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Influence of Ground Unevenness and of Line Hybrid Configuration on the Lightning Performance of Medium-Voltage Overhead Distribution Systems

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***Abstract*— This invited lecture deals with the influence of a) ground unevenness and of b) line hybrid configuration on the lightning performance of medium-voltage overhead distribution systems. Point a) is addressed by showing the effects of the presence of tall objects around the power line, such as trees or building, while point b) is addressed by making reference to hybrid lines with high voltage (HV) line conductors at the top and medium voltage (MV) conductors underneath. The analysis is carried out making reference to three cases: i) MV overhead line in an open ground, i.e. without nearby objects; ii) MV line surrounded by elevated objects, such as trees or buildings; iii) MV line conductors mounted on the poles of a HV line. The presence of nearby objects or additional line conductors on the same poles has a twofold effect: the objects (buildings, trees or HV line conductors) may intercept several lightning flashes that would strike the MV line in their absence, and the objects perturb the lightning electromagnetic pulse. The appraisal of the lightning performance of the distribution system is performed by using the LIOV-EMTP-RV code, for the calculation of lightning originated voltages, and the Monte Carlo method. The results relevant to the three cases mentioned above are presented and discussed for ideal and lossy soils, considering the occurrence of both indirect and direct strikes. The paper presents also an analysis of the effectiveness of shield wires and of surge arresters installed along the line.**

Keywords—lightning performance of distribution lines; lightning protection; hybrid lines; Monte Carlo method; LIOV-EMTP

I. INTRODUCTION

In urban or suburban areas, indirect lightning is usually the main problem of interest for distribution lines because the protection against direct strikes is in general economically unjustified, in particular when taller objects around lines are more likely hit by lightning, thus providing a shielding effect against the direct strikes. The assessment of the lightning performance of an overhead distribution line has been, however, most frequently accomplished referring to the situation of a line above an open ground, which certainly simplifies the inherent complexity of the electromagnetic coupling problem.

Nevertheless, the ground around the line can be very different from a flat plane, in that it can include the presence of elevated objects, such as trees, poles or buildings. Additionally, in some cases, such as for hybrid configurations in which a MV and a HV line are mounted together on the same poles, direct lightning flashes to the structure hosting the lines becomes more likely to occur and, therefore, the estimation of the lightning performance should consider also the occurrence of direct strikes.

In view of the above we find it worthwhile to analyze and compare the following three cases:

i) the MV overhead line is above an open ground;
ii) the MV overhead line is surrounded by elevated objects, such as trees or buildings;
ii) the MV line conductors are mounted on the same pole of a high voltage line (hybrid configuration).

Case (i) has been the subject of several interesting papers that allowed to gain important insight on the mechanism of formation of lightning-induced voltages, e.g. [1]–[8]. For cases (ii) and (iii), the presence of objects nearby the line or of an additional line on the same poles has a twofold effect: the objects intercept several lightning flashes that would strike the line conductors in their absence, and the lightning electromagnetic pulse (LEMP) exciting the MV line conductors is modified by the presence of the objects. Concerning the first point, the 'attachment process' can be represented by striking distance expressions, as reviewed in [9]. Concerning the second point, models to represent the LEMP alteration due to elevated objects or the presence of buildings around the line have been proposed in e.g., [10], [11], and [12], [13], respectively.

II. LINE LOCATED IN OPEN TERRAIN

A. Unprotected lines

As mentioned in the Introduction, the problem has been analyzed by several authors (see e.g., [1]–[8]), which show that simplicity is only apparent. Nowadays, a calculation approach that is generally considered appropriate by the scientific community is based on the following three steps:

1) The spatial-temporal distribution of the lightning current along the return stroke channel is specified starting from the channel-base current by means of a return stroke current model (e.g. [14], [15], [16]), then

2) the relevant exciting lightning electromagnetic pulse, LEMP, is calculated, with the finite conductivity of the soil accounted for if necessary, and
3) the induced voltage resulting from the LEMP to transmission line coupling is calculated by means of one of the available EM coupling models based on the transmission line approximation (e.g. Taylor *et al.* [17], Agrawal *et al.* [3], Rachidi [18], Rusk extended by Piantini [8]).

For the calculations presented in this paper use is made of the LIOV-EMTP-RV code [19], [20]. The TL return stroke model by Uman and McLain [14] is adopted when the procedure for the LEMP calculation proposed in [21] is applied. The code implements the numerical solution of the Agrawal *et al.* model for the multi-conductor line response calculation, suitably adapted to the case of interest ([6], [22], [19]).

The lightning performance of a distribution line/system is expressed by means of a curve providing the number of flashovers per year as a function of the insulation level of the line. In general, if referred to a single straight line, the lightning performance is expressed in terms of number of events per year per unit length of line, e.g. 100 km of line as usually done for transmission line.

In particular, the lightning performance of a line is the expected annual number of events $F_p(V)$ that causes overvoltages with an amplitude larger than a given value V:

$$F_p(V) = 2 y_{\max} L \, N_g \frac{n}{n_{tot}} \tag{1}$$

where $y_{\max}$ is the distance of the farthest lightning stroke, the factor 2 accounts for the two sides around the line, L is the line length, n is the numbers of events resulting in overvoltages larger than V and N_g is the annual ground flash density (assumed equal to $N_g = 1$ flash/km^2/yr in this paper).

Fig. 1 shows the comparison between the flashover rates of the single conductor line, as a function of the CFO, above an ideal ground and above a lossy ground with resistivities of 100 Ωm and 1000 Ωm.

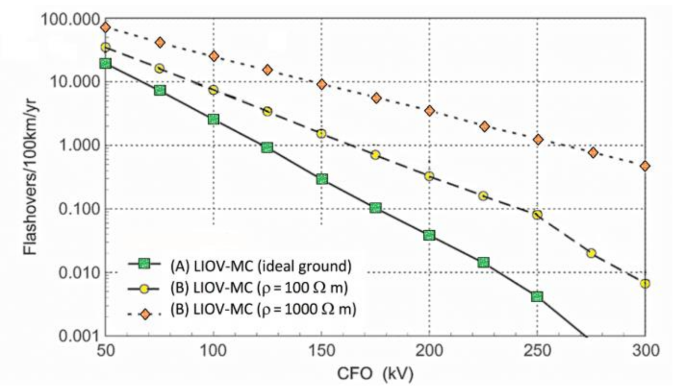


Fig. 1. Flashover rates of a single conductor 10 m high line above an ideal ground and above a lossy ground with resistivities of 100 Ωm and 1000 Ωm. (Adapted from [23]).

The obtained results can be explained observing that, as known [24], when evaluating lightning-induced voltages, the finite value of the ground conductivity on the one hand increases the transient propagation losses in the line but, on the other hand, has also an influence on the LEMP propagation. While the former effect tends to decrease the surges propagating along the line, the latter tends to enhance the amplitude of the induced voltages. It is this second effect that, overall, causes maximum values of induced voltages higher than those calculated for the case of an ideal ground [19], [24].

B. Lines with a shield wire or neutral conductor

The results of Fig. 2 are obtained by assuming the flashover occurring only from the phase conductor to ground. In principle, the line could experience flashovers between the phase conductor and the grounded conductor too.

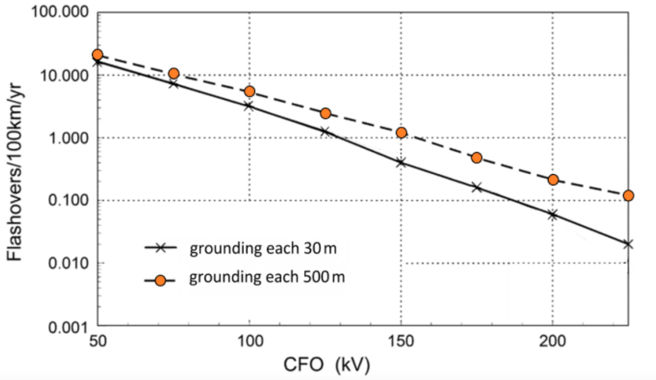


Fig. 2. Flashover rates of a 10 m high single-phase line with a shield (neutral) wire at the height of 8.37 m for grounding spacings of 30 m and 500 m and fixed stroke current front time of 1 μs. Perfectly conducting ground. (Adapted from Reference [23]).

Fig. 3 shows the flashover rates calculated by considering the two different flashover paths, namely the phase-to-ground path and the phase-to-grounded wire one. The results of Fig. 3 must be interpreted by keeping in mind that the two different flashover paths are characterized by different CFOs, especially for wooden poles and crossarms. Let us consider, for example, the curves of Fig. 3 relevant to the soil resistivity of 1000 Ωm and $R_g = 100$ Ω. If we assume a CFO of 200 kV for a phase-to-ground path and a CFO of 130 kV for a phase-to-grounded wire path, we obtain 2.2 flashovers/100 km/year and 4.8 flashovers/100 km/year (and not 0.52 flashovers/100 km/year, as would be the case by improperly assuming the same CFO, 200 kV, for the two cases), respectively.

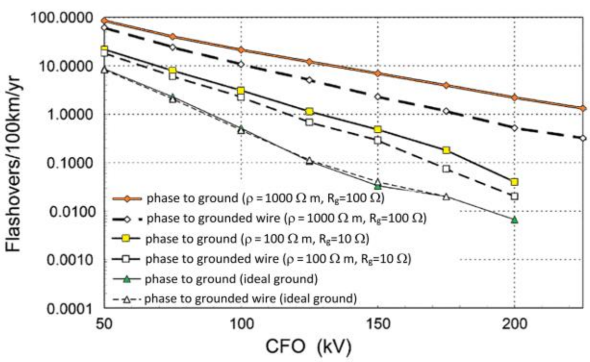
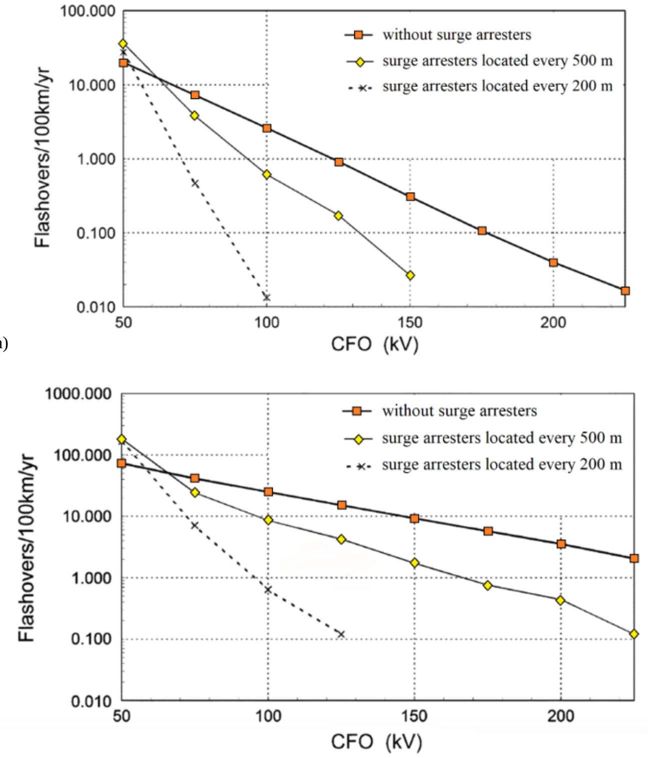


Fig. 3. Phase-to-ground and phase-to-grounded-wire flashover rates of a 10 m high single-phase line with a shield (neutral) wire at the height of 8.37 m for grounding spacing of 200 m and different soil resistivities and ground resistances. (Adapted from [23]).

C. *Lines with surge arresters*

The influence of the presence of surge arresters on the line lightning performance, considering different arrester spacings, is illustrated in Fig. 4. both for the case of ideal and lossy ground. The surge arresters were simulated by using the V–I nonlinear characteristics reported in [25].

The results show that a significant improvement of the line lightning performance can be obtained by reducing the spacing between the surge arresters below 300 m, which is in accordance with the results published in Reference [26]. Interestingly, for low CFO values, the lightning performance of the line may be even worsened by the presence of surge arresters. This is due to the surge reflections occurring in correspondence of surge arrester operations, particularly important for stroke locations distant from the line and for large intervals between consecutive arrester stations [27], [28].



b)

Fig. 4. Flashover rates of the single conductor 10 m high line in absence of surge arresters and with surge arresters located every 200 m and every 500 m for $R_g = 0\ \Omega$ and different soil resistivities. a) perfectly conducting ground, b) lossy ground ($\rho = 1000\ \Omega$m). (Adapted from [23]).

It is worth adding a final remark. The lightning-induced voltage calculations performed to obtain the lightning performances of distribution lines presented so far have been obtained using the commercial version of LIOV-EMTP [19], [20], in which the incident voltage is approximated by multiplying the vertical field calculated at ground level times the height of the line. Such an approximation is valid, in general, as long as the distance between the stroke location and the line is not lower than 50 m or so [29], as according to the electro-geometric model (EGM), a typical first stroke with current peak equal to 30 kA is expected to hit the line if the perspective stroke location distance is lower than 50 m from the line itself. Closer indirect lightning flashes to the line can occur only due to the presence of nearby elevated objects. For these cases the LEMP calculation considers the presence of the nearby object. In particular, the analytical expressions available for the case of a stroke to ground needs to be modified in order to account for a) the current reflections at the top and bottom of the stricken object, and b) the spatial-temporal distribution of the lightning current along the above channel. Also, the presence of the nearby building can have a remarkable impact on the LEMP calculation, and more complex LEMP models are required. The following sections cover matter relevant to these mentioned cases.

III. LINES SURROUNDED BY ELEVATED OBJECTS OR BUILDINGS

A. *Elevated objects nearby the overhead line*

The lightning induced voltages of Fig. 5 and Fig. 6 refer to a negative return stroke and a positive one. The strikes hit a 200 m tall tower located 200 m from an overhead line where the induced voltages are measured. The measured curves are those reported by Yokoyama *et al.* in [30] for strikes labelled as 81-02 and 82-01. In order to account for the effect on the LEMP of the multiple reflections due to the tower struck by lightning, the model proposed in [31] has been implemented in the LIOV-EMTP code. The multiple reflections along the tower and along the lightning channel are calculated by assuming 1000 Ω, 300 Ω and 10 Ω for the lightning channel surge impedance, tower surge impedance and tower grounding resistance, respectively. The return stroke speed is assumed to be equal to half of the speed of light. The surges propagate at the speed of light along the tower and, after reflections, in the lightning channel. Reflections at the wavefront are neglected (an approach to account for these reflections is described in [32]). The assumed ground conductivity is σ_g = 0.01 S/m and its effect on the radial component of the electric field is accounted for by using the Cooray-Rubinstein formula [33], [34]. Fig. 5 compares the induced voltage measured at pole 5 with the induced voltage calculated with and without the effect of the tower calculated by assuming the same channel-base current, reported in Table I (assumed, in case with tower, as the undisturbed current, i.e. the current that would take place in absence of the object).

Table 1. Undisturbed current used for the calculation of the induced voltages shown in Fig. 5.

Time (μs)	Current (kA)
0.0	0.0
3.9	5.0
4.8	7.6
6.6	8.9
20	8.9

The experimental distribution line is represented in LIOV-EMTP according to the description given in [35]. The comparison appears to be good and in accordance with the comparisons shown in [36] and [37].

Fig. 6 presents the induced voltages measured at pole 5 for the case 82-01 (positive lightning) with 11.5 kA peak amplitude, reproduced by assuming a trapezoidal current waveform (i.e. linear front and flat top) with a front time equal to 1 μs and peak amplitude equal to 10 kA as undisturbed current. The comparisons are satisfactory, given the non-linear response of the measurement setup.

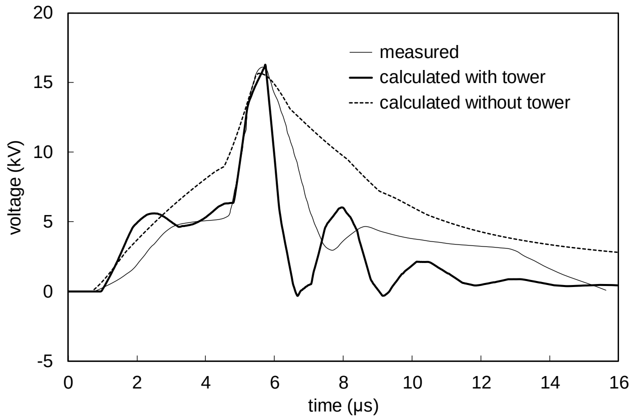


Fig. 5. Comparison between measured voltage (sampled by [30]) and calculated voltage, pole n.5, case 81-02. Negative return stroke.

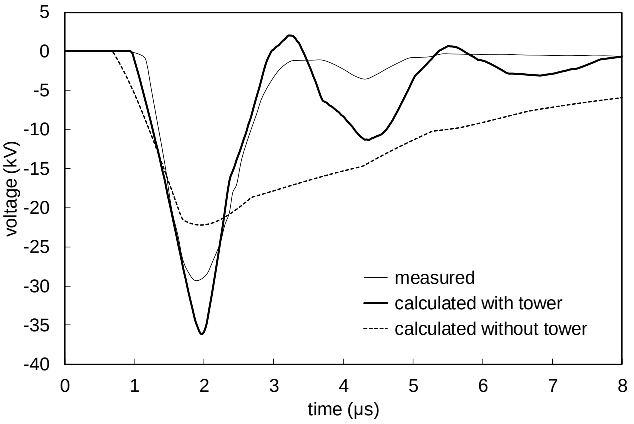


Fig. 6. Comparison between measured voltage (sampled by [30]) and calculated voltage, pole n. 5, case 82-01. Positive return stroke.

B. Buildings nearby the overhead line

In order to evaluate the lightning performance of a line located in an urban area, the effects due to the presence of nearby buildings should be taken into account. In the calculations presented in this subsection, the reduction of the number of flashes collected by the line is accounted for by applying the EGM to distinguish direct strikes to the line, strikes to the buildings or to ground. Also, the attenuation of the LEMP due to nearby buildings is taken into account. In particular, for accomplishing a fast calculation of the LEMP attenuation, Tossani et al. [13] propose to apply weighting functions to the electrostatic, induction and radiation field terms calculated by using the Master and Uman equations [4] and the Cooray-Rubinstein formula for the case of lossy ground [33], [34]. The parameters of the weighting functions are identified through the least square minimization of the differences with the results provided by the FEM model presented in [12]. The LEMP attenuated by the surrounding buildings is used for the calculation of the induced voltages due to indirect lightning events by using the LIOV code (described in Reference [19]) based on the LEMP-to-line coupling model proposed by Agrawal *et al.* [3].

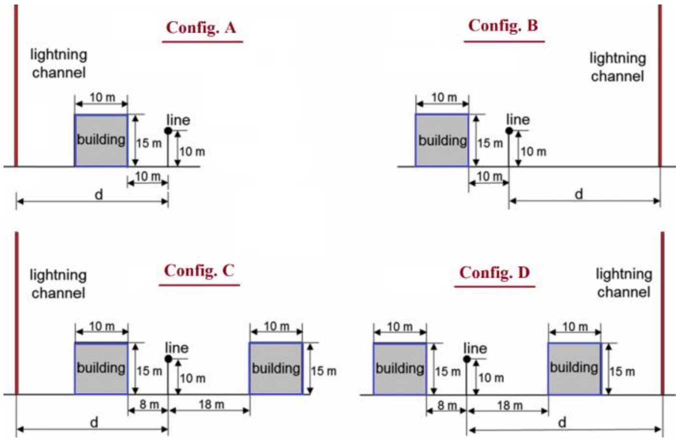


Fig. 7. Considered line-building configurations: A and B with one building; C and D with the line in the space between two buildings. Adapted from [13].

Fig. 7 presents the four line-building configurations considered in the analysis, while Fig. 8 and Fig. 9 show the lightning performances $F_p(V)$ of the line with buildings at one or both sides, respectively. The distances between the line and the buildings are those illustrated in Fig. 7. Both figures show the results calculated:

- without the presence of the buildings;
- by taking into account the presence of the buildings concerning only the distinction between direct strikes to the line and indirect events, i.e. only the shielding effect of the buildings is considered;
- by taking into account both the shielding effect and the attenuation of the LEMP provided by the buildings.

As shown in the figures, all the calculations are carried out for the cases of both ideal and lossy ground with resistivity ρ = 100 Ωm.

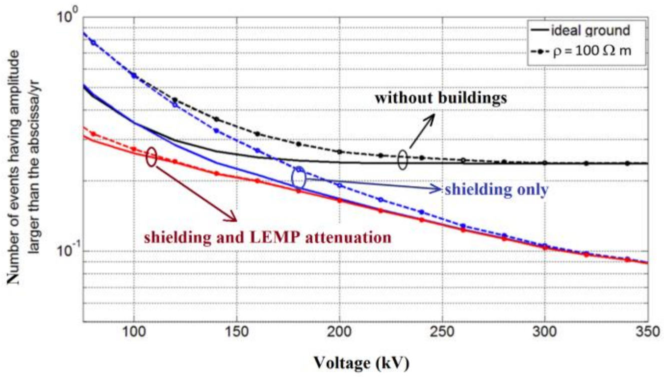


Fig. 8. Lightning performance of the line with buildings at one side and without buildings. (Adapted from [13]).

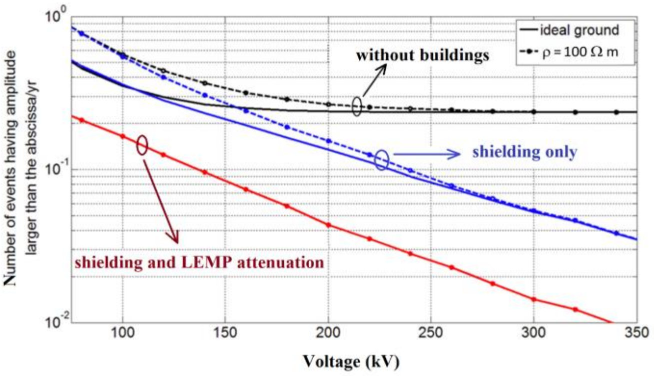


Fig. 9. Lightning performance of the line with buildings at both sides and without buildings. (Adapted from [13].)

Without buildings, the expected annual number of overvoltages with peak amplitude larger than 150 kV (typical insulation level of MV lines [38]) is 0.26 for ideal ground and 0.34 for lossy ground, with an increment of 31%.

For the case of a line with buildings at one side only (Fig. 8), if only the shielding effect is taken into account the numbers of overvoltages larger than 150 kV are 0.22 (ideal ground) and 0.30 (lossy ground), with an increment of 36%, whilst when LEMP attenuation is also taken into account the number is 0.21 for both ideal and lossy ground.

For the case of a line with buildings at both sides (Fig. 9), if only the shielding effect is taken into account the numbers of overvoltages are 0.21 (ideal ground) and 0.27 (lossy ground), with an increment of 29%. On the other hand, when the LEMP attenuation is also considered, the number is 0.08 for both ideal and lossy ground.

Fig. 8 and Fig. 9 show that when the LEMP attenuation due to the presence of the buildings is considered, the influence of the finite soil conductivity becomes almost negligible, especially for the case of a line with buildings at both sides. According to these results, the LEMP attenuation provided by the buildings improves significantly the lightning performance: for a line with a 150 kV withstand voltage and buildings on both sides, the annual number of overvoltages is reduced by around 70% and 76% for the cases of ideal and lossy ground, respectively. It is important, therefore, to consider the LEMP reduction effect in addition to the shielding effect already included in the procedures recommended by the Standards.

IV. Hybrid Configuration (MV and HV Lines Mounted on the Same Poles)

As known, in some areas characterized by low availability either of land or ways of right for building overhead lines, it is convenient to install a medium voltage distribution line on the same pylons or poles holding a high voltage transmission line. The resulting multi-voltage overhead line configuration poses peculiar issues with respect to both the electromagnetic coupling between the conductors of the MV and HV lines, as analyzed in [39], and the voltages across the insulators due to direct strikes [40].

The presence of the HV conductors reduces the induced overvoltages in the MV line due to indirect lightning events. However, due to the presence of the HV conductors, the number of direct events hitting the overhead ground wire (OHGW) of the hybrid line is significantly higher than the one expected to strike a MV line in open terrain. This justify a specific section for this double circuit configuration. The two configurations considered in this subsection are depicted in Fig. 10a (69-kV line) and Fig. 10b (138-kV line). In both cases the MV line (15-kV insulation class) has a compact structure, i.e. insulated phase wires (without shield) with reduced distances secured by periodical spacers suspended by an upper unenergized wire called messenger.

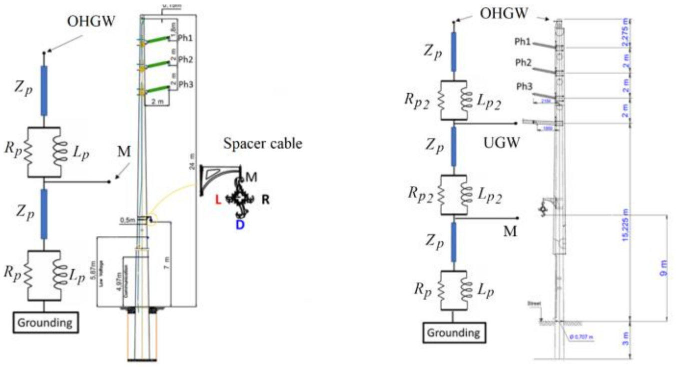
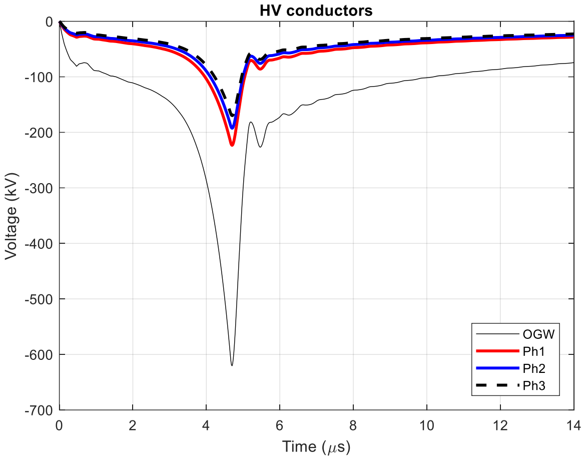


Fig. 10. Geometry and EMTP model of the considered concrete poles of the double-circuit line. left) 69-kV transmission line; right) 138-kV transmission line (adapted from [41]).

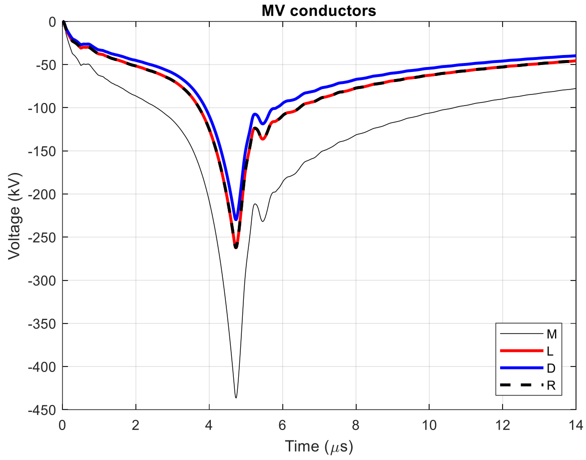
The MV line conductors are located below the HV conductors, 7 m above ground in the case of the 69-kV line and 9 m in the 138-kV line. On the top of both structures there is an OGHW grounded at every pole. Moreover, the 138-kV line has an underbuilt ground wire (UGW) located 2 m below the lowest phase conductor, grounded at each pole, that reduces the back flashover rate, as described in Reference [41]. Between two consecutive poles of the HV line, in the middle of each span, there is a shorter MV pole, having the function of sustaining the compact MV line. The span distances between the 69-kV line poles and the 138-kV line poles are 70 m and 80 m, respectively. The value adopted for the ground resistivity is equal to 1000 Ωm in all the simulations presented in this subsection.

The value of the pole surge impedance has been assumed equal to $Z_p = 200\ \Omega$ according to the experimental data presented in Reference [42]. As shown in Fig. 10a, the pole of the 69-kV configuration has been split in two equal parts, one between the OHGW connection and the messenger connection (point M) and the other between point M and ground. The 138-kV pole has been split in three portions: 5 m between OHGW and UGW, 5 m between UGW and point M, and 10 m between point M and ground (Fig. 10b). The values of the damping resistance and inductance of the model shown in Fig. 10 have been estimated according to Reference [43]. Their values are $R_p = 33\ \Omega$ and $L_p = 5.33\ \mu$H for the 69-kV line and $R_{p2} = 16.6\ \Omega$ and $L_{p2} = 2.66\ \mu$H for the 138-kV line. The effect of soil ionization is represented by using Weck's formula [44].

Fig. 11a and b show the overvoltages due to a direct strike to the OGW on the 69-kV line HV conductors and the MV conductors, respectively. The considered channel-base current has a peak value of 31 kA and a maximum time-derivative of 26 kA/µs, assumed as typical of a first negative return stroke, represented by the CIGRE current function [44]. The same comparison is shown in Fig. 12a and b for the case of the 138-kV configuration.



a)

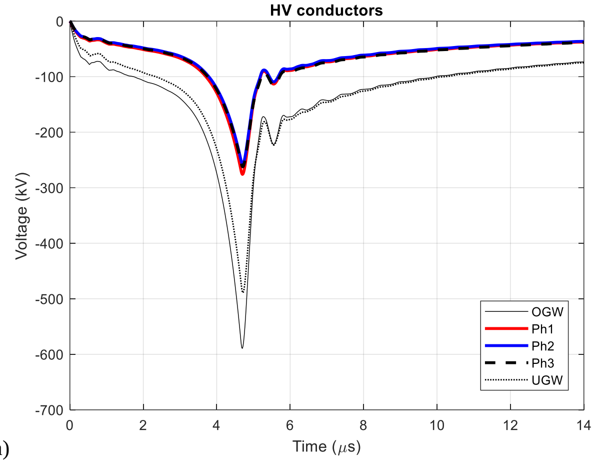


b)

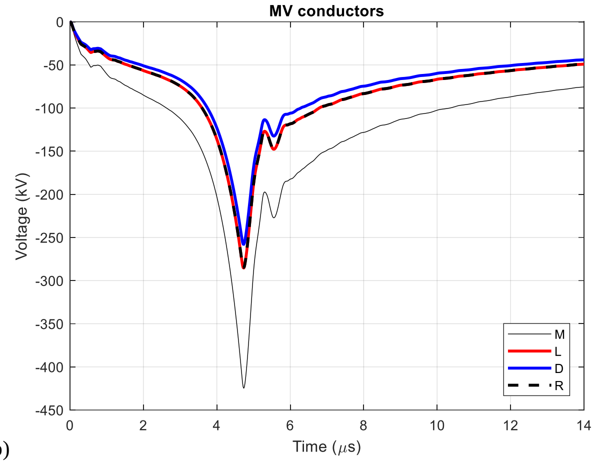
Fig. 11. Overvoltages in the 69-kV line due to a direct strike to OGW in the middle of the line: a) HV conductors; b) MV conductors. R_g=40 Ω.

The presence of the UGW in the 138-kV line reduces the potential difference between the phases and the OGW and UGW, decreasing the back-flashover rate of the HV phase conductors, especially concerning the lowest one (phase 3), which is the farthest from the OGW. By comparing Fig. 11b and Fig. 12b it can be observed that also the voltage between conductors M and D is slightly lower in the 138-kV configuration than in the 69-kV one.

Fig. 13 - Fig. 16 show the lightning performance of the MV line in case the HV conductors are present or not, for the four different configurations: 69 kV and R_g = 20 Ω (Fig. 13), 138-kV and R_g = 20 Ω (Fig. 14), 69-kV and R_g = 40 Ω (Fig. 15), 138-kV and R_g = 40 Ω (Fig. 16). Both direct and indirect events are considered.



a)



b)

Fig. 12. Overvoltages in the 138-kV line due to a direct strike to OGW in the middle of the line: a) HV conductors; b) MV conductors. R_g=40 Ω.

As anticipated, the overall lightning performance of the MV line of the multi-circuit configuration is improved with respect to the case of a MV line alone. The main reasons for the better performance are:

- although the number of direct strikes increases in the double-circuit configurations with respect to the MV line alone, the groundings of the overhead ground wire and of the underbuilt ground wire, when present, are effective in limiting the voltage stress of the MV line;
- the voltage induced in the overhead ground wire is larger than in the messenger, causing a significant ground potential rise that reduces the voltage across spacers and insulators.

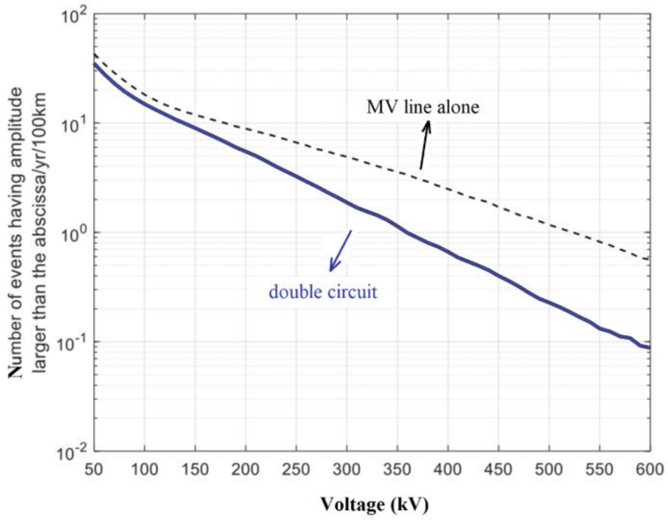


Fig. 13. Lightning performance of the 69-kV configuration considering both direct and indirect events. R_g = 20 Ω. (Adapted from [45]).

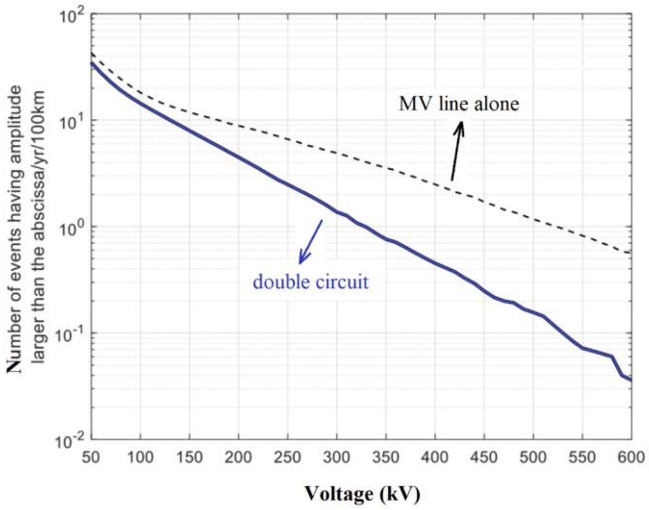


Fig. 14. Lightning performance of the 138-kV configuration considering both direct and indirect events. R_g = 20 Ω. (Adapted from [45]).

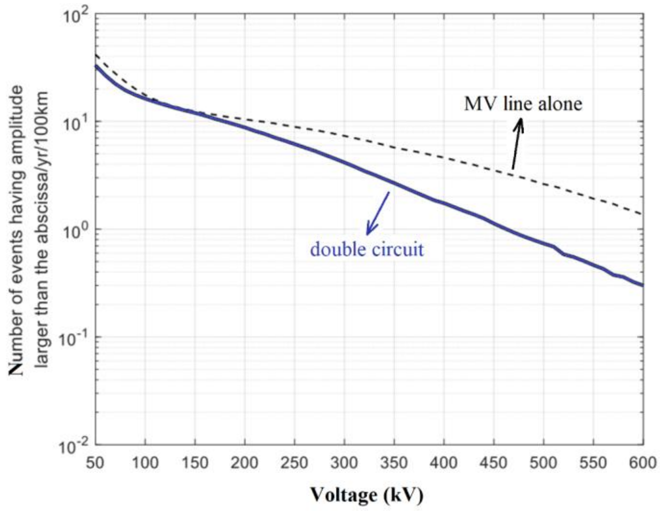


Fig. 15. Lightning performance of the 69-kV configuration considering both direct and indirect events. R_g = 40 Ω. (Adapted from [45]).

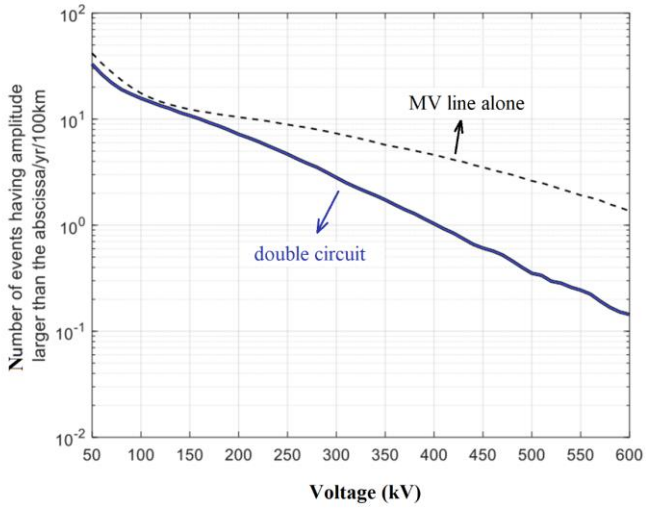


Fig. 16. Lightning performance of the 138-kV configuration considering both direct and indirect events. R_g = 40 Ω. (Adapted from [45]).

V. CONCLUSIONS

This paper introduces step by step some complexities to the case of an overhead line above an open ground, in order to progressively approach the lightning performance of more realistic cases, such as the one of a line surrounded by buildings or the case of a distribution MV-line sharing the same poles of a transmission HV-line.

The statistical analysis showed that, for each of the considered cases, the factor that contributes most to the worsening of the lightning performance is the soil resistivity: the larger the resistivity, the poorer the lightning performance. On the other hand, the presence of buildings around the line causes an improvement in its lightning performance by providing a shielding that leads to a decrease of the number of direct strokes that hit the line conductors and by modifying the lightning electromagnetic pulse.

Concerning shield wires, the shorter the grounding spacing, the larger the effectiveness in attenuating lightning-induced voltages. Similarly, the shorter the arrester spacing, the better the line lightning performance.

For distribution systems located in urban or suburban areas, indirect lightning is usually the main problem of interest due to the presence of tall objects around the lines, which are capable of attracting lightning strokes in lieu of their conductors. However, for hybrid configurations, in which both a MV and a HV line are mounted together on the same poles, direct lightning flashes becomes more likely to occur, and should be considered. The performances of lines with hybrid configurations are analyzed considering different conditions and the results showed that the performance of a MV line that shares the structures with a HV line tends to be better than that of a MV line alone.

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