On the Role of Shield Wires in Mitigating Lightning-Induced Overvoltages in Overhead Lines - Part I: A Critical Review and a New Analysis

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***Abstract*—The ability of shield wires installed in overhead lines to mitigate lightning-induced overvoltages has been extensively investigated. Unfortunately, these studies came to different results, sometimes contradicting each other: some authors found that shield wires produce a significant overvoltage reduction, while others found the reduction negligible; conflicting results also pertain to the role played by the various parameters involved, such as the relative height of the shield wire(s) compared to the phase conductors. This paper aims to clarify this topic. The paper is organized in two parts: Part I, which starts from the analysis of the theory behind the mitigation effect, is devoted to establishing a more solid base to the topic. Two fundamental improvements are proposed. The first one is the distinction between *internal* and *external* of the parameters involved: current literature makes an indiscriminate grouping of all of them; the second one is concerned with the point along the line where the mitigation effect needs to be assessed. Thanks to this new approach, we show that this effect can be precisely quantified. The analysis in this Part I is limited to the basic case of a single grounding point of the shield wire, which represents an unrealistic case. Part II is devoted to completing the study, by applying the proposed approach to more realistic and practical cases.**

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

I. Introduction

LIGHTNING-INDUCED overvoltages can be very severe in overhead distribution lines, causing temporary or permanent faults (e.g., [1], [2]). Three mitigating solutions can be adopted: increase the Critical Flashover (CFO), install surge arresters, install Shield Wire(s) (SW)[1]. In this paper we will focus on the latter solution.

A. Problem Statement and State of the Art

SWs are seldom installed in distribution lines: few countries adopt such a solution, and, when installed, their design is primarily devoted to protection from direct lightning (e.g., [3], [4]). Even fewer countries address both direct and indirect lightning issues in their SW design (e.g., [5], [6]). Nonetheless, the ability of SWs to mitigate lightning-induced overvoltages in overhead distribution lines has been extensively investigated (e.g., [7]–[22]). Unfortunately, these studies have achieved different results, sometimes contradicting each other. According to some authors, SWs produce a significant overvoltage reduction, e.g., [7], [11]; while others found this reduction negligible, e.g., [12]. There is also a debate about the influence of some parameters in producing this mitigation effect: for instance, some researchers (including the authors) give to the SW height an important role (varying the SW height will significantly affect the mitigation effect, e.g., [7]–[11], [13]), while for others the SW height plays virtually no role (varying the SW height will not affect the mitigation effect, e.g., [15]). Moreover, an additional issue must be acknowledged: current literature generally agrees that it is practically impossible to associate a precise value of mitigation to a specific line configuration equipped with SW(s). This is because this effect does not depend only on the line characteristics (conductors' arrangement, span length, etc.) but is also variable with random (uncontrollable) parameters, such as the front time of the lightning current, the distance between the lightning channel and the overhead line, etc. **At present, such conflicting and uncertain results prevent a specific quantification of the mitigation effect and of the benefits which can**

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[1]Note that in this context we are using the term shield wire according to the IEEE Standard 1410 [1]: shield wires are grounded wires placed near the phase conductors (they can be placed both above and below the phase conductors) with the aim of reducing the induced voltages from external electromagnetic fields, lowering the self surge impedance, and rising the mutual surge impedance to the protected phase conductors. They have also the aim of reducing the incidence of direct lightning strokes to phase conductors when they are placed above the phase conductors.

TABLE I
PARAMETERS AFFECTING THE MITIGATION EFFECT

Parameter	Notes
a) SW absolute height	Height compared to ground level. *Internal* parameter (controllable)
b) SW relative height	Relative to the phase conductors. *Internal* parameter (controllable)
c) SW Grounding resistance	*Internal* parameter* (controllable)
d) Grounding spacing	*Internal* parameter (controllable)
e) Distance between the line and the lightning channel	*External* parameter (uncontrollable)
f) Offset distance of the lightning channel compared to the SW grounding point	*External* parameter (uncontrollable)
g) Front time of the lightning current**	*External* parameter (uncontrollable)
h) Ground conductivity	*External* parameter (uncontrollable)

*The SW grounding resistance (classified as internal parameter) is strictly linked to the ground conductivity (external parameter). However, in this context, it is assumed that the designer may control (by a proper choice of shape, dimension, and arrangement of the grounding electrodes) the SW grounding resistance within limits, which are compatible with the present classification (internal parameter). We stress that the designer has some flexibility by acting on the different internal parameters to gain the desired SF: if this is not the case, without affecting the present approach, he will necessarily choose a less effective SF.
**The decay time has been correctly omitted in the list presented in [14] since it does not significantly affect the mitigation [13].

be gained by installing SWs; this represents a significant limitation, also from a techno-economic perspective.

In the light of the above considerations, although some authors - mainly Yokoyama (e.g., [8], [23]–[26]) and Piantini (e.g., [11], [14], [18], [27]) - have significantly contributed to these studies with fundamental results, the influence of SWs in mitigating lightning-induced voltages is still not completely clear, and further clarification and organization is warranted.

B. Contribution

Starting with the approach proposed in the literature, and retracing all the fundamental steps, the paper will identify and clarify its shortcomings and explain why the literature has produced such conflicting results. A more robust approach will be presented, that will also provide, from a practical perspective, a guide to relate a given line design to a precise degree of mitigation.

Going into more technical details, we recall that the overvoltage reduction produced by SWs can be quantified by the ratio of the voltage induced on the considered conductor to the voltage that would be induced on the same conductor if the SWs were not in place. This ratio is referred to as Shielding Factor (SF) (e.g., [7]) or Protective Ratio (PR) (e.g., [8]–[10]).

It should be emphasized that all the parameters affecting this mitigation effect (see Table I) have been commonly collected in a general and indiscriminate group. In the authors' opinion, such indiscriminate grouping is misleading, and likely the main reason for such contrasting results. It is more appropriate instead to distinguish between parameters of the line (e.g., the height of the SW(s), the relative height of the SW(s) compared to the phase conductors, etc.), which can be controlled by the line designer, and the parameters which are not related to the line design, thus uncontrollable (e.g., the front time of the lightning current, the distance between the line and the lightning channel, etc.). We will make the following fundamental distinction: the first ones will be referred to as *internal* parameters, the latter as *external*. The reader will be easily convinced that the most favorable case would be when the degree of mitigation varies significantly[2] with the internal parameters and is practically insensitive to the external parameters. In this case, the mitigation effect could be entirely under the line designer's control.

Regarding the point on the line where the mitigation is to be assessed, we will present a divergent view from the current literature, which makes this assessment at the point closest to the lighting channel in most of the cases.

By making the important distinction between *internal* and *external* parameters and revising the approach regarding the point along the line where the mitigation effect is to be assessed, we will find that this effect **may be precisely quantified and controlled. The main implication of this result is that this quantity can be one of the line design specifications.**

C. Paper Structure

The paper is organized as follows: in Section II, the parameters affecting the mitigation effect are analyzed; Section III presents the proposed approach; Section IV analyzes the impact of internal parameters on the SF, while the impact of external parameters is analyzed in Section V; concluding remarks are presented in Section VI.

II. PARAMETERS AFFECTING THE MITIGATION EFFECT

Assessing the overvoltage reduction produced by SWs is fundamental when it comes to lightning-induced overvoltages on overhead lines. The first systematic study on this topic was carried out by Rusck [7]. He quantified this effect by the ratio between the voltage $v'_a(t)$ induced on the considered conductor - we denote the considered conductor as conductor *a* - and the voltage $v_a(t)$ that would be induced on the same conductor in the absence of SWs, calling it Shielding Factor (later, also identified by other authors as Protective Ratio, as mentioned above). In his study, a very schematic case was analyzed, consisting of an infinitely long lossless line, over a perfectly conducting ground, equipped with one or more SWs grounded at one point only. Subsequently, several studies have been devoted to analyzing more complex configurations, for instance lines with multiple grounding of SW(s) (e.g., [14]), lines with both multiple grounding and laterals (e.g., [15]). At this juncture, it is important to emphasize that the mitigation effect is affected by several different parameters. A comprehensive list of these parameters is presented in [14] and listed in Table I with additional notes.

As mentioned earlier, no distinction (between external and internal) of the parameters affecting the SF is available in

[2]A significant variation with internal parameters will give the designer more flexible solutions during the design: for instance, if there are some constraints in placing the SW sufficiently close to the phase conductor, not allowing for obtaining the desired SF, the designer may act on the value of the grounding resistance to regain the desired value of SF.

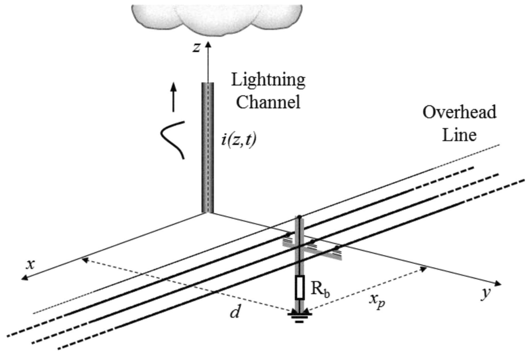

Fig. 1. Infinitely long line with single SW grounding point (d is the distance between the lightning channel and the line, x_p is the offset between the point of the line closest to the lightning channel and the SW grounding point, R_b is the grounding resistance).

the literature: here, we propose to make such a distinction. The importance of distinguishing between internal and external parameters is immediately apparent if we frame the problem in its mathematical context, which is that of the generalized telegraphers' equations (telegraphers' equations with source terms) modeling the phenomenon. External parameters, such as the front time of the lightning current, or the distance between the line and lightning channel, will act on the source terms of these equations, while the internal parameters, such as the relative position of the SW(s) to the phase conductors, are relevant to the characterization of the line through its *RLGC* per-unit-length parameters.

III. Proposed Approach

To accurately investigate the role of SW(s) in reducing lightning-induced overvoltages, we need to analyze different cases of growing complexity, starting, as done in [7]–[9], from the most basic case: all conductors, including the SW, are lossless, infinitely long, in presence of perfectly conducting ground,[3] and the SW is grounded at one point only. The configuration is depicted in Fig. 1.

This configuration, although unrealistic, gives us the opportunity to develop analytical solutions to a great extent, giving in this way important insights into the physical process, and greater understanding of the role played by each parameter [7]–[9]; it also constitutes a starting point for the analysis of more complex and realistic configurations developed in Part II. For this configuration, the mitigation (quantified by the SF/PR) **at the SW grounding point** is given by [7], [8]:

$$SF = \frac{v'_a(t)}{v_a(t)} = 1 - \frac{Z_{ba}}{Z_{bb} + 2\,R_b}\frac{v_b(t)}{v_a(t)}. \tag{1}$$

where $v'_a(t)$and $v_b(t)$are the voltages induced on the phase conductor and on the SW, respectively, $v_a(t)$ is the voltage that would be induced on the phase conductor if the SW was not in place. Z_{bb} and Z_{ba} are the entries of the surge impedance matrix of the line (a real symmetric matrix). Z_{bb}, the self-surge impedance of the SW, and Z_{ba}, the mutual surge impedance between the SW and the phase wire, are given by:

$$Z_{bb} = \frac{\zeta_0}{2\pi}\ln\left(\frac{2h_b}{r_b}\right),\ Z_{ba} = \frac{\zeta_0}{2\pi}\ln\left(\frac{(h_b+h_a)^2+s^2}{(h_b-h_a)^2+s^2}\right)^{1/2} \tag{2}$$

ζ_0= 377 Ω being the impedance of free space; h_b and h_a heights (above ground) of the SW and the phase conductor, respectively, r_b the radius of the SW, and *s* is their horizontal separation.

The SF depends on the conductor arrangement through Z_{ba} and Z_{bb} (which are function of all *internal* parameters), on the grounding resistance R_b (*internal* parameter), and on the ratio between the induced voltages: this ratio is a function of *external* parameters, which in this case are the distance *d*, the offset distance x_p, the front time of the lightning current, and the time [13]. We will preliminarily investigate the step-function lightning current case.[4] The response to arbitrary waveforms can be obtained by a convolution integral [13].

In the case of a step-function lightning current, the induced voltage on the k^{th} wire at height h_k (for $k = a, b$), at the SW grounding point ($x = x_p$, $y = d$), is given by the exact solution offered in [29], [30]:

$$v_k(t,h_k) = \frac{\zeta_0 I}{4\pi}(v_1+v_2+v_3) \tag{3}$$

with

$$v_1 = \ln\left(\frac{(-\lambda_s+\beta x_p)^2+d^2}{(-\lambda_d+\beta x_p)^2+d^2}\right) \tag{4}$$

$$v_2 = \ln\left(\frac{\left(\sqrt{\lambda_d^2+\delta^2}+x_p/\gamma^2+\beta\lambda_d\right)^2}{\left(\sqrt{\lambda_s^2+\delta^2}+x_p/\gamma^2-\beta\lambda_s\right)\left(\sqrt{\lambda_d^2+\delta^2}+x_p/\gamma^2+\beta\lambda_s\right)}\right) \tag{5}$$

$$v_3 = 2\beta\ln\left(\frac{1}{\delta^2}\left(\sqrt{\lambda_d^2+\delta^2}-\lambda_d\right)\left(\sqrt{\lambda_s^2+\delta^2}+\lambda_s\right)\right) \tag{6}$$

having considered the following auxiliary quantities

$$\begin{cases} \lambda_s = \beta ct + h_k \\ \lambda_d = \beta ct - h_k \\ \delta = \frac{1}{\gamma}(d^2+x_p^2)^{1/2} \end{cases} \tag{7}$$

and where *I* is the step value of the lightning current, β is the ratio between the propagation speed of stroke current along the channel and the light speed in vacuum *c*, the corresponding Lorentz factor being $\gamma = 1-\beta^2$ (for *d* and x_p see Fig. 1). In [29], [30], it was found that an excellent approximation of the exact solution (3) is its first-order approximation (first-order term of the Taylor expansion about $h = 0$), which corresponds to the Rusck solution [7], given by:

$$v_k(t,h_k) = \frac{\zeta_0 I\beta\, h_k}{2\pi}\frac{(ct-x_p)}{d^2+\beta^2(ct-x_p)^2}$$

[3]The assumption of perfectly conducting ground regards the propagation of the lightning electromagnetic field and the surge propagation along the line: note that ground is intrinsically lossy to characterize the grounding resistance. All assumptions regarding these ideal conditions will be removed in Part II.

[4]We will also assume a return stroke model of the TL type [28].

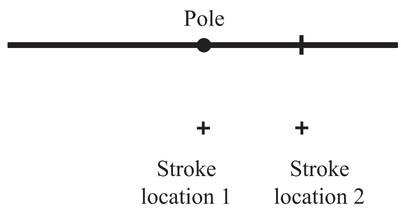

Fig. 2. Different stroke locations.

$$\times\left\{1+\frac{x_p+\beta^2\left(ct-x_p\right)}{\sqrt{\left(\beta ct\right)^2+\delta^2}}\right\} \quad (8)$$

By using this approximation, the induced voltage **at the SW grounding point** (whatever the offset x_p between the lightning channel and the SW grounding point, see Fig. 1) is proportional to the height *h* of the considered conductor. Hence, the ratio v_b/v_a is reduced to h_b/h_a and the problem greatly simplifies [3][5]:

$$SF=\frac{v'_a}{v_a}=1-\frac{Z_{ba}}{Z_{bb}+2\,R_b}\frac{h_b}{h_a}. \quad (9)$$

The importance of (9) lies in the fact that the SF, in this case, **depends only on internal parameters**, namely the conductors' arrangement, by Z_{ba}, Z_{bb}, h_a, h_b , and the SW grounding resistance R_b. It does not depend on external parameters, which are, as noted, the distance *d*, the offset distance x_p, and the time *t*.[6]

At this stage, a fundamental problem must be faced when an offset between the lightning channel and the SW grounding point exists ($x_p \neq 0$, see Fig. 1): should the mitigation effect be evaluated at the point along the line closest to the lightning channel (where the induced voltages are the most severe [31], [32]), or at the SW grounding point? Literature, in most cases (e.g., [14], [35]), agrees in evaluating the mitigation effect always at the point closest to the lightning channel, irrespective of the stroke location: to show this approach, let us see Fig. 2: for Stroke location 2 assessment will be made at the point of the line shown by the small vertical segment; one will make the assessment at the SW grounding point (shown by the writing "Pole") only when this point happens to be right in front of the lightning channel as in Stroke location 1. Some authors even assert that the assessment at the point of the line closest to the lightning channel is inherent to the definition of SF (e.g., [14]).

The rationale for this approach should be probably found in the fact that the most severe induced voltage happens to be at this point (e.g., [31], [32]; this is a general result, independent of presence or absence of SW). We will first analyze the current approach in literature, and our approach immediately afterwards to allow for comparison. This comparison will show where the problem is. We consider the configuration depicted in Fig. 3, already employed in [13], with the following parameters: height of the phase conductor $h_a = 10$ m (we will make, without loss of generality, our investigation for the central conductor); height of the SW: $h_b = 11$ m, when fixed, and h_b between 7 and 12 m when variable; phase conductor section $S_a = 25$ mm^2; SW section $S_b = 16$ mm^2. Similarly to previous studies [7]–[9], we will start from the most basic case, consisting of a step-function lightning current and a perfectly conducting ground for both the lightning electromagnetic field propagation and the surge propagation along the line. The SF is evaluated by applying its definition, namely assessing the ratio $v'_a/\,v_a$. As explained above, we need to assess the mitigation effect not only at SW grounding points, but also at points along the line: in the latter case (1) and (9) no longer apply, hence we will resort to a general tool, the CiLIV code [33], [34] (note that a brief description of the CiLIV code can be found in Part II) to make our assessments: comparisons with (1) and (9) will be made whenever applicable, namely when the assessment will be made at the SW grounding point. We start assessing the SF as a function of time and offset distance x_p. The results, presented here for the first time (to the best of authors' knowledge), are shown in Fig. 4: they are worth particular attention. When the SW grounding point is in front of the lightning channel (one should observe in Fig. 4(a) the very first line at $x_p = 0$ which is virtually horizontal) the SF is a well-defined quantity, and the average value calculated by CiLIV is SF = 0.694; but for offset positions, the definition of the SF is questionable, as an extreme variability may be observed with time and offset distance: there is also a valley, due to the combination of transmitted and reflected waves of the induced voltage which prevents a possible conceptualization. It should be added that, according to some authors (e.g., [9], [10]), the SF/PR is defined differently, namely it is defined as the ratio of the peak values of the induced voltages disregarding their time evolution. According to this different definition (which is preferred by the authors because it is more logical and technically sound) we obtain the black line in Fig. 4(a), at the time instant $t = 0.4$ µs, when peak values occur; the corresponding 2-D plot (at time $t = 0.4$ µs) is shown in Fig. 4(b). However, even adopting this different definition, an extreme variability of the SF with the offset distance x_p is seen, preventing a precise quantification of this parameter. It is also interesting to note that, for offset

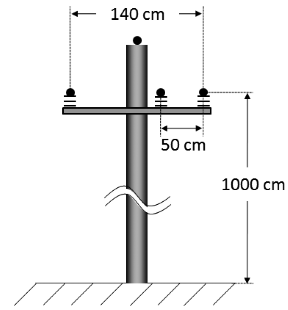

Fig. 3. Line arrangement.

[5]Note that, in this approximation, the distance of all the wires (including the SW) from the lightning channel is assumed to be the same, since it is usually much greater than their height above ground, namely $d>>h$, otherwise the indirect would turn into direct lightning.

[6]Note that according to (1), time is a parameter which affects the SF since it does not cancel out in the ratio v_b/v_a when applying the exact solution (3). Hence, strictly speaking, it should be added to the list of parameters affecting the SF [14] (but omitted in that list). It happens to cancel out only when the first order approximation (8) is considered.

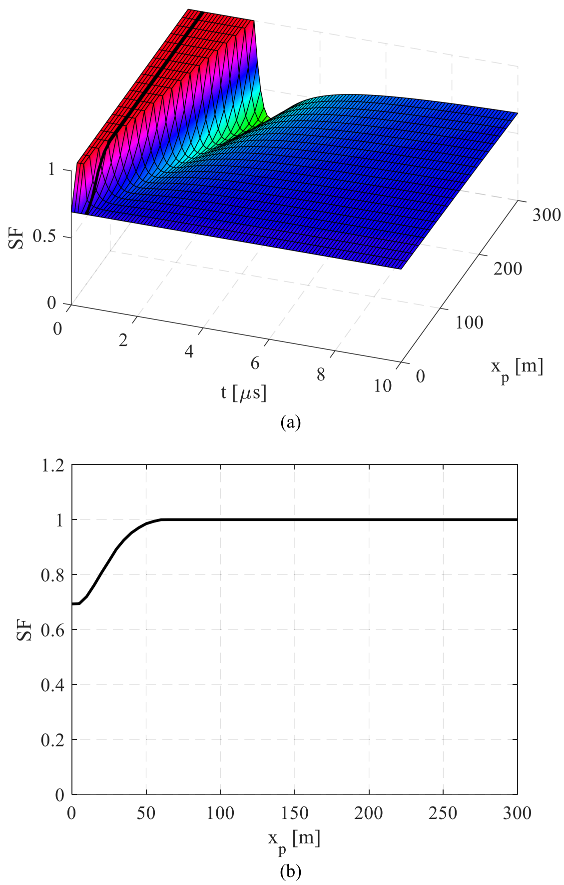

Fig. 4. (a) 3-D surface plot of SF versus time t and offset distance x_p assessing the SF at the point of the line closest to the lightning channel (see Fig. 1); (b) SF versus offset distance x_p calculated according to the alternative definition, namely ratio of the peak values ($d = 50$ m, $R_b = 50\ \Omega$, $h_b = 11$ m, $I_0 = 10$ kA, $\beta = 0.4$).

distance x_p which starts to be greater than the distance d (See Fig. 1), the mitigation effect progressively vanishes.

Despite the impossibility, as shown so far, to univocally assess the mitigation effect, literature confines itself to stating that this effect is significantly variable with many parameters including the offset distance, e.g., [14], [35]. This approach leads to an ambiguous, hence impractical, mitigation assessment. Let us now resume the case examined before, but this time assessing the SF according to the proposed approach (namely, at the SW grounding point): by varying the offset distance x_p and time t in Fig. 5(a), and by varying the offset distance x_p in Fig. 5(b), the SF is now a precise and constant value, practically independent from these external parameters (compare to Fig. 4(a) and (b)); note also that, in the case of Fig. 5(a), the black line is skewed, since peak values will build up at increasing times as the offset x_p increases. The average value calculated by CiLIV is SF $= 0.694$. In this case, since we are making the assessment at the SW grounding pole, we can compare this result with that provided by (1) and (9), which is SF $= 0.691$ in both cases: outputs provided by CiLIV and by (1) and (9) are all very close. Assessing the SF at the SW grounding point has now a solid and clear meaning.[7]

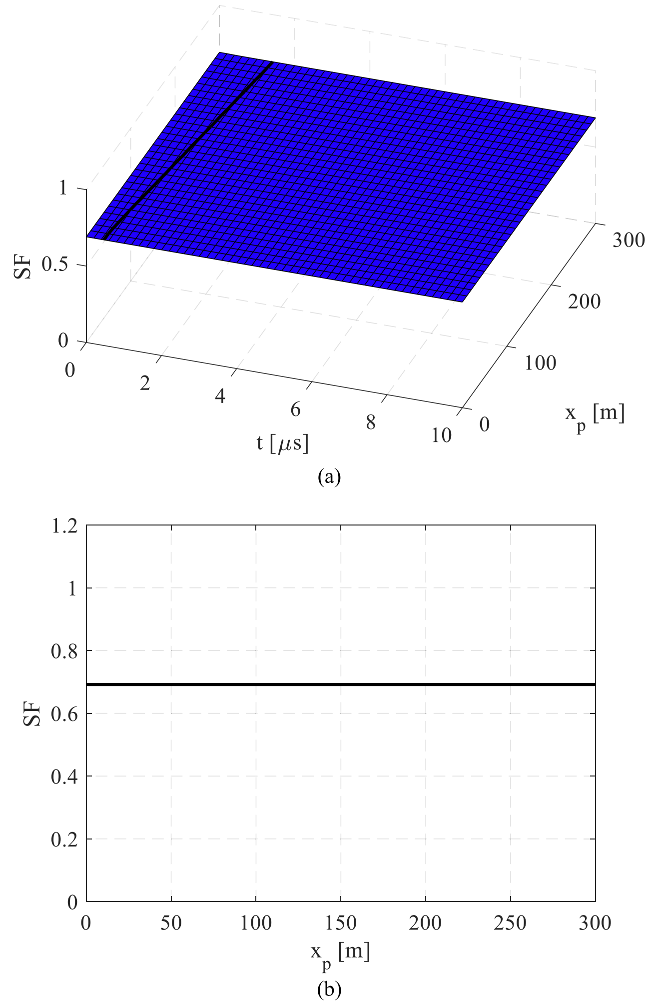

Fig. 5. (a) 3-D plot of SF versus time t and offset distance x_p assessing the SF at the SW grounding (see Fig. 1); (b) SF versus offset distance x_p calculated according to the alternative definition, namely ratio of peak values ($d = 50$ m, $R_b = 50\ \Omega$, $h_b = 11$ m, $I_0 = 10$ kA, $\beta = 0.4$).

This choice has a technical base too: if a flashover must take place at all, it will likely not take place at a point away from the tower (pole) where insulation levels are relatively high [1], [35] but will take place at a tower (pole), where insulation levels are weaker. Equipment failure and system outage under indirect lightning are commonly caused by the overvoltage at these points [35].

To improve the present investigation under more realistic assumptions, we show the comparison between the two approaches for a linearly rising current with $t_f = 0.5$ µs, Fig. 6(a) and (b), and for a linearly rising current with $t_f = 1$ µs, Fig. 6(c) and (d). Similar considerations to the previous case of step-function lightning current apply, however, with a further consideration: the black lines of Fig. 6(a) and (c) show that increasing the front time will improve the mitigation effect on average. In the first case the mitigation completely vanishes at an offset distance x_p

[7]We can now explain why literature ran into this error: we are dealing with distributed-parameter circuits; this will imply delays. The effect of the SW (in particular, of its grounding point) will be "felt" at the point closest to the lightning channel only after a time interval which is related to the distance d and the offset distance x_p (see Fig. 1). This can explain such an irregular trend of the SF in Fig. 4(a) and (b). Regularity is regained once we observe the phenomenon at the pole, as prescribed by the present approach (Fig. 5(a) and (b)).

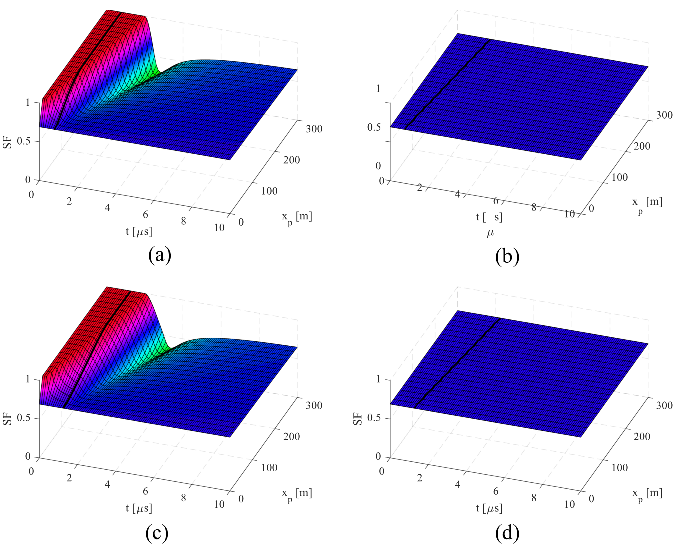

Fig. 6. SF versus time t and offset distance x_p in case of linearly rising current, with $t_f = 0.5$ µs: (a) Current approach, (b) Proposed approach; and with $t_f = 1$ µs: (c) Current approach, (d) Proposed approach ($d = 50$ m, $R_b = 50\ \Omega$, $h_b = 11$ m, $I_0 = 10$ kA, $\beta = 0.4$).

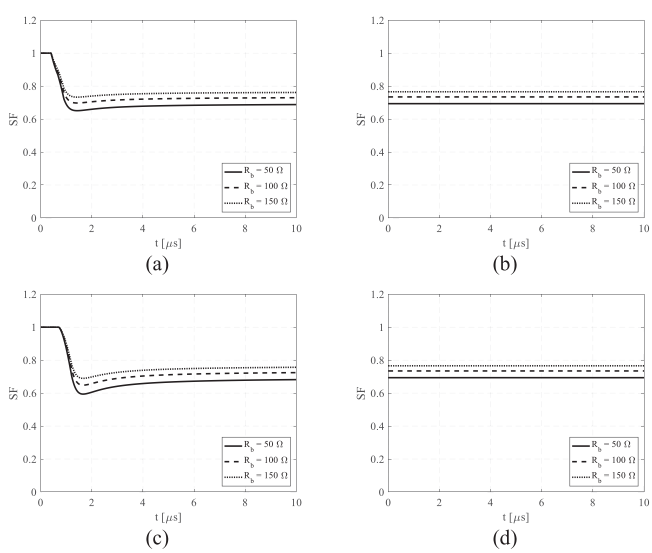

Fig. 7. Comparison of SF plots assessed for different values of R_b, for an offset distance $x_p = 50$ m: (a) and (b); and an offset distance $x_p = 100$ m: (c) and (d) ($t_f = 0.5$ µs, $d = 50$ m, $h_b = 11$ m, $I_0 = 10$ kA, $\beta = 0.4$).

of approximately 100 m and, in the second one, at an offset distance of approximately 180 m.

We further add some more investigations in terms of parametric behavior to compare the two approaches (we show 2-D plots, according to the alternative definition of SF, ratio of peak values, without loss of generality, since parametric plots would be very difficult in 3-D). In Fig. 7(a) and (b) the comparison is made for varying grounding resistance R_b assuming an offset distance of $x_p = 50$ m, and in (c) and (d) assuming an offset distance of $x_p = 100$ m. All previous considerations apply.

As a final comparison, we show in Fig. 8 the effects of the distance d (see Fig. 1) analyzing the two approaches: it is confirmed that the external parameter d has no practical effect, confirming the value of the proposed approach.

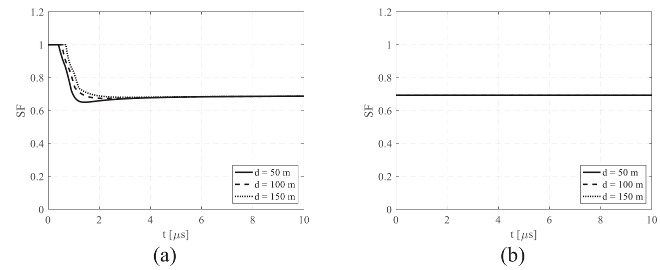

Fig. 8. Comparison of SF plots assessed for different values of the distance d, ($t_f = 0.5$ µs, $x_p = 50$ m, $h_b = 11$ m, $I_0 = 10$ kA, $\beta = 0.4$). Note that SF waveforms are perfectly overlapped in (b).

In this Section we have shown and explained the reasons underlying the assessment of the SF at the SW grounding: in this way we gain a precise and clear meaning for this parameter. Further, such an assessment has the important implication that the SF is mainly dependent on internal (controllable) parameter and practically independent on external (uncontrollable) parameters. The role of internal and external parameters is further discussed in the next two Sections.

IV. Role of the Internal Parameters

In this Section we will analyze the influence of internal parameters: as previously explained, a desirable condition would be when the degree of mitigation varies only with these parameters and is practically insensitive to external parameters. We further point out that in the following, since our approach is independent from the definition of SF (we got identical results whether we consider the ratio of the peak voltages, or the ratio of the voltages over the time (see Fig. 5(a) and (b)), we will report only the results relevant to the definition involving the peak values.

A. SW Height

As clearly detailed in [14], when SWs are installed above the phase conductors to protect the latter from direct lightning, their relative height compared to the phase conductors is generally limited to reduce the probability of attracting lightning. For instance, for a line where the phase conductors are placed at 10 m, SWs are placed at the height of about 11 to 12 m [14]. Different considerations hold for wires installed below the phase conductors: they are usually neutral conductors which act as SWs, usually placed at a height approximately equal to 7 m [14].

The role of the SW height in the case of step-function current was extensively analyzed in [13]. The reader is asked to refer to Fig. 15 of [13]: it was assessed that, in the range of variation of the SW height (10-12 m, for phase conductors placed at 10 m), we have a significant variation of the SF (around 40%). As for the neutral beneath the phase conductor (acting as SW), the variation with the height of installation (between 7 and 10 m) is significant as well (around 75%). The aim now is to demonstrate that this result is practically not influenced by external parameters. To this aim, we will again consider the line arrangement of Fig. 3(studied in [13] too), by varying front time of the lightning current and ground conductivity. We analyze the case of three

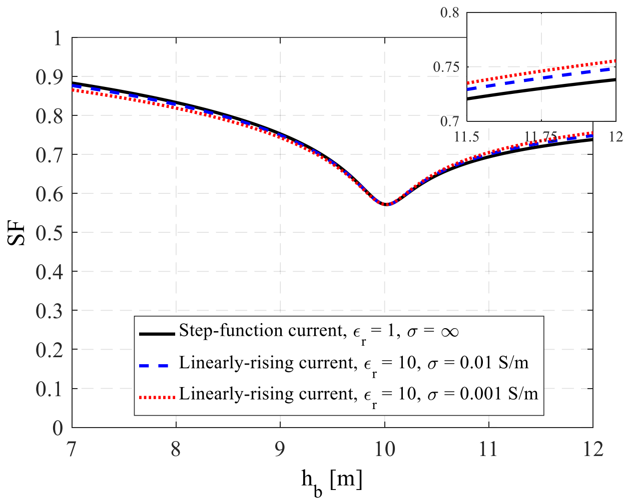

Fig. 9. SF versus SW height h_b (with an inset to highlight differences between graphs) in case of step-function current and perfectly conducting ground (solid line), and linearly rising current, $t_f = 1$ µs, for two different values of ground conductivity (dashed and dotted lines), ($x_p = 0$, $d = 50$ m, $R_b = 50$ Ω, $I_0 = 10$ kA, $\beta = 0.4$).

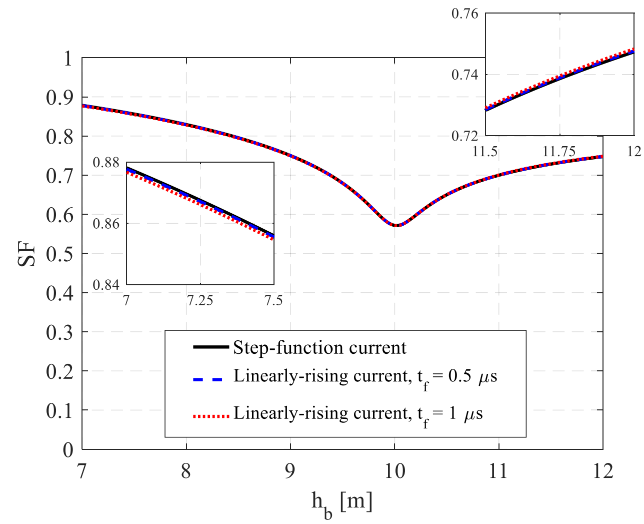

Fig. 10. SF versus SW height h_b (with two inset to highlight differences between graphs) in case of step-function current (solid line), and linearly rising current with $t_f = 0.5$ µs (dashed line) and $t_f = 1$ µs (dotted line), ($x_p = 0$, $d = 50$ m, $\varepsilon_r = 10$, $\sigma = 0.01$ S/m, $R_b = 50$ Ω, $I_0 = 10$ kA, $\beta = 0.4$).

different lightning currents (step-function, linearly rising with a front time $t_f = 0.5$ µs, and linearly rising with a front time $t_f = 1$ µs) and three different soil conductivities (perfectly conducting ground, 0.01 and 0.001 S/m). Note also that, as explained earlier, since we are interested in analyzing the validity of our approach against conditions of growing complexity, we will now assume a finitely conducting ground, but only for the propagation of the lightning electromagnetic field, and not for the surge propagation along the line: this correspond to the "ideal line" condition presented in [36] which is shown to be valid for lines of length up to 2 km. Note also that this limitation will be removed in Part II where more realistic cases will be analyzed.

In Fig. 9 we show the SF against SW height for different cases. We note that, since no variation of the SF behavior over the time was seen (this was expected with our approach), we will just show the value corresponding to the time where the peak values occur (based on the alternative definition of SF): it can be seen that in the range 10-12 m there are no significant differences between the cases, with a maximum deviation of 1.4% for $\sigma = 0.01$ S/m and 2.2% for $\sigma = 0.001$ S/m, when the SW is placed at 12 m (see inset in Fig. 9). No significant differences can be seen too when the conductor is below the phase conductor (between 7-10 m, we reiterate that in this case we are typically dealing with a neutral conductor acting as SW). Similar comparison, with similar considerations, but on this occasion varying the front time, can be found in Fig. 10. We emphasize that we ran many cases with different combinations of front times and ground conductivities and tried also more realistic current waveforms (Heidler expression [37]): similar results held in all cases. We can conclude that the SF is variable with the SW height (internal parameter) and practically insensitive to external parameters.

B. SW Grounding Resistance

The role of the grounding resistance is shown in Fig. 11. Note that, in the simulations carried out to obtain this figure, ground

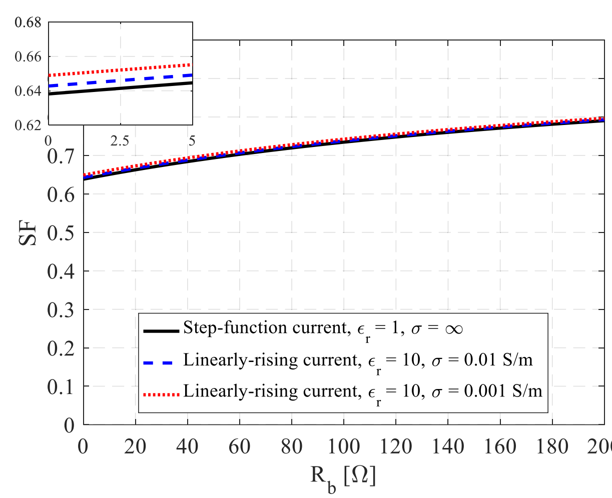

Fig. 11. SF versus SW grounding resistance R_b (with an inset to highlight differences between graphs) in case of step-function current and perfectly conducting ground (solid line), and linearly rising current, $t_f = 1$ µs, for two different values of ground conductivity (dashed and dotted line), ($x_p = 0$, $d = 50$ m, $h_b = 11$ m, $I_0 = 10$ kA, $\beta = 0.4$).

losses effects are delinked. This is a common approach in the literature, (e.g., [14], Fig. 6): as specified earlier, finitely conducting ground effects are accounted for only in the propagation of the electromagnetic field (this can cause large differences in the induced voltages [36]) and not in the surge propagation of the line; further, ground losses are intrinsically accounted for in the characterization of the grounding resistance, whose value is varied, and ideally taken to the limit of $R_b = 0$. There are no practical differences among the proposed cases, as the three graphs overlap. Many simulations were carried out in this case too, including different values of external parameters, and again they all resulted in a practical insensitivity to these parameters, as desired. The result shown in Fig. 11 are particularly interesting since an ineffective grounding system (because of

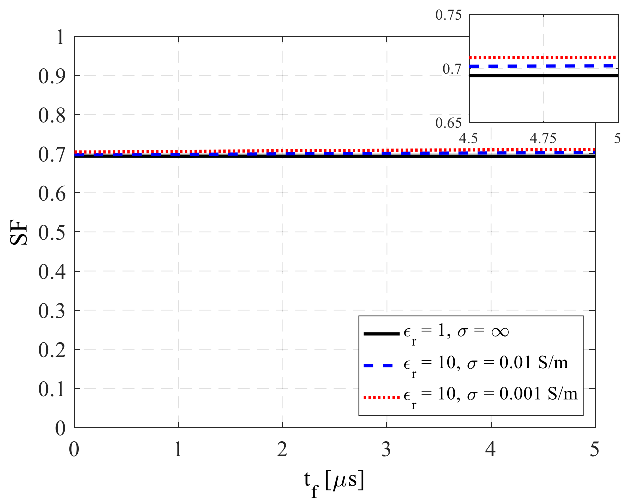

Fig. 12. SF versus current front time t_f (with an inset to highlight differences between graphs) in case of perfectly conducting ground (solid line), and finitely conducting ground (for two different values of ground conductivity, dashed and dotted line), ($x_p = 0$, $d = 50$ m, $R_b = 50\ \Omega$, $h_b = 11$ m, $I_0 = 10$ kA, $\beta = 0.4$).

the low ground conductivity and/or the limited extension of the grounding rod or grid) will still guarantee a fairly effective SF; on the other hand, the designer still has a margin, although limited, of obtaining the desired SF by changing the grounding system design.

V. Role of the External Parameters

In this Section we analyze the influence of external parameters: as explained, it would be desirable that, once a set of internal parameters has been fixed, hence fixing the line characteristics, any variation of external parameters will have no practical effect on the SF value.

A. Distance Between Line and Lightning Channel, and Offset Distance of SW Grounding Point to Lightning Channel

The independence of the SF from the offset distance x_p and the distance d has been extensively analyzed under different conditions to introduce and explain the reasons substantiating the proposed approach: in particular, we refer to the paragraph III from Figs. 4 to 8. We also point out we ran many other cases, not shown, since identical results were obtained leading to a constant value of SF.

B. Lightning Current Parameters (Front Time and Return Stroke Speed)

In the case of perfectly conducting ground and single SW grounding, the invariability of the SF with the front time, and in general with the current waveform, was discussed in [13]. In Fig. 12, we extend our analysis to the case of finitely conducting ground (but only for the propagation of the lightning electromagnetic field, as mentioned earlier): the SF is confirmed to be practically independent of the front time. No significant differences were found by varying the return stroke speed too.

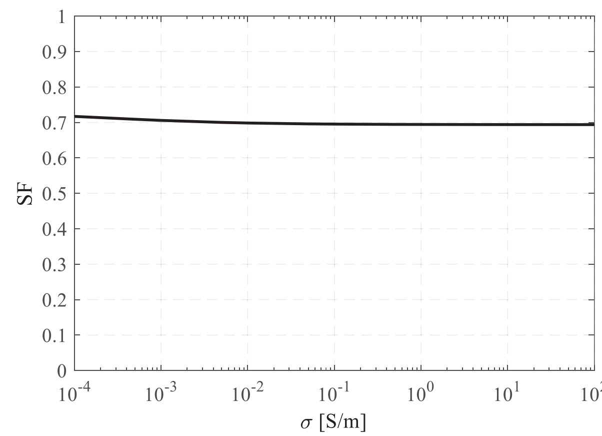

Fig. 13. SF versus ground conductivity σ for the line geometry of Fig. 3($x_p = 0$, $d = 50$ m, $R_b = 50\ \Omega$, $h_b = 11$ m, $I_0 = 10$ kA, $\beta = 0.4$).

C. Ground Conductivity

In Fig. 13, we show the SF against ground conductivity σ assumed as a variable parameter for the lightning electromagnetic field propagation. It can be seen that, apart from a slight variation for poorly conducting ground, the SF is practically independent on ground conductivity, and its value can still be evaluated by (1) or (9). The average value calculated by CiLIV is SF = 0.698; this value is close to the one calculated by (1) and (9) which is SF = 0.691 in both cases.

VI. Concluding Remarks

In this Part I we have assessed the mitigation of lightning-induced overvoltages produced by SWs. We have proposed a novel classification of the parameters influencing the mitigation effect namely distinguishing between *internal* and *external* parameters; the point along the line where to compute the SF has been clarified and identified with the SW grounding point. According to this new approach, the SF gains an important role in the precise quantification of the mitigation effect. Further, in the case presented in this Part I (unrealistic, but used in the literature for analytical developments) the SF, in opposition to the current literature, can be accurately calculated by the simple formulas (1) and (9). These results will be further investigated in Part II.

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