On the Role of Shield Wires in Mitigating Lightning-Induced Overvoltages in Overhead Lines - Part II: Simulation Results for Practical Configurations

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***Abstract*—In the companion Part I, the theory relevant to the role of shield wires in mitigating lightning-induced overvoltages in overhead lines has been analyzed and clarified. A more consistent meaning has been assigned to the concept of Shielding Factor by introducing two innovations compared to the current literature: the first one concerning the distinction between *internal* and *external* parameters, and the other one concerning the point along the line where to assess the mitigation effect. Thanks to this new approach, uncertainties seen in the literature have been sorted out, and the Shielding Factor has been shown to be a parameter which can be precisely quantified. However, our new contribution was applied to a schematic (unrealistic) configuration: a line with a shield wire grounded at only one point. This Part II is precisely devoted to confirming the results obtained in Part I, by applying the proposed approach to more realistic and practical line configurations, namely a line with multi-grounded shield wire, and a line equipped with laterals too.**

***Index Terms*—Lightning, lightning-induced voltages, shielding factor, shield wires.**

I. Introduction

In THE companion Part I [1], an analysis on the role of Shield Wires (SWs) in mitigating lightning-induced overvoltages in overhead lines was carried out. The concept of Shielding Factor (SF) (also called Protective Ratio (PR)) was presented, and the relevant theory was outlined. After a critical review of this theory, two important innovations compared to the current literature were proposed: the first one concerns the distinction between *internal* (controllable) and *external* (uncontrollable) parameters, and the other one refers to the point along the line where to assess the mitigation effect. As for the distinction between internal and external parameters it was demonstrated, both theoretically and by numerical simulations, that in the case of SW with a single grounding point, the SF varies significantly with internal parameters and, at the same time, has no practical variations with external parameters. As for the point along the line where to assess the mitigation effect, unlike common approaches found in the literature (generally identifying this point as the one closest to the lightning channel), it was shown that such point should always be where the SW is grounded. From this new perspective, the SF assumes a more precise and specific meaning, and may be one of the line design specifications, being under the designer's control to a large extent. The key point, now, is to see how much of the results obtained for the simplistic (unrealistic) solution analyzed in Part I (line with SW grounded at a single point) may be preserved on moving to more realistic cases, such as lines with multi-grounded SW and with laterals too. This kind of investigations will be carried out in the present paper.

We will analyze two realistic cases of growing complexity: a line with multi-grounded SW, whose topology is the same as in [2], and a line with multiple grounding points and laterals, similarly to the situation analyzed in [3]. These two cases will be referred to as Case A and Case B, respectively.

The paper is organized as follows: a brief description of the CiLIV tool used for the simulations is provided in Section II; Case A is analyzed in Section III with reference to all parameters which may affect the mitigation effect, investigating both internal and external parameters; the same approach will be adopted in Section IV for the analysis of the more complex Case B. Concluding remarks and future perspectives are presented in Section V.

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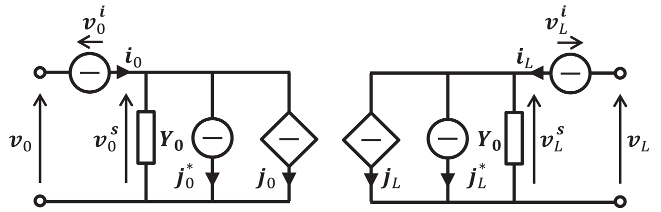


Fig. 1. Equivalent circuit of an excited multiconductor line (time domain) used in the CiLIV code.

II. Brief Description of the CiLIV Tool

The simulation tool "Circuit for Lightning-Induced Voltage" (CiLIV) [4], [5] is a circuit in the frequency domain, which is then solved in the time domain: this hybrid approach is particularly suitable for lightning-induced voltage calculations in power systems. Approaches in the frequency domain allow to treat conductors and ground losses in a very easy and direct way, but their applicability is limited to linear problems; approaches in the time domain can easily treat non-linearities such as those introduced by surge arresters, but complex convolution integrations are needed to account for conductors and ground losses. The CiLIV code implements the dipole technique for the assessment of the lighting electromagnetic field [6] and the Agrawal *et al.* model [7] for the coupling between the lightning electromagnetic field and the overhead line. The equivalent circuit in the time domain is presented in Fig. 1(symbols' meaning can be found in [4]).

A fundamental feature of CiLIV code is that the time-domain solution is divided into two parts: the *principal part*, which accounts for the surge propagation along the line, is solved entirely analytically [4]; the *regular remainder*, which accounts for the surge attenuation and distortion due to line losses, is described by regular functions [4], and can solved either analytically or numerically (it depends on the complexity of the considered model) [4]. In particular, with lines which can be treated as lossless, such as lines shorter than 2 km [8], the solution can be entirely derived analytically. Configurations with lossy lines which can be treated as frequency-independent, show regular remainders: they can be solved analytically, in some cases [4]. Configurations with lossy lines having frequency-dependent parameters show regular remainder that are generally solved numerically [4]. Accuracy of CiLIV code has been thoroughly analyzed in [5].

III. Case A: Line With Multi-Grounded SW

Case A refers to a more realistic configuration compared to the case analyzed in Part I: it consists in a line extending for 3 km with multiple grounding of the SW. The configuration is depicted in Fig. 2. The line, except for the conductors arrangement, which is given in Fig. 4 of Part I (the reader is referred to Part I for all the line parameters too), is identical to the one proposed in [2]. We will make here more realistic assumptions compared to the cases analyzed in Part I: in particular, we will assume that the grounding system of the SW is represented by a series of an inductor and a resistor (e.g., [2], [9]) (in Part I we assumed just a resistor). The inductor is introduced to account for the

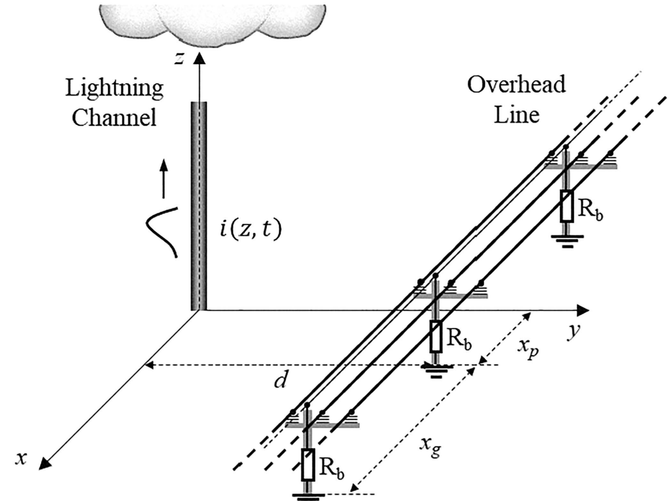
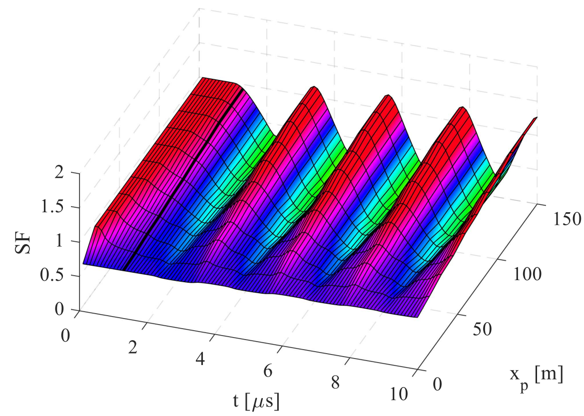


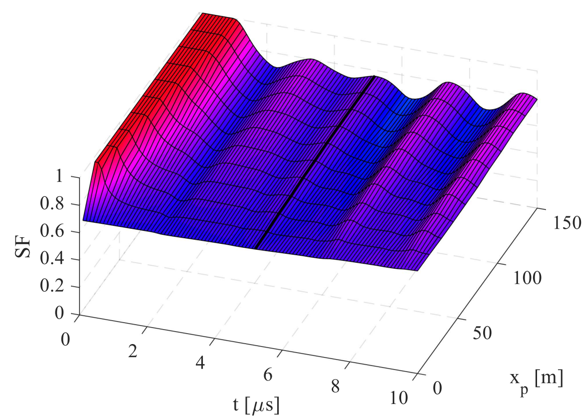
Fig. 2. Line with multi-grounded SW (d is the distance between the lightning channel and the line, x_p is the offset between the point of the line closest to the lightning channel and the SW grounding point, x_g is the grounding spacing, R_b is the grounding resistance).

inductance of the grounding lead, assuming a value of $1\mu\mathrm{H/m}$ [2] (we will assume a value of $11\mu\mathrm{H}$ when the SW is located in a fixed position, that is 11 m; otherwise we will assume the value corresponding to the height of the SW, which is variable in some of the simulations). The influence of finitely conducting ground will be considered both on the surge propagation along the line and on the propagation of the lightning electromagnetic field. Such realistic assumptions are accurately handled by the CiLIV tool [4], [5].

The first check to be made concerns the point where to assess the SF, to confirm that this point should be the SW grounding point (in this case of multiple grounding, the SW grounding point closest to the lightning channel). To this end, we will examine (analogously to Part I) both the approach of the current literature, which assesses the SF at the point closest to the lightning channel, and the proposed approach, which recommends making this assessment at the closest SW grounding point. Let us consider Fig. 2: we will evaluate the SF at the point closest to the lightning channel for different positions of the SW grounding point (by varying the offset distance x_p). In particular, x_p will be varied between $x_p = 0$ (i.e., lightning channel in front of the SW grounding point) and $x_p = 150$ m (i.e., lightning channel in front of the point at the middle of the span, assuming a span x_g of 300 m). The results are shown in Fig. 3 for three different values of the front time ($t_f = 1$ μs, $t_f = 5$ μs, and $t_f = 10$ μs). We report the plots referring to both definitions of SF: as usual, the one referring to the ratio of the peaks of the induced voltages is marked by the solid black line. Results of Part I still hold (compare with Figs. 4 and 5 of Part I): one can notice a large variability of the SF when the front time is that typical of subsequent strokes, whereas this variability is more limited for front times which are typical of first strokes. As in Part I, this irregularity does not allow one to attribute a specific meaning to the SF; furthermore, Fig. 3 shows another criticality of the approach proposed in the literature, which is physically incoherent: according to the current approach, it is found that, due to bouncing of induced voltages



(a)



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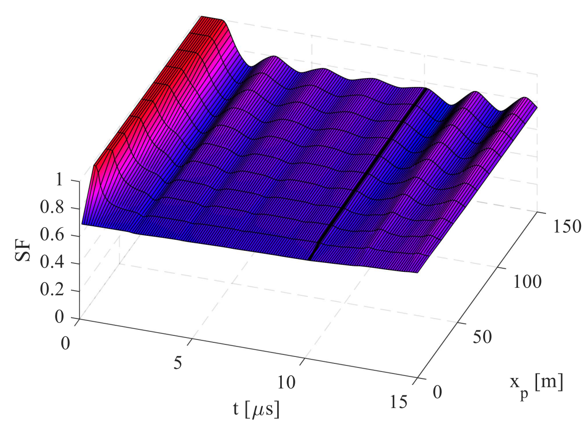
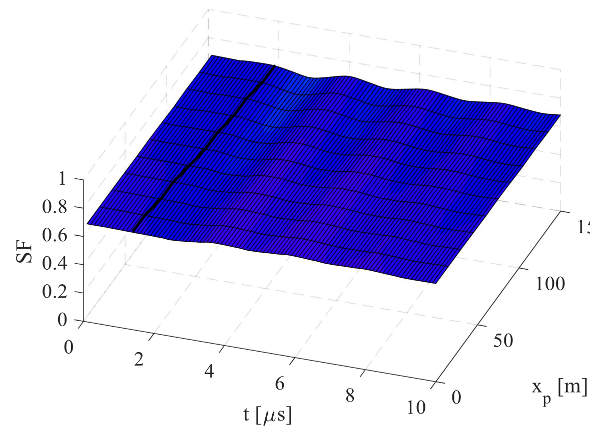
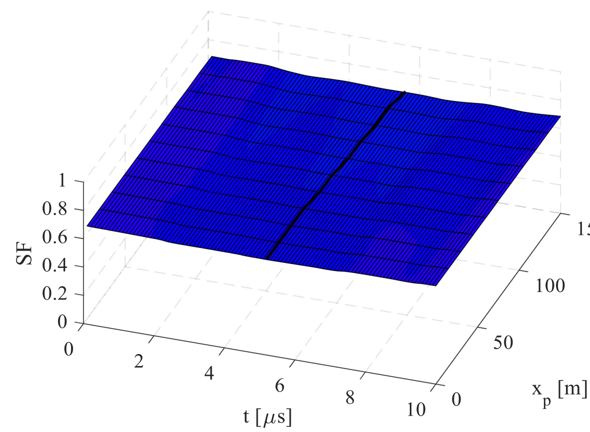


(c)

Fig. 3. SF versus time t and offset distance x_p assessing the SF at the point of the line closest to the lightning channel (see Fig. 2) for three different front times ($t_f = 1$ μs (a), $t_f = 5$ μs (b), $t_f = 10$ μs (c)), ($d = 50$ m, $R_b = 50$ Ω, $h_b = 11$ m, $x_g = 300$ m, $I_0 = 10$ kA, $\beta = 0.4$, $\varepsilon_r = 10$, $\sigma = 0.01$ S/m).



(a)



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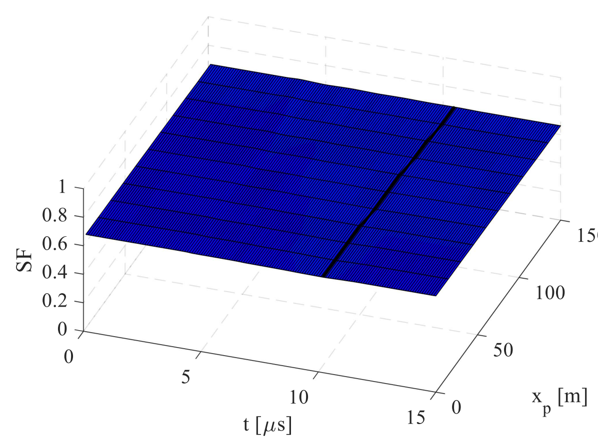

(c)

Fig. 4. SF versus time t and offset distance x_p assessing the SF at the SW grounding point (see Fig. 2) for three different front times ($t_f = 1$ μs (a), $t_f = 5$ μs (b), $t_f = 10$ μs (c)), ($d = 50$ m, $R_b = 50$ Ω, $h_b = 11$ m, $x_g = 300$ m, $I_0 = 10$ kA, $\beta = 0.4$, $\varepsilon_r = 10$, $\sigma = 0.01$ S/m).

between poles where the SW is grounded, the SW may present an amplifying effect instead of a shielding effect (induced voltages may become higher than those produced when the shield wire is not in place), presenting a value of the SF greater than 1. This is an inconsistency that our approach fixes: indeed, if we evaluate the SF at the closest SW grounding point, we obtain the plot shown in Fig. 4. In this case, the SF completely regains a consistent meaning, allowing to quantify the mitigation effect. It should be noted that a small ripple (especially for fast front times) is still apparent due to significant reflections produced at the grounding points. The validity of the approach presented in Part I, which suggest to assess the SF at a SW grounding point, is confirmed for this more realistic configuration; as for the distinction between internal and external parameters, this

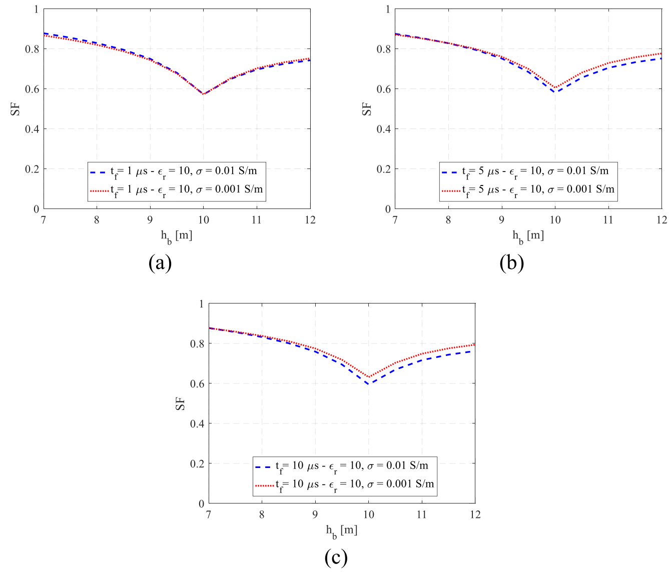

Fig. 5. SF versus SW height h_b for three different front times ($t_f = 1\mu$s (a), $t_f = 5$ μs (b), and 10 μs (c)) and finitely conducting ground ($\varepsilon_r = 10$, $\sigma = 0.01$ S/m and $\sigma = 0.001$ S/m), ($x_p = 0$, $d = 50$ m, $R_b = 50$ Ω, $h_b = 11$ m, $x_g = 300$ m, $I_0 = 10$ kA, $\beta = 0.4$).

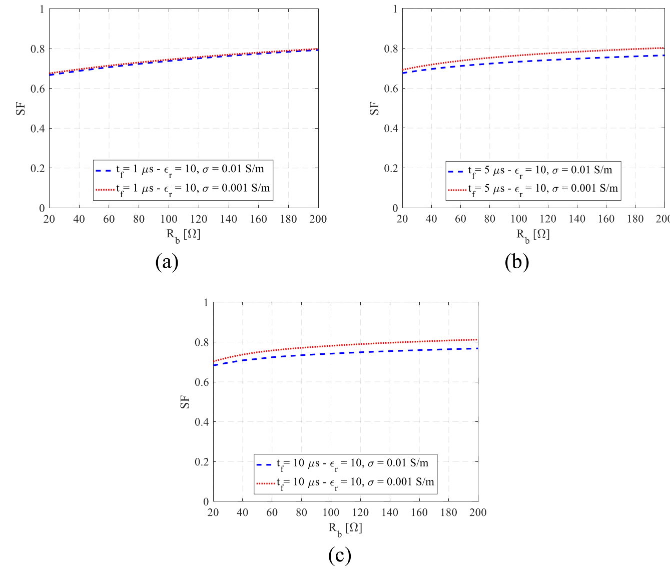

Fig. 6. SF versus SW grounding resistance R_b for three different front times ($t_f = 1\mu$s (a), $t_f = 5$ μs (b), and 10 μs (c)) and finitely conducting ground ($\varepsilon_r = 10$, $\sigma = 0.01$ S/m and $\sigma = 0.001$ S/m), ($x_p = 0$, $d = 50$ m, $h_b = 11$ m, $x_g = 300$ m, $I_0 = 10$ kA, $\beta = 0.4$).

will be assessed in the following Sections, in the same fashion as in Part I.

A. Variability of SF With Internal Parameters

Analogously to Part I, in this Section we will analyze the influence of internal parameters. We reiterate that, also in this case of a more complex configuration, the proposed approach is practically independent of the definition of SF: similar results are obtained whether it is defined as the ratio of the peak voltages, or as the ratio of the voltages along the time (see Fig. 4). For this reason, only results relevant to the definition involving the peak values will be displayed. This was also a practical choice: we will show parametric behaviors which would be very difficult to see on 3-D surface plots, especially when differences are limited, as in our case. Furthermore, compared to Part I, the grounding spacing is considered as an additional internal parameter (not applicable to Part I).

1) SW Height: In Fig. 5, we show three plots with different combinations of front times and ground conductivities: three front times, $t_f = 1$ μs, 5 μs and 10 μs, and two ground conductivities, $\sigma = 0.01$ and 0.001 S/m[1]. Analogously to the simple case of one SW grounding point analyzed in Part I, there are no significant differences in the SF values due to external parameters in all analyzed cases: the maximum difference is about 0.035 (4%) at 12 m for $t_f = 10\mu$s. The height of the SW (internal parameter) has a large impact on the SF (important for design purposes, as commented in Part I). A large number of numerical simulations was carried out, employing different values for these parameters, and similar results were obtained.

2) SW Grounding Resistance: The role of the grounding resistance R_b can be seen in Fig. 6. As previously found for the schematic case of Part I, external parameters do not significantly affect the SF as desired. We reiterate that in the present investigation the effects due to finitely conducting ground have been accounted for both in the propagation of the lightning electromagnetic field and in the surge propagation along the line; furthermore, these ground losses are intrinsically accounted for in the characterization of the grounding resistance. At this juncture it is very interesting to make a comparison between our approach and the one proposed in the current literature: at the value $R_b = 20$ Ω, according to the proposed approach, the SF is practically constant, varying from 0.668 at 0.01 S/m to 0.673 at 0.001 S/m, for $t_f = 1$ μs, whereas in the approach of the current literature, which can be found in [2, Fig. 6], we see an extremely variable SF with values ranging from 0.64 at 0.1 S/m to 0.8 at 0.001 S/m. This confirms that in the approach of the current literature the SF has no precise meaning, which is regained once the alternative proposal presented here is implemented.

3) Grounding Spacing: Grounding spacing x_g (see Fig. 2) must be considered as an additional internal parameter compared to the configuration used in Part I (in Part I we analyzed the case of a single grounding point). In Fig. 7, we show the SF computed for variable grounding spacing x_g (assuming that one of the SW grounding points is placed in front of the lightning channel). A large variability of this parameter is considered, ranging from 50 m to 300 m: outputs show a negligible dependency of the SF from the external parameters front time t_f, and ground conductivity σ, as expected. We further comment that the grounding spacing has no significant impact on the SF. It is also interesting to make a comparison between the average SF calculated for Fig 7(a) (using CiLIV), SF = 0.693 for 0.01 S/m and SF = 0.700 for 0.001S/m, and the value calculated by expressions (1) and (9) of Part I, obtained for the configuration of a single grounding

[1]It should be noted that, since we are dealing with more realistic configurations, idealized cases of a lightning current of the step-function type ($t_f = 0\mu$s) and perfectly conducting ground condition ($\sigma = \infty$) have been disregarded.

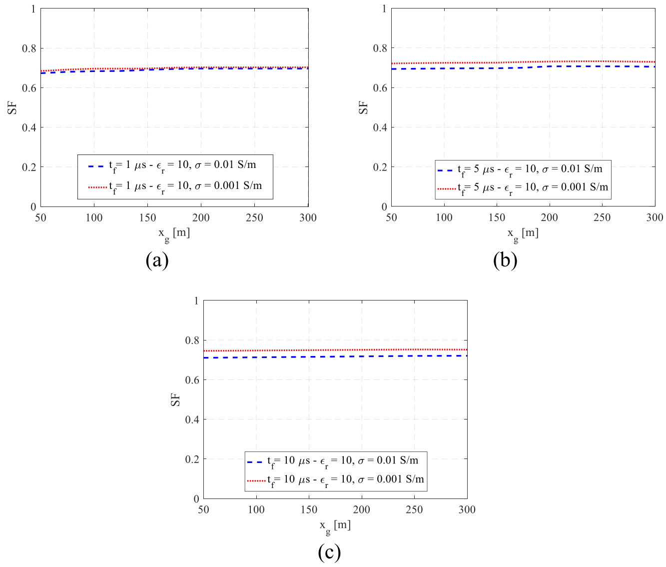

Fig. 7. SF versus grounding spacing x_g for three different front times ($t_f = 1 \mu$s (a), $t_f = 5$ μs (b), and 10 μs (c)) and finitely conducting ground ($\varepsilon_r = 10$, $\sigma = 0.01$ S/m and $\sigma = 0.001$ S/m), ($x_p = 0$, $d = 50$ m, $h_b = 11$ m, $x_g = 300$ m, $I_0 = 10$ kA, $\beta = 0.4$).

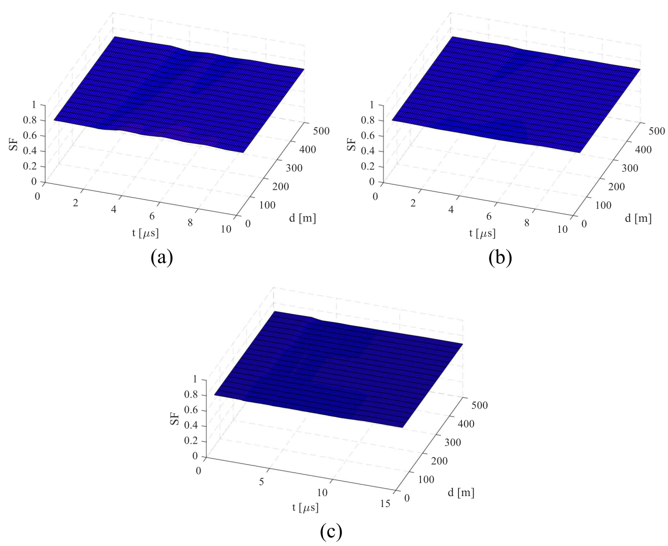

Fig. 8. SF versus time t and distance d for three different front times ($t_f = 1 \mu$s (a), $t_f = 5$ μs (b), and 10 μs (c)) and finitely conducting ground ($\varepsilon_r = 10$, $\sigma = 0.01$ S/m), ($x_p = 0$, $R_b = 50$ Ω, $h_b = 11$ m, $x_g = 300$ m, $I_0 = 10$ kA, $\beta = 0.4$).

point, which is SF = 0.691: being all these values very close, the simple formulas presented in Part I can be considered sufficiently accurate and may be used as practical tools for these calculations.

B. Variability of SF With External Parameters

1) Distance Between the Line and Lightning Channel; Offset Distance of the Lightning Channel to SW Grounding Point: We show the SF versus time t and distance d for a front time $t_f = 1$ μs (Fig. 8(a)), $t_f = 5$ μs (Fig. 8(b)), and $t_f = 10$ μs (Fig. 8(c)): it can be seen, as in Part I, that the SF is practically independent of the distance d; the independence of the SF from the offset distance x_p was already shown in Fig. 4.

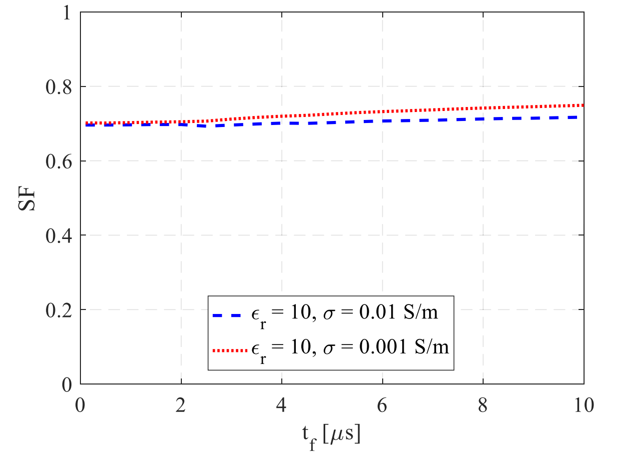

Fig. 9. SF versus front time t_f for two different values of ground conductivity ($\varepsilon_r = 10$, $\sigma = 0.01$ S/m and $\sigma = 0.001$ S/m), ($x_p = 0$, $d = 50$ m, $R_b = 50$ Ω, $h_b = 11$ m, $x_g = 300$ m, $I_0 = 10$ kA, $\beta = 0.4$).

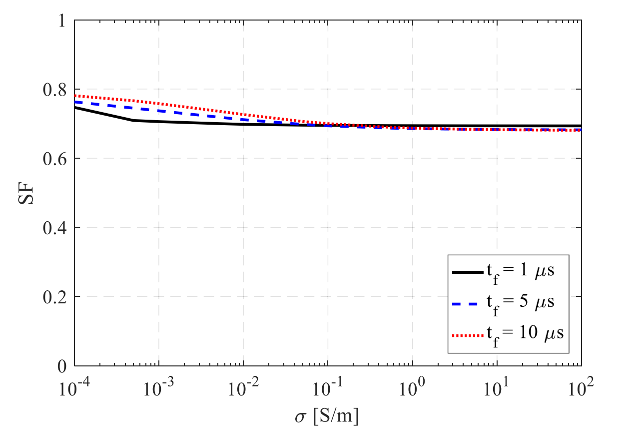

Fig. 10. SF versus ground conductivity σ for three different values of front time ($t_f = 1\mu$s, 5 μs and 10 μs), ($x_p = 0$, $d = 50$ m, $R_b = 50$ Ω, $h_b = 11$ m, $x_g = 300$ m, $I_0 = 10$ kA, $\beta = 0.4$).

2) Front Time: In Fig. 9, we analyze the SF versus front time t_f for two different ground conductivities: the SF is practically independent for fast front times, even for a significant variation of the ground conductivity; a slight variation is seen for slow front times.

3) Ground Conductivity: We show the SF versus ground conductivity in Fig. 10. Apart from a certain variation for very poorly conducting ground, the SF value gradually settles to a constant value. The initial variability can be explained: in presence of poorly conducting ground the lightning electromagnetic field tends to spread and penetrate more deeply into the soil, and the ratio $v'_a(t)/v_a(t)$ tends to become significantly different compared to the simple proportionality h_b/h_a appearing in (9) of Part I.

This proportionality is regained for good ground conductivities.

C. Multi-Grounded SW, Not Grounded at Each Pole

At this stage we need to investigate cases in which the SW is not grounded at each pole: this is also a common practice, e.g., [10], [11]. The configuration is depicted in Fig. 11. We can

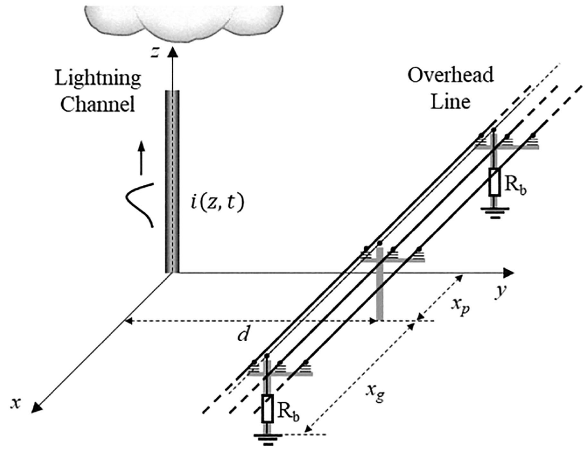

Fig. 11. Line with multi-grounded SW, not grounded at each pole.

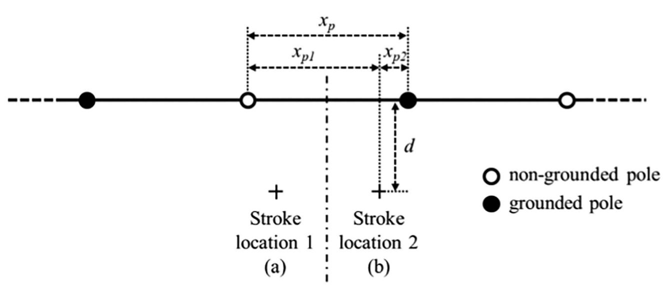

Fig. 12. Multi-grounded SW, not grounded at each pole.

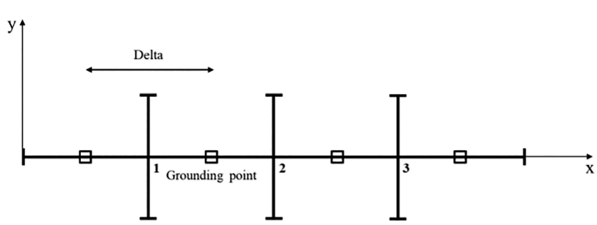

Fig. 13. Line with laterals. Same configuration of the line used in [3]; conductors arrangement same as [1].

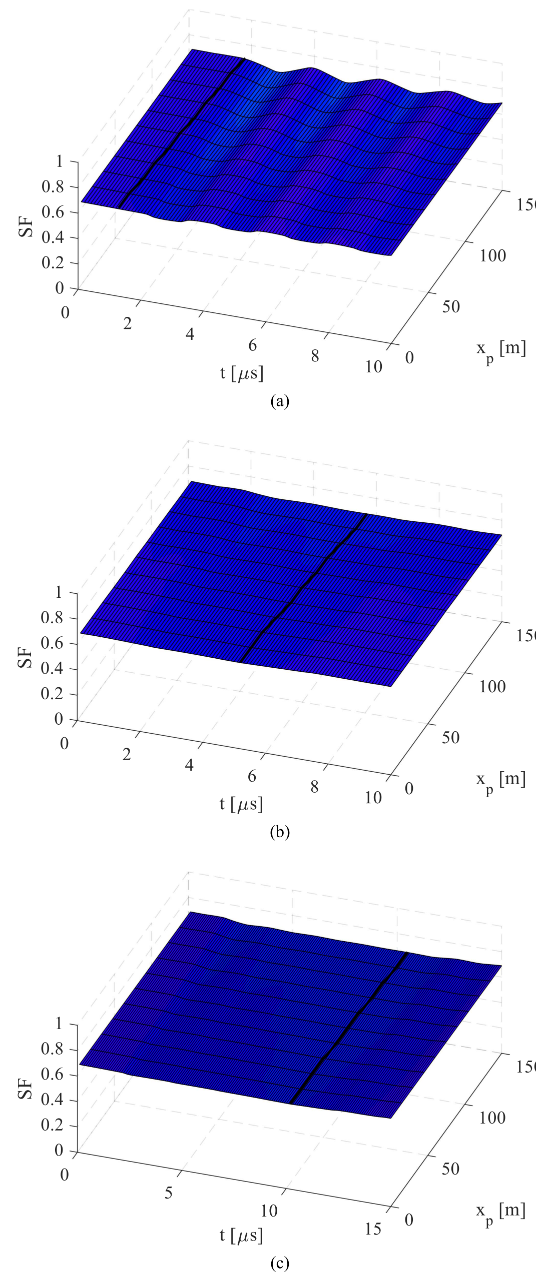

Fig. 14. SF versus time t and x_p for three different front times: (a) $t_f = 1$ μs, (b) $t_f = 5$ μs, (c) $t_f = 10$ μs ($d = 50$ m, $R_b = 50$ Ω, $h_b = 11$ m, $x_g = 300$ m, $I_0 = 10$ kA, $\beta = 0.4$, $\varepsilon_r = 10$, $\sigma = 0.01$ S/m).

face two different situations, shown in Fig. 12: case a), stroke location 1, and case b), stroke location 2. The first one regards the condition when the lightning channel is closer to a tower (pole) where the SW is not grounded; the second one corresponds to the opposite condition. If the situation is that of Fig 12, case a), we are in a condition that we could define "unprotected": the condition is exactly the same as if the SW were not installed and the present analysis just do not apply (indeed, the closest pole has no SW grounded and, at the same time, the pole with the grounded SW will not have the time, due to delays along the line, to mitigate the induced voltage at the ungrounded pole). The situation in Fig. 12, case b) is much more complex: a flashover will not occur at the non-grounded pole if time will be allowed for the grounded pole to make effective its mitigation at the non-grounded one. This time depends (see Fig. 12) on the distance d, on the offset distances x_{p1} and x_{p2}, and on the front time t_f of the lightning current; further, this assessment should be carried out on a statistical basis. Such an assessment deserves an in-depth investigation, outside the scope of the present paper, which we will address in future studies.

IV. Case B: Line With Multiple Grounding Points and Laterals

Case B is a more complex case in which, besides the main feeder, laterals are considered. The line arrangement is the same as in Case A, but with a more complex topology, shown in Fig. 13. This configuration is the one used in [3]. The 1200 m main feeder, and three laterals (at 300, 600, and 900 m from the beginning of the feeder), each one 300 m in length, are shown.

Note that all line terminations (i.e., main feeder and laterals) are closed on their characteristic impedances not to produce

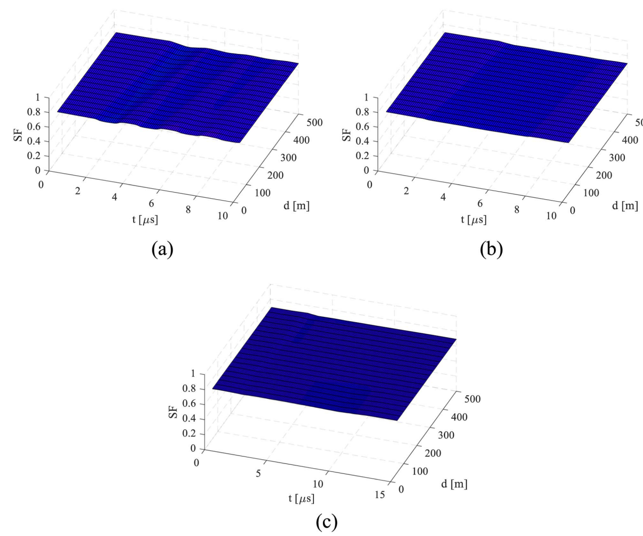

Fig. 15. SF versus time t and distance d for three different front times ($t_f = 1 \mu$s (a), $t_f = 5$ μs (b), and 10 μs (c)) and finitely conducting ground ($\varepsilon_r = 10$, $\sigma = 0.01$ S/m), ($x_p = 0$, $R_b = 50\,\Omega$, $h_b = 11$ m, $x_g = 300$ m, $I_0 = 10$ kA, $\beta = 0.4$).

further reflections in addition to those due to the grounding points.

Firstly, we analyze the SF for three different front times (Fig. 14). The variation of x_p is obtained by moving horizontally the lightning channel, starting from the position when it is front of the "grounding point" ($x_p = 0$), and moving it to the right until point "2" which is located at $x_p = 150$ m (note that Delta $= 300$ m in Fig. 13).

For fast front times ($t_f = 1$ μs) a certain ripple is observed; however, the plot was presented for a very large temporal window to show the difference between this Case B and the simpler Case A (Fig. 4). As discussed above, an equally appropriate analysis should focus at time instants when the peak values form, according to the alternative definition of the SF, i.e., within the first 2 μs (compare for example with Fig. 4(a)). In this time interval, the SF is very regular, confirming the proposed approach. We made a further investigation on the influence of the distance d on the SF: again, a practical invariability of the SF with this parameter was found, as shown in Fig. 15. We ran several different combinations of parameters for this Case B, and very similar results to Case A were found: the validity of the proposed approach can be considered confirmed.

V. Concluding Remarks and Future Perspectives

In this paper we investigated the validity of the approach proposed in Part I regarding the role of SWs in mitigating lightning-induced voltages. Compared to Part I, this investigation analyzed two more complex and realistic cases: a) a line with multi-grounded SW, and b) a line with multi-grounded SW and laterals. The main results found in Part I have been essentially confirmed; small differences were expected: indeed, in the cases analyzed in this Part II, very significant reflections occur due to the presence of multiple grounding points.

Assuming that the SW is grounded at each pole, the SF is a well defined concept and can be quantified through the proposed approach, even for more realistic configurations. It was also shown that, if the SW is grounded at each pole, the designer may rely on the simple formulas (1) and (9) of Part I as a practical tool to quantify the mitigation. Regarding a more accurate assessment of the mitigation, considering the role of other components/devices typically installed in distribution networks, and not analyzed in the present investigations, such as transformers installed at the lines terminations, this assessment should be carried out on a case-by-case basis, considering the peculiarities of the specific network. Further, in the light of the results obtained in this paper, some topics could be explored in the future:

1) lightning performance assessment in case of multi-grounded SW not grounded at each pole;
2) a new definition of the SF in the frequency domain. This definition would not preclude the subsequent calculation of the time-dependent SF, but could be very useful in this context;
3) non-periodicity of SW grounding (by this we mean that distances between grounding points are different pole to pole, which is a typical condition): this to remove resonances which may occur under assumption of periodicity.

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