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Lightning-Induced Voltages on Distribution Lines with Shield Wires

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***Abstract*— One of the methods that can be applied to improve the lightning performance of overhead power distribution lines is the use of shield wires. Although the effectiveness of this measure against direct strokes is quite limited unless the shield wire is grounded at every pole, the ground resistances are low, and the line has sufficient CFO between the ground lead and the phase conductors, the line performance against indirect strokes can be improved. In this paper an analysis is presented of the effectiveness of shield wires in reducing the magnitudes of lightning-induced voltages on medium-voltage distribution lines considering various realistic situations.**

Keywords-lightning; overvoltages; power distribution lines; shield wires.

I. INTRODUCTION

Shield wires are used on transmission and subtransmission lines in order to intercept 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 [1].

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 [1, 2].

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, grounding spacing, ground resistance, soil resistivity, stroke current waveshape etc.

Various theoretical and experimental studies, involving different assumptions and conditions, have been conducted on the influence of shield wires on lightning-induced voltages. Both in [3] and [4] 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 [3] and the adoption of the shield wires is an effective means of reduction of the yearly line outage rate [4]. In [5], assuming just one connection of the shield wire to ground, an 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. However, it applies only for points situated close to the grounding point.

The case of a multi-grounded shield wire has been treated, e.g., in [2, 6-12]. The basis for the analysis carried out in [12] was the Extended Rusck Model (ERM) [10, 13-15], a model whose validity has been demonstrated from hundreds of comparisons between measured and calculated induced voltages under different conditions. In [12], however, the evaluation of the shielding effect of the ground wire considered only the case of a perfectly conducting ground. In this paper the analysis is extended to the case of lines located in areas with higher soil resistivity. The calculations are performed using an improved version of the ERM, which is capable of taking into account the effect of the finite ground conductivity. The horizontal component of the electric field associated with the stroke current is calculated according to the Barbosa-Paulino equation [16].

II. SIMULATION CONDITIONS

The line configuration adopted in the simulations is similar to that considered in [12]. The line length is 3 km and the height *(h)* of the three phase conductors is 10 m, with distance of 0.75 m between adjacent phases. The shield wire is at the height *(hg)* of 11 m, exactly above the middle phase. The diameter of all the conductors is 1 cm, the grounding interval *(xg)* is 300 m, and the inductance of the down conductor is 1 μH/m.

The stroke channel is vertical, 3 km long, without branches, and the Transmission Line model [17] is assumed for the calculation of the current distribution along the lightning channel. The stroke current is represented by a triangular waveshape with peak value *(I)* of 50 kA, time to half-value of 50 µs, and propagation velocity *(v_f)* of 30 % of that of light in free space *(c)*. The induced voltages are calculated at the point of the line closest to the stroke location, which is equidistant to the line terminations. Two situations are considered regarding the stroke location: either in front or equidistant from the closest grounding points. The stroke current front time *(t_f)*, the ground resistance *(Rg)*, the soil resistivity (ρ), and the distance between the line and the lightning strike point *(d)* vary from case to case.

III. Results And Analysis

The influences of some of the most important parameters on the effectiveness of the shield wire are analyzed in this section. The results are presented in terms of two shield wire factors, namely *SWFsw and SWFg*. The former is defined as the ratio of the peak values of the voltage between the phase conductor and the shield wire *(Up-sw)* and the voltage that would be induced on the phase conductor in the absence of the shield wire *(Up')* at the point of the line closest to the stroke location. The latter is defined in a similar way, but with the voltage *Up-sw* replaced with *Up*, which is the phase-to-ground induced voltage in the presence of the shield wire.

$$SWFsw = Up\text{-}sw \,/\, Up' \quad (1)$$

$$SWFg = Up \,/\, Up' \quad (2)$$

For illustration, Fig. 1 presents, for a specific case, the induced voltage waveforms *Up-sw, Up',* and *Up,* as well as the shield wire-to-ground voltage.

A. Soil Resistivity and Ground Resistance

The influence of the ground resistance *(Rg)* on the shield wire factors *SWFsw* and *SWFg* can be visualized in Fig. 2a for *hg* = 9 m, *xg* = 300 m, t_f =3 µs, *d* = 50 m, and soil resistivities of 100 Ωm and 1000 Ωm. The results corresponding to *d* = 200 m are presented in Fig. 2b.

According to the definitions shown in (1) and (2), a lower factor indicates a more significant voltage reduction in relation to *Up'* and, consequently, a higher effectiveness of the shield wire.

Fig. 2 shows that the shield wire factors *SWFg* and *SWFsw* have opposite behaviors with respect to the ground resistance; the former increases and the latter decreases as *Rg* increases. This means that the effectiveness of the shield wire in reducing the phase-to-ground voltages is lower for high values of *Rg*. On the other hand, the higher the value of *Rg*, the higher the effectiveness of the shield wire in reducing the phase-to-shield wire induced voltage.

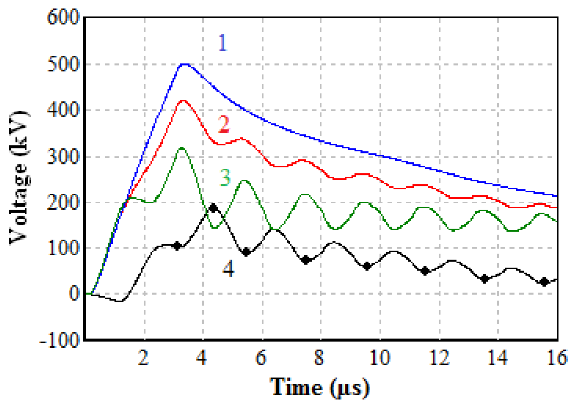
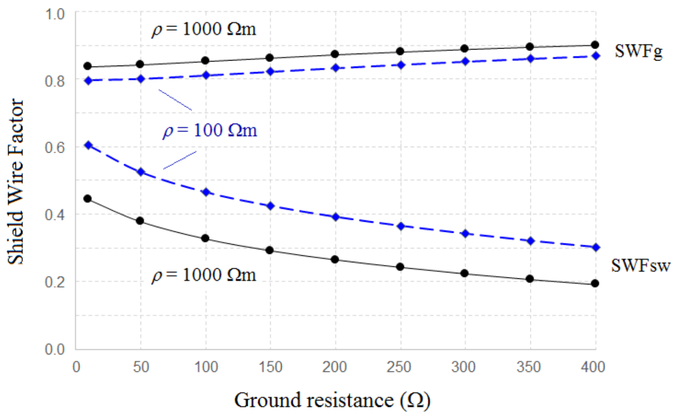
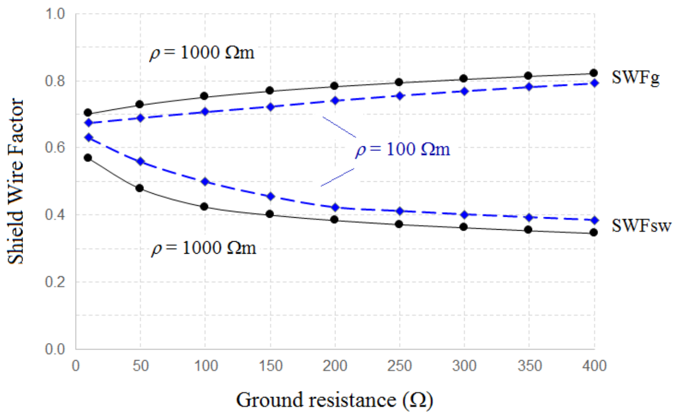


Figure 1. Lightning-induced voltages at the point closest to the stroke location. *I* = 50 kA; t_f = 3 µs; v_f = 0.3 *c*; *d* = 50 m; *h* = 10 m; *hg* = 11 m; *xg* = 300 m; *Rg* = 50 Ω; ρ = 1000 Ωm; stroke location equidistant from the closest grounding points. 1) phase-to-ground voltage which would be induced in the absence of the shield wire *(Up')*; 2) phase-to-ground voltage *(Up)*; 3) shield wire-to-ground voltage; 4) phase-to-shield wire voltage *(Up-sw)*



(a)



(b)

Figure 2. Shield wire factors SWFg and SWFsw at the point of the line closest to the stroke location as function of the ground resistance *Rg* for two values of the soil resistivity. *I* = 50 kA; t_f = 3 µs; v_f = 0.3 *c*; *h* = 10 m; *hg* = 11 m; *xg* = 300 m; *Rg* = 50 Ω; stroke location equidistant from the closest grounding points. a) *d* = 50 m b) *d* = 200 m

This can be explained as follows: an increase in the ground resistance leads to an increase in the phase-to-ground voltages *Up,* since higher values of *Rg* correspond to lower currents to ground and, consequently, to lower amplitudes of the voltage component responsible for the reduction of the induced voltages [12]. On the other hand, as the shield wire-to-ground voltage is more sensitive to the variation of *Rg*, the increase of this voltage is more significant than the decrease of *Up*, and therefore the net result is a decrease of the voltage between phase and shield wire *(Up-sw)* as *Rg* increases.

Fig. 2 also shows that an increase in the soil resistivity causes an increase in *SWFg* and a decrease in *SWFsw* as *Rg* increases. In other words, the reduction on the phase-to-shield wire induced voltages with the increase of the ground resistance is more significant in the case of a high value for the soil resistivity. As shown in Fig.2a, the variation of *SWFsw* for $d = 50$ m and $\rho = 100\ \Omega$m was from 0.60 to 0.30 for *Rg* in the range $10\ \Omega - 400\ \Omega$, while for $\rho = 1000\ \Omega$m and the same ground resistance range the variation was from 0.44 to 0.19. The corresponding variation of *SWFg* was from 0.80 to 0.87 for $\rho = 100\ \Omega$m and from 0.84 to 0.90 for $\rho = 1000\ \Omega$m.

The distance between the line and the lightning strike point also affects *SWFg* and *SWFsw*. The closer the distance, the greater the reduction of the phase-to-shield wire voltages and the lower the reduction of the phase-to-ground voltages. For $\rho = 1000\ \Omega$m and *Rg* in the range $10\ \Omega - 400\ \Omega$, the variation of *SWFsw* was from 0.44 to 0.19 for $d = 50$ m and from 0.57 to 0.34 for $d = 200$ m. The corresponding variation of *SWFg* was from 0.84 to 0.90 for $d = 50$ m and from 0.70 to 0.82 for $d = 200$ m.

B. Relative Position of the Stroke Location and Grounding Points

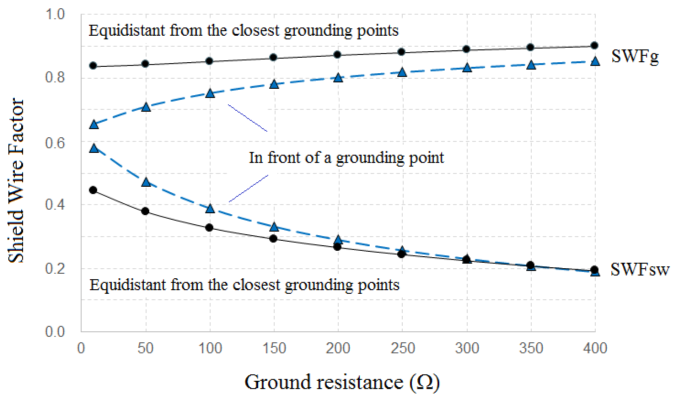
The shield wire factors depend also on the relative position of the stroke location and the closest grounding point. In Fig. 3 the variations of *SWFg* and *SWFsw* with the ground resistance are compared for $\rho = 1000\ \Omega$m and two different cases: stroke location in front of a grounding point and equidistant from two grounding points.

When lightning strikes in front of a grounding point, the effectiveness of the shield wire increases or decreases in relation to the previous case (stroke location equidistant between the closest grounding points), depending on whether the voltage of interest is that between the phase and the shield wire *(Up-sw)* or between the phase and ground *(Up)*. As the observation point approaches a grounding point, both *Up-sw* and *Up* decrease, as the delay of the effect of the grounding point becomes shorter. However, as the variation of the shield wire-to-ground voltage is greater than that of *Up,* the voltage *Up-sw* and the factor *SWFsw* increase and thus the effectiveness is reduced. On the other hand, the reduction of *Up* causes a reduction of *SWFg,* so that a higher effectiveness is observed if *Up* is the voltage of interest.

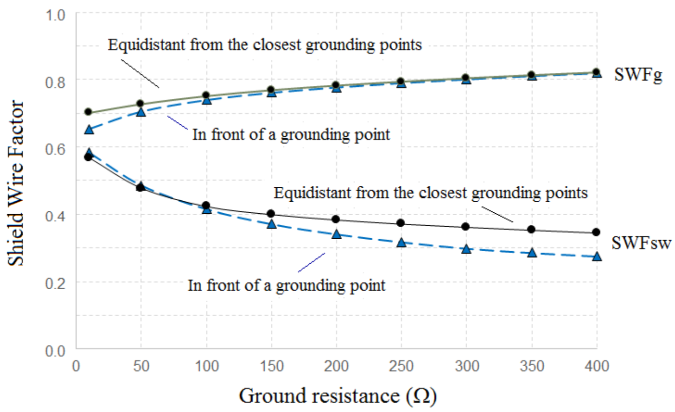
As expected, larger variations of the shield wire factors with *Rg* are observed when the stroke location is in front of a grounding point.

A comparison between Fig. 3a and Fig. 3b shows that, for the situations considered, the influence of the position of the lightning strike point on *SWFg* tends to be less important in the case of larger distances to the line. For $d = 200$ m, *SWFg* is about the same for the two relative positions considered. On the other hand, the differences between the *SWFsw* curves corresponding to the two stroke locations decrease with *Rg* for $d = 50$ m and increase with *Rg* for $d = 200$ m.

In order to better illustrate the behaviors of *SWFsw* and *SWFg*, Fig. 4a presents the induced voltages *Up* and *Up-sw* corresponding to $Rg = 50\ \Omega$; $\rho = 1000\ \Omega$m, $d = 50$ m, and the two positions considered for the lightning strike point. For comparison, the voltage *Up*' is also shown. In Fig. 4b the calculations refer to the same conditions, except that $Rg = 300\ \Omega$.



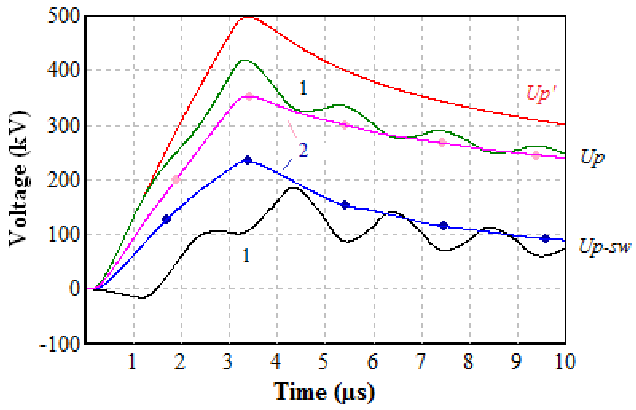
(a)



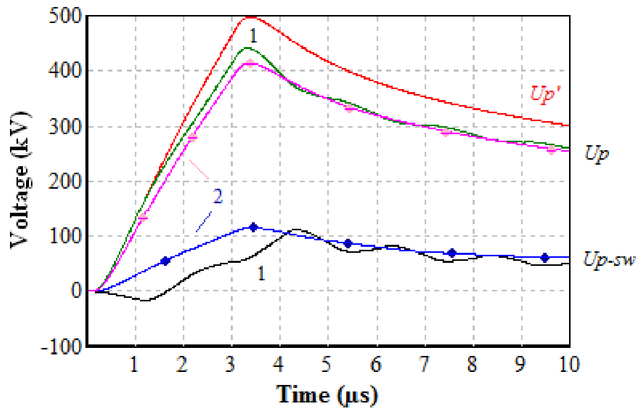
(b)

Figure 3. Shield wire factors at the point of the line closest to the stroke location as function of the ground resistance *Rg*, for two different positions of the stroke location in relation to the closest grounding point. $I = 50$ kA; $t_f = 3\ \mu$s; $v_f = 0.3\ c$; $h = 10$ m; $hg = 11$ m; $xg = 300$ m; $Rg = 50\ \Omega$; $\rho = 1000\ \Omega$m. a) $d = 50$ m b) $d = 200$ m

It can be observed that, both for the phase-to-ground *(Up)* and phase-to-shield wire *(Up-sw)* voltages, the differences corresponding to the two positions of the stroke location in relation to the grounding points decrease with *Rg*. The absolute values of the differences in the values of *SWFg*, taking the stroke location in front of a grounding point as the reference, are approximately 19 % for *Rg* = 50 Ω and 7 % for *Rg* = 300 Ω, while for *SWFsw* the corresponding differences are about 20 % for *Rg* = 50 Ω and only 3 % for *Rg* = 300 Ω.



(a)



(b)

Figure 4. Lightning-induced voltages *Up'*, *Up*, and *Up-sw* at the point closest to the stroke location. I = 50 kA; t_f = 3 μs; v_f = 0.3 c; d = 50 m; h = 10 m; hg = 11 m; xg = 300 m; ρ = 1000 Ωm.
1) stroke location equidistant from the closest grounding points
2) stroke location in front of a grounding point
a) *Rg* = 50 Ω b) *Rg* = 300 Ω

IV. CONCLUSIONS

An analysis of the effect of a multi-grounded shield wire in mitigating lightning-induced voltages on overhead distribution lines has been carried out. The effectiveness of this protection measure depends on the combination of the values of various parameters, and the influences of some of the most important ones have been discussed in this paper.

The results indicate that the use of a shield wire can substantially reduce the magnitudes of lightning-induced voltages between the terminals of power equipment such as distribution transformers (i.e., the phase-to-shield wire voltages). Although the decrease of the phase-to-ground induced voltages may not be significant in the case of high values of soil resistivity or ground resistance, as far as phase-to-shield wire voltages are concerned, the effectiveness of the shield wire actually tends to increase under such unfavorable conditions.

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