution lines and the evaluation of the effectiveness of shield wires is proposed in [10]. Measurements of induced voltages by real lightning flashes are presented in [11,12], while in [13–18] the analyses involve scale model experiments. Comparisons between voltages induced by typical first and subsequent downward negative flashes on lines with different configurations are presented in [19,20].

This paper deals with the evaluation of the effectiveness of shield wires in reducing the magnitudes of the surges induced by nearby lightning strokes on MV overhead distribution lines. Such effectiveness depends on the combination of several parameters such as the relative position of the shield wire with respect to the phase conductors, the grounding interval, the ground resistance, the stroke current steepness, and the relative position of the stroke channel with respect to the grounding points.

Initially, the basis for the calculations is described for the simplest case, which consists in a shield wire grounded at one point only. Afterwards, realistic situations corresponding to typical configurations of a rural distribution line with either an overhead ground wire or a neutral conductor are considered and simulation and experimental results are compared to confirm the validity of the method. Finally, the effects of various line and lightning parameters on the induced voltages are evaluated through the use of both computer simulations and test results obtained from scale model experiments, under controlled conditions.

2. Methodology

Consider an infinite line with a phase conductor and either a neutral or a shield wire connected to ground at a single point x_1. Neglecting the ground lead inductance, the current $I_g(x_1, t)$ which will flow to ground in the event of a nearby lightning strike can be calculated as [6,21]:

$$I_g(x_1, t) = \frac{U_g(x_1, t)}{R_g + 0.5\, Z_g} \quad (1)$$

where $U_g(x_1, t)$ corresponds to the voltage that would be induced at point x_1 in the absence of the connection to ground, Z_g is the surge impedance of the shield wire, and R_g represents the ground resistance.

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

$$U_p(x_2, t) = U'_p(x_2, t) - 0.5 Z_m I_g \left(x_1, t - \frac{|x_2 - x_1|}{c}\right) \quad (2)$$

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.

As indicated in Eq. (2), 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. For a given lightning current and stroke location, the amount of reduction will depend on the coupling between the conductors, on the value of the ground resistance, and on the distance between the observation and grounding points.

The induced voltages on the phase and shield wires in the absence of the connection to ground are calculated by using the Extended Rusck Model (ERM), which is based on Rusck's theory [6]. The ERM, which is described in [20], has some features that, unlike the original model, allow for taking into account situations of practical interest such as, e.g., a line with a multi-grounded neutral or shield wire and equipment such as transformers and surge arresters

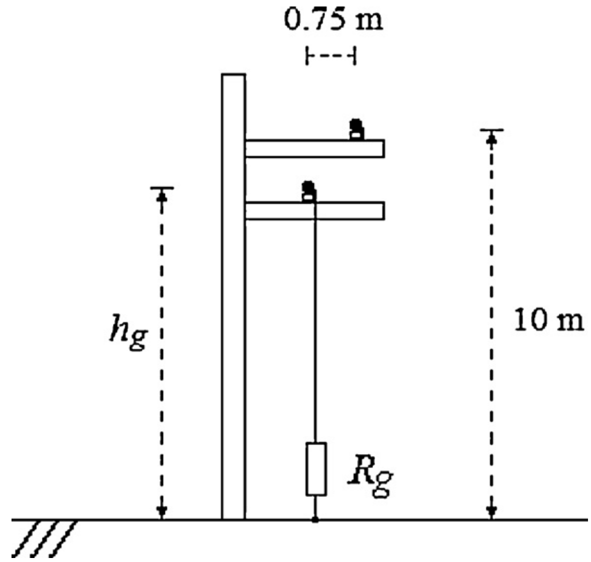

Fig. 1. Configuration of the line with the shield wire (dimensions referred to the full-scale system).

[4,22]. The incidence of lightning flashes to nearby elevated objects [23,24] and the occurrence of upward leaders [24–26] can also be considered. 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 effect of an overhead ground wire or of a neutral conductor is considered 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 currents that, due to the coupling between the wires, are induced on the phase conductors.

In order to validate the model, several tests were performed on a reduced scale system, under controlled conditions, and measured and calculated induced voltages were compared. The system, whose scale factor for length was 1:50, comprised models of the lightning channel, the ground plane, and of two overhead distribution lines. The ground was simulated by aluminum plates interconnected, thus representing a perfectly conducting plane. The length of the lines was 28 m, which is equivalent to 1.4 km on a full-scale basis. The lines were parallel, matched at both terminations, and symmetric with respect to the lightning channel model, which was equidistant from the lines' ends. The height of the phase conductors (h) was 20 cm, corresponding to 10 m. The distance between the lightning channel model and each line (d) was equivalent to 70 m. One of the lines had just one conductor, while the other had one phase and also a shield wire, placed at height h_g, as shown in Fig. 1. Different heights were considered for the shield wire and tests were performed for various combinations of grounding spacing (x_g) and ground resistance values. A detailed description of the system and of its various components can be found in [20,27,28].

Fig. 2 shows comparisons between measured and calculated voltages induced on the line with the shield wire, in different situations. The main characteristics of the stroke current, whose waveform is presented in [25], are: magnitude I = 36 kA, front time t_f = 3.1 μs, and propagation velocity of 11% of that of light in free space. These values, referred to the full-scale system, can be converted to the values actually recorded in the scale model experiments by applying the scale factors for time (1:50) and for voltage and current (1:30,000). As a matter of fact, as there are no nonlinearities in the system, the choice of the scale factor for voltage