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Effect of the multi-grounded neutral on the lightning induced voltages in an overhead power line

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Abstract— **This paper analyzed the effect of the multi-grounded neutral on the peak values and waveforms of the lightning induced voltages (LIVs) in an overhead power distribution line. The results show that the LIV waveforms observed close to a neutral grounding point are smooth, while those observed around the mid-point between two consecutive grounding points are oscillatory. The waveform oscillations are reduced with reducing the spacing between grounding points, increasing the distance between the strike and the line, and increasing the value of ground resistivity. For a first negative stroke, these oscillations can be neglected if the distance between the strike and the line is higher than 50 m and the spacing between grounding points is shorter than 200 m. It is also shown that, under certain conditions, the indirect lightning flashover rate of a line with multi-grounded neutral can be assessed from the peak-values of the LIVs of a single wire above ground.**

Keywords- lightning; induced voltage; distribution line; waveform; neutral conductor

I. INTRODUCTION

Lightning induced voltages (LIVs) are an important cause of outages in power distribution lines, especially those installed in rural environment [1]. The probability of a LIV to produce insulation breakdown depends not only on its peak value, but also on its waveform [2]-[5]. The technique proposed by the IEEE Guide 1410 [1] for the assessment of the line flashover rate is based only on the LIV peak value, but uses a factor 1.5 to multiply the line critical flashover overvoltage (CFO). As stated in the Guide, "this factor is an approximation which accounts for the turn-up in the insulation volt–time curve," as the LIVs "are assumed to have much shorter duration wave shapes than the standard 1.2/50-μs test wave" used for CFO determination.

De Conti et al. [6] showed that the simplified 1.5 CFO flashover criterion is likely to underestimate the number of flashovers an overhead line may experience due to nearby lightning flashes and that more realistic flashover rate estimates could be obtained by using a CFO factor lower than 1.5. Paulino et al. [7] investigated this subject and proposed a set of CFO correction factors for different values of ground resistivity and line length. These factors were derived considering a single overhead wire, whereas actual power distribution lines have one to three phase conductors and often also a multi-grounded neutral conductor. As demonstrated by Napolitano [8], the mutual effect of the phase conductors on the LIV can be neglected, as long as the line losses are negligible, so that the results from a single conductor would apply to a three phase line. However, the multi-grounded neutral may affect the LIVs, so that the presence of such conductor should be considered when assessing the flashover rate.

It is important to highlight that it is possible to compute the LIV waveforms and assess its effects on the line flashover rate directly, i.e., without resorting to a CFO correction factor [6], [7], [9]. However, due to the large number of simulations required to assess the line flashover rate, this approach requires significant computational resources, limiting its application to selected cases. Therefore, it seems that the simplified approach as the one contained in the IEEE Guide [1] could still be used, as long as the due improvements are considered [10]-[12].

This paper investigates the effect of the multi-grounded neutral on the LIVs, in order to determine to which extend the presence of the multi-grounded neutral conductor can be taken into account in the simplified flashover assessment based on LIV peak values. The paper is organized as follows. Initially, the model used to compute the LIV in a two-wire line, one of which is regularly grounded, is described and validated. Next, the general conditions considered in the analysis are outlined. A set of simulation results is presented in order to assess the effect of the multi-grounded neutral on the peak values and waveforms of the LIVs. Finally, the results are discussed and some conclusions are provided.

II. TWO-WIRE OVERHEAD LINE MODEL

The model used in this paper to compute the induced voltage in a lossless two-wire line is the one described by Rusck [13]. In this model, compensating voltage sources are introduced in the line to represent the effect of the grounding points along the multi-grounded conductor. This model was implemented in the computer code TIDA, which was described and validated in [14] for a single wire line.

In order to validate the two-wire line model implemented in TIDA, a comparison is made with results obtained by Hoidalen [15]. A 1 km long overhead line is considered. The line is composed of one phase and one neutral conductors, with the

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latter connected to ground at both ends with null ground resistance, as shown in Fig. 1. The characteristic impedance of both conductors is 400 Ω, and the phase conductor is matched to ground at both ends. The ground resistivity is 100 Ω·m and the line height is 10 m. The lightning stroke current has a triangular waveform, with 30 kA peak, 2 µs front-time, and 50 µs time-to-half-value. The return stroke velocity is 150 m/µs.

Fig. 2 shows the LIVs on the phase conductor calculated at both sides of the line, which are identified by A and B in Fig. 1. These LIVs are calculated for three different values of mutual impedances (Z_M) between the conductors: 0, 100, and 200 Ω. In the same figure are shown the LIVs calculated by Hoidalen [15]. It can be seen that the agreement is very good, which validates the two-wire model used in this paper.

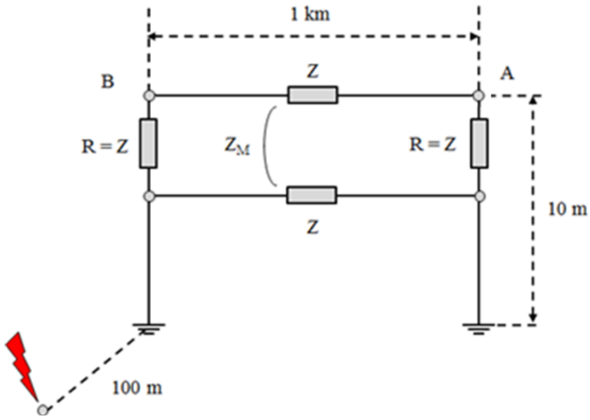

Figure 1. Line configuration used to validate the model.

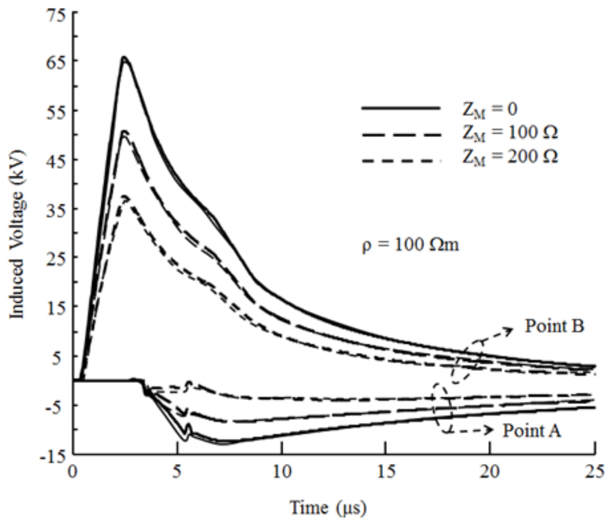

Figure 2. LIVs on both sides of the phase conductor of Fig. 1, for different values of mutual impedances between the conductors. Bold line: this paper; Thin line: results from [15].

III. CONDITIONS CONSIDERED

The diagram of the 5 km line considered in this paper is shown in Fig. 3, which has an upper phase conductor and a lower neutral conductor, placed at 10 m and 8.37 m high, respectively. Both conductors are diagonally matched at line ends, as described in [8], and the neutral conductor is grounded at regular intervals *d*. The soil resistivity values considered are 0, 100, and 1000 Ω·m, and its relative permittivity value is 10.

The return stroke current waveform is the one proposed by Rachidi et al. [16] for the first stroke, having 30 kA peak value, and the return stroke velocity is 120 m/µs. Subsequent strokes are not considered in this study because their contribution to the flashover rate is not significant [11]. The distance between the stroke location and the line is 50 m for close strokes and 500 m for distant strokes.

Two stroke locations are considered, as shown in Fig. 4. The stroke location (a) is aligned with a neutral grounding point and the stroke location (b) is aligned with the mid-point between two adjacent grounding points. The stroke location (b) is equidistant to the line ends, whereas the stroke location (a) is next to stroke location (b). The LIVs are calculated at the points P_1 and P_2 on the phase conductor, for stroke locations (a) and (b), respectively. Fig. 3 shows the points P_1 and P_2.

The value of the grounding resistance varies according to the ground resistivity value, as considered by Borghetti et al. [10]. The ground resistance values are 0, 10, and 100 Ω, for ground resistivity values 0, 100, and 1000 Ω·m, respectively.

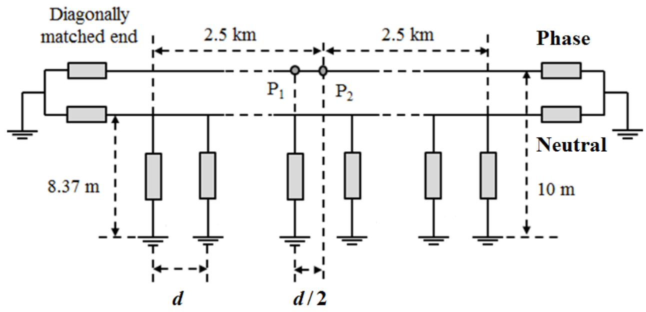

Figure 3. Line diagram for the two wire line simulations.

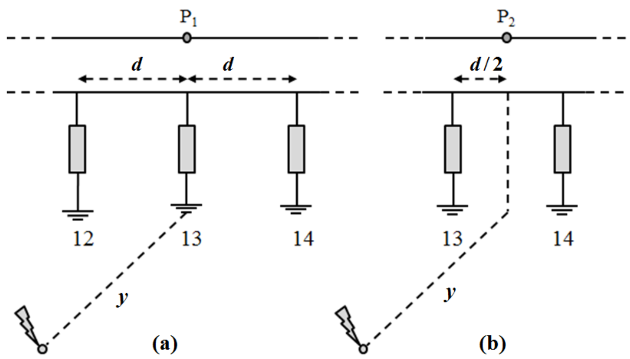

Figure 4. Stroke locations considered. (a) stroke location facing a grounding point; (b) stroke location equidistant to two consecutive grounding points.

IV. Simulation Results

A. Ground spacing

A first set of simulations is carried out in order to investigate the effect of the spacing between grounding points of the neutral conductor. Figs. 5 and 6 show the LIVs for grounding spacing d = 200 m and d = 400 m, respectively. In each figure are shown the LIVs for the phase-to-ground and phase-to-neutral modes, and for the Cases (a) and (b). The distance between the stroke and the line is 50 m and the soil is perfectly conducting.

It is clear from these figures that the LIVs for Case (b) are oscillatory, whereas for the Case (a) they are smooth. As expected, the oscillations are more pronounced for the larger distance between grounding points. As will be shown later, the oscillations are less pronounced for increasing distances from the strike and for increasing soil resistivity. Therefore, the conditions considered in Figs. 5 and 6 (nearby strike and perfect soil) enhance the oscillations.

The other aspect that can be depicted from these figures is that the oscillations do not disturb significantly the LIV waveshape parameters for the 200 m spacing, so that the waveshape parameters from Case (a) and Case (b) come close to each other. This will be investigated in the following sections.

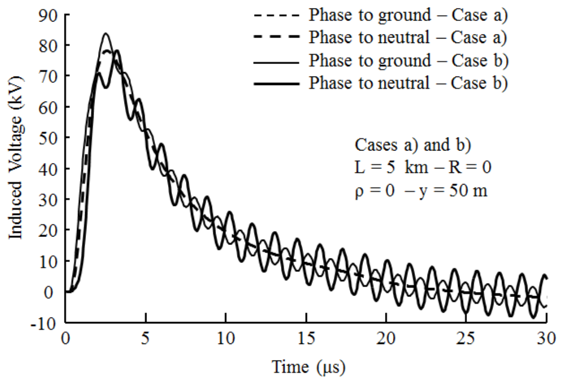

Figure 5. Phase-to-ground and phase-to-neutral LIVs for an ideal soil and y = 50 m. Neutral conductor grounded with 0 Ω at each 200 m.

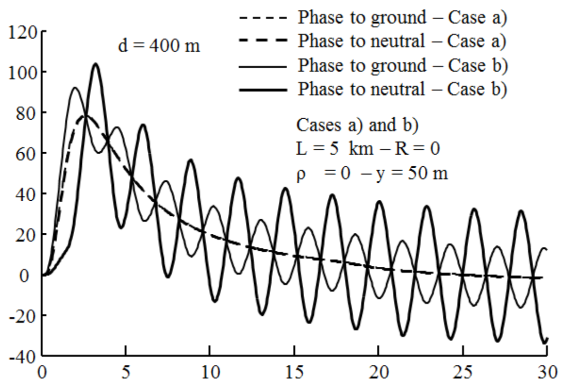

Figure 6. Phase-to-ground and phase-to-neutral LIVs for an ideal soil and y = 50 m. Neutral conductor grounded with 0 Ω at each 400 m.

B. Nearby strikes

This section investigates the LIV due to nearby strikes, i.e., those that hit the ground at 50 m from the line. It is worth to mention that shorter distances are not considered for indirect lightning flashes, as for distances shorter than 50 m the flash is likely to hit the line directly. The distance between grounding points along the neutral conductor is 200 m.

Figs. 7 to 9 show the LIVs for the soil resistivity values 0, 100, and 1000 Ω·m, whereas the corresponding grounding resistances are 0, 10, and 100 Ω. These figures also show the phase-to-ground LIVs when the neutral is absent, referred as Base Case. It can be seen that the oscillations are reduced with increasing ground resistivity values. Moreover, the phase-to-ground voltage is less oscillatory than the phase-to-neutral.

As expected, the LIVs are close to each other for perfectly conducting ground, as the grounding resistance is null. In this case, the phase-to-ground and phase-to-neutral voltages are identical. As the ground resistivity (and grounding resistance) increases, there is a distinction between the phase-to-ground and phase-to-neutral LIVs, which is evident in Fig. 9.

A comparison between the phase-to-ground LIVs with and without the neutral conductor (Base Case) shows that the multi-grounded neutral provides a reduction on the peak value of the LIVs, which is usually referred to as a shielding effect.

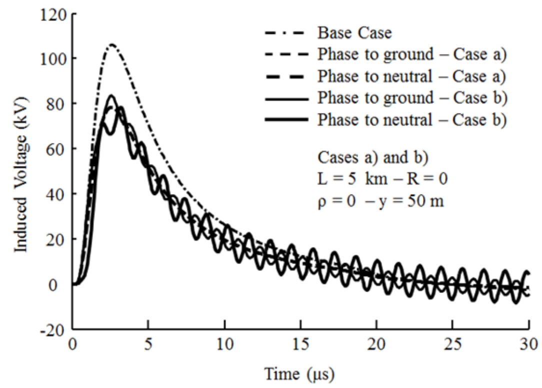

Figure 7. Phase-to-ground and phase-to-neutral LIVs for an ideal soil and y = 50 m. Neutral conductor grounded with 0 Ω at each 200 m.

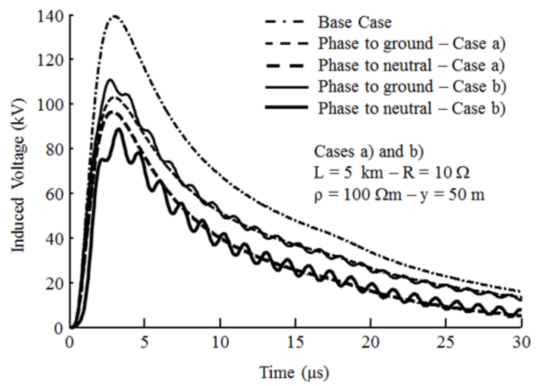

Figure 8. Phase-to-ground and phase-to-neutral LIVs for y = 50 m and 100 Ω·m soil. Neutral conductor grounded with 10 Ω at each 200 m.

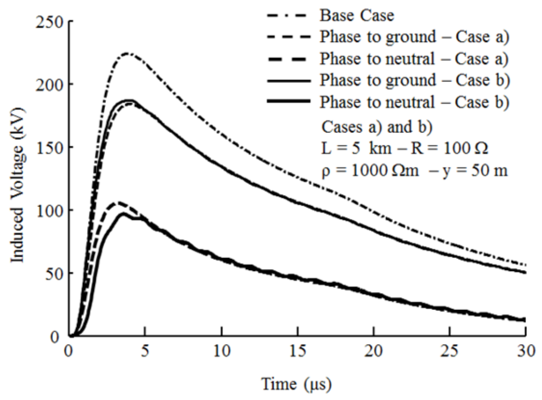

Figure 9. Phase-to-ground and phase-to-neutral LIVs for *y* = 50 m and 1000 Ω·m soil. Neutral conductor grounded with 100 Ω at each 200 m.

C. Distant strikes

This section investigates the LIVs due to distant strikes, i.e., those that hit the ground at 500 m from the line. It is worth to mention that more distant strikes are not considered here, as the resulting LIVs become progressively unlikely to produce insulation breakdown in power distribution lines.

Figs. 10 to 12 show the LIVs for the soil resistivity values 0, 100, and 1000 Ω·m, remembering that the corresponding grounding resistances are 0, 10, and 100 Ω. The phase-to-ground LIVs when the neutral is absent are also shown in these figures, referred as Base Case. It can be seen that the oscillations are significantly reduced when compared with those from nearby strikes (Section IV.B).

Similarly to what was observed for nearby strikes, the LIVs are close to each other for perfectly conducting ground, as the grounding resistance is null. As the ground resistivity (and the grounding resistance) increases, there is a clear distinction between the phase-to-ground and phase-to-neutral LIVs, which is more evident in Fig. 12. Moreover, the voltages for Case (a) and Case (b) are almost identical for distant strikes.

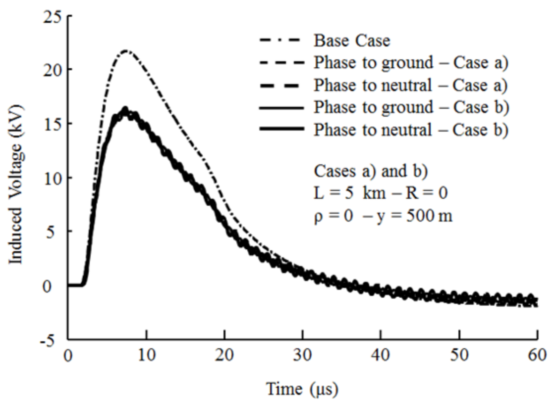

Figure 10. Phase-to-ground and phase-to-neutral LIVs for an ideal soil and *y* = 500 m. Neutral conductor grounded with 0 Ω at each 200 m.

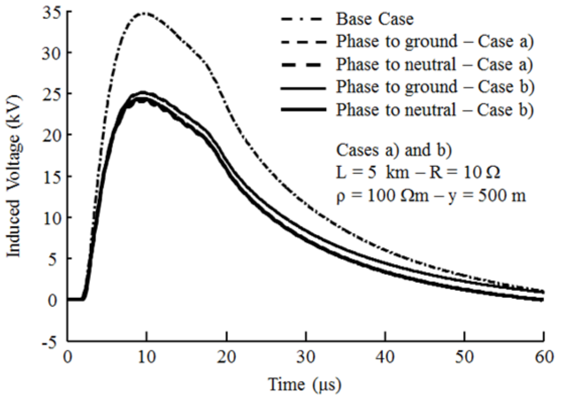

Figure 11. Phase-to-ground and phase-to-neutral LIVs for *y* = 500 m and 100 Ω·m soil. Neutral conductor grounded with 10 Ω at each 200 m.

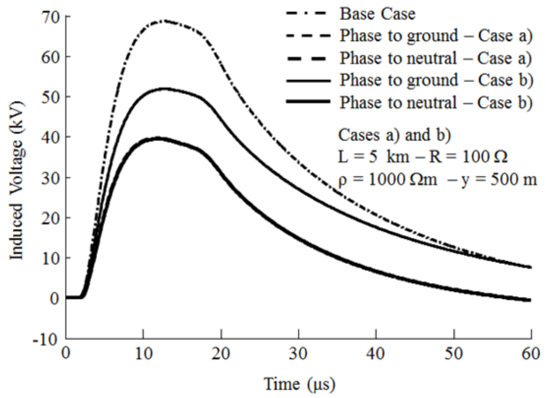

Figure 12. Phase-to-ground and phase-to-neutral LIVs for a 1000 Ω·m soil and *y* = 500 m. Neutral conductor grounded with 100 Ω at each 200 m.

V. ANALYSIS OF THE RESULTS

A. Peak values

Considering perfectly conducting ground, the peak value of the phase-to-ground LIVs on a line with multi-grounded neutral can be obtained by multiplying the peak value of the phase-to-ground voltage when the neutral is absent (Base Case) by the conversion factor proposed by Rusck [13]:

$$\eta = 1 - \frac{h_N}{h_P}\frac{Z_M}{(Z_N + 2R)}\ , \qquad (1)$$

where h_N and h_P are the heights of the neutral and phase conductors, respectively, Z_M is the mutual impedance between these conductors, Z_N is the self-impedance of the neutral conductor, and R is the value of the grounding resistance.

Similarly, the peak value of the phase-to-neutral LIVs on a line with multi-grounded neutral can be obtained by multiplying the peak value of the phase-to-ground voltage when the neutral is absent (Base Case) by the conversion factor proposed by Paulino et al. [16]:

$$\alpha = 1 - \frac{h_N}{h_P} \frac{(Z_M + 2R)}{(Z_N + 2R)} \ . \tag{2}$$

The conversion factor values for the phase-to-ground LIVs considering the simulated waveforms of the previous section are shown in Table I, alongside with those calculated by (1). The simulated values were taken from the curves for the Case (a), as they are smooth. The data considered for the calculation are: h_N = 8.37 m, h_P = 10 m, Z_M = 145 Ω, and Z_N = 461 Ω.

It can be seen in Table I that the simulated conversion factor values for good conducting ground (0 and 100 Ω·m) agree very well with those calculated by (1). This is in line with the conclusion expressed by Paolone et al. [18]: "Rusck simplified formula gives quite accurate results for short spacings between two adjacent groundings (less than 200 m) and when assuming a perfectly conducting ground". For poor conducting ground (1000 Ω·m), the simulated value for nearby strokes agrees well with the one calculated from (1), but the agreement is not so good for distant strokes.

TABLE I. CONVERSION FACTOR VALUES FOR THE PHASE-TO-GROUND VOLTAGE

Ground resistivity value (Ω·m)	**Stroke location**		**Calculated from (1)**
	Nearby strike	***Distant strike***	
0	0.737	0.737	0.737
100	0.739	0.722	0.748
1000	0.820	0.755	0.816

The conversion factor values for the phase-to-neutral LIVs are shown in Table II, alongside with those calculated by (2). It can be seen in Table I that the simulated values for good conducting ground (0 and 100 Ω·m) agree very well with those calculated by (2). For poor conducting ground (1000 Ω·m), the simulated value for distant strokes agrees reasonably well with the one calculated from (2), but the agreement is not so good for nearby strokes.

TABLE II. CONVERSION FACTOR VALUES FOR THE PHASE-TO-NEUTRAL VOLTAGE

Ground resistivity value (Ω·m)	**Stroke location**		**Calculated from (2)**
	Nearby strike	***Distant strike***	
0	0.737	0.737	0.737
100	0.691	0.700	0.713
1000	0.470	0.572	0.563

B. Waveshape parameters

This section presents an analysis of the waveshape parameters of the LIVs, i.e., the front-time (T_F) and the time-to-half-value ($T_{50\%}$), both computed according to [19]. As the LIVs waveforms for Case (b) have oscillations and those for Case (a) are smooth, the latter were used for the waveshape assessment.

Tables III and IV show the waveshape parameters of the Base Case, phase-to-ground, and phase-to-neutral LIVs. Table III is for nearby strikes (y = 50 m) and Table IV is for distant strikes (y = 500 m). As can be seen in these tables, the waveshape parameters of the phase-to-ground LIVs are very close to those of the Base Case. Similarly, the waveshape parameters of the phase-to-neutral LIVs are close to those of the Base Case for good-conducting soil, but the waveshape parameters of the former get smaller than the ones of the latter as the ground resistivity increases.

TABLE III. LIVS WAVESHAPE PARAMETERS FOR NEARBY STRIKES

Soil resistivity (Ω·m)	**Type of line**	**T_F (μs)**	**$T_{50\%}$ (μs)**
0	Base Case	1.7	6.1
	Phase-to-ground	1.7	6.1
	Phase-to-neutral	1.7	6.1
100	Base Case	1.8	9.6
	Phase-to-ground	1.9	9.9
	Phase-to-neutral	1.8	8.2
1000	Base Case	2.2	17.6
	Phase-to-ground	2.4	18.2
	Phase-to-neutral	2.0	12.0

TABLE IV. LIVS WAVESHAPE PARAMETERS FOR DISTANT STRIKES

Soil resistivity (Ωm)	**Number of wires**	**T_F (μs)**	**$T_{50\%}$ (μs)**
0	Base Case	4.0	16.0
	Phase-to-ground	4.0	16.3
	Phase-to-neutral	4.0	16.3
100	Base Case	5.7	22.4
	Phase-to-ground	5.5	22.3
	Phase-to-neutral	5.5	21.5
1000	Base Case	7.5	28.0
	Phase-to-ground	7.5	29.3
	Phase-to-neutral	7.0	24.4

VI. DISCUSSION

The peak value of the LIV in a distribution line without neutral (Base Case) can be easily obtained by means of straightforward formulas [13], [17], [20]-[22]. Considering good conducting soil ($\rho \leq 100$ Ω·m) and closely spaced neutral grounding points ($d \leq 200$ m), Section V.A showed that the LIVs peak values of a distribution line with multi-grounded neutral can be obtained by multiplying the peak values of the Base Case by the conversion factors calculated by (1) or (2), for the phase-to-ground or the phase-to-neutral voltages, respectively. Under these conditions, Section V.B showed that the waveshape parameters of the phase-to-ground and phase-to-neutral LIVs are close to those from the Base Case. Therefore, the flashover rate of a distribution line with multi-grounded neutral could be obtained from the peak values of the Base Case using (1) or (2) and the waveshape-dependent CFO correction factor from [7].

This technique could also be applied to a higher ground resistivity range ($\rho \leq 1000$ Ω·m), as long as the spacing of neutral grounding points is around 200 m and a lower accuracy in the results is acceptable.

For a line with multi-grounded neutral, the relative relevance of the phase-to-ground and the phase-to-neutral voltages to the flashover rate depends on the characteristics of the line. Considering a line with conductive poles (metallic poles or poles made of concrete with steel reinforcement), where the neutral is either directly attached to the pole or insulated by means of a low-CFO insulator, the relevant overvoltage is the phase-to-neutral LIV. In this case, an increase in the pole-foot ground resistance would lead to a reduction in the phase-to-neutral voltage that would stress the phase insulator (see Figs. 9 and 12). This may explain why the flashover rate of distribution lines installed in poorly conducting soils (e.g., State of Minas Gerais, Brazil) experience a significantly lower flashover rate than would be expected from calculations based on the phase-to-ground voltage.

The spacing between consecutive grounding points was limited in 200 m so that oscillations for the Case (b) could be neglected. Of course, this spacing value is related to the front-time of the lightning stroke current considered. The negative first stroke was selected for the analysis carried out in this paper as it is the most relevant source of distribution line outages. Although subsequent strokes are not relevant for line outages [11], it is interesting to assess the waveforms of the LIVs for the same 200 m ground spacing due to a subsequent stroke. Fig. 13 shows the LIVs related to the same case shown in Fig. 5, where the stroke current was substituted by the subsequent stroke waveform proposed by Rachidi et al. [16], which has a peak value of 12 kA and maximum time-derivative of 40 kA/µs. It is clear in Fig. 13 that the oscillations for Case (b) cannot be neglected.

In this paper the ground was considered as homogeneous, while it is generally recognized that the real ground is better described by horizontal layers and that this influence the induced voltages [23]-[26]. An approximate method of taking into account a two-layer ground structure for LIV calculation is considering an equivalent resistivity value, as described by Paulino et al. [12].

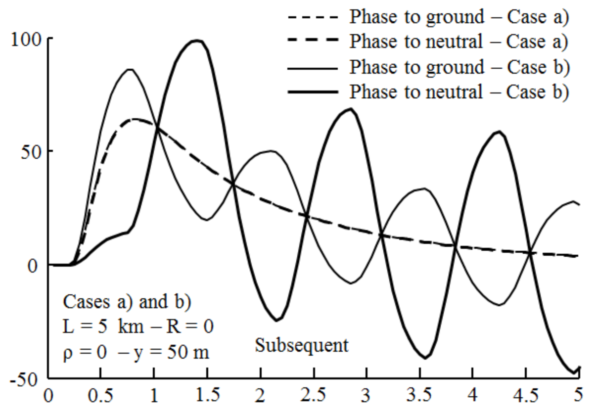

Figure 13. Phase-to-ground and phase-to-neutral LIVs for an ideal soil and y = 50 m. Neutral conductor grounded with 0 Ω at each 200 m. Subsequent stroke current waveform.

A comparison of the results presented in this paper with those published by other authors shows a general good agreement. Most of the previous published data on lightning induced voltages on aerial lines considering the effect of a shield wire or grounded neutral are related to the phase-to-ground voltage. This is the case of data presented by Yokoyama et al. [27], Hoidalen [15], and Paolone et al. [18], which show phase-to-ground voltage waveforms for a point aligned with a grounding connection, indicated Case (a) in Fig. 4. In all cases, the waveforms are smooth (i.e., without oscillations), and the same feature is displayed by the waveforms presented in this paper for this stroke location. Moreover, Fig. 2 shows a good correspondence with the waveform presented by Hoidalen [15].

On the other hand, there are not many published results for the phase-to-neutral voltages. Piantini and Janiszewski [28] presented a set of results considering perfectly conducting ground, while Piantini [29] recently presented results considering finitely conducting ground. The waveforms they presented for Case (b) (See Fig. 4) are oscillatory, especially those for the phase-to-neutral voltage, which agrees with the results presented in this paper. Moreover, similarly to the results of this paper, the waveshape parameters of the phase-to-ground LIVs of a line with multi-grounded neutral are very close to those of a single wire above ground.

Finally, the conclusion from [x] that "the phase-to-ground voltages increase with R_g, while the phase-to-shield wire or phase-to-neutral voltages have opposite behavior" is also in good agreement with the results presented in this paper (R_g is the grounding resistance value, which is designated as R in this paper). As discussed before, this is a relevant finding, as it could explain the relatively good lightning performance of power distribution lines in poorly conducting soils.

VII. Conclusions

This paper shows that the waveshape parameters (front-time and time-to-half-value) of the phase-to-ground LIVs of a line with multi-grounded neutral are very close to those of a single wire above ground. Similarly, the waveshape parameters of the phase-to-neutral LIVs are close to those of a single wire above ground for good-conducting soil, but the waveshape parameters of the former get smaller than the ones of the latter as the ground resistivity increases. These conclusions are valid for a first negative stroke and for spacing between adjacent grounding points not larger than 200 m.

This paper also shows that the indirect lightning flashover rate of a line with multi-grounded neutral can be assessed from the peak-values of the LIVs of a single wire above ground, provided that they are corrected by the factors given in Tables I and II, and that the CFO correction factors given in [7] are used. This technique applies to good conducting soil ($\rho \leq 100$ Ω·m) and closely spaced neutral grounding points ($d \leq 200$ m). This technique could also be applied to a higher ground resistivity range ($\rho \leq 1000$ Ω·m) and a fixed spacing of neutral grounding points ($d = 200$ m), as long as a lower accuracy in the results is acceptable.

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