On Concise Representations of Grounding Electrodes for Assessment of the Lightning Performance of Transmission Lines

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***Abstract*—This paper discusses concise representations of tower footing electrodes for assessment of the lightning performance of transmission lines. It shows that using the impulse impedance obtained for representative first-stroke lightning currents yields practically the same performance obtained under the physical representation of such electrodes.**

Keywords- lightning response tower-footing electrodes; lightning performance of transimission lines; concise representation of electrodes; impulse grounding impedance.

I. Introduction

The response of grounding electrodes has a relevant influence on the lightning performance of electrical systems. On the other hand, though the full response comprises the entire grounding-potential-rise wave (GPR) of the electrode subject to the lightning current, in engineering applications it is worth adopting simplified approaches to express this response in a concise representation. This might improve the computational efficiency of methods employed to estimate the lightning performance of electrical systems.

In spite of the practical interest in using such simplified representations, their adoption requires assessing the impact of their use in the calculated lightning performance in relation to that obtained under the physical representation of the electrodes.

This is the topic addressed in this work, using as reference the performance of transmission lines. The developments of this work are based on the results expressed in two recent authors' publications [1] and [2] and complement them.

II. Considerations About the Response of Electrodes Subject to Lightning Currents

The grounding potential rise is the primary response of buried electrodes subject to impressed currents. For very fast time-varying currents, such as those of lightning return strokes, this response is quite different from that resulting from the impression of low-frequency currents. In addition to the conductive effects in the soil, inductive and capacitive effects are also important, along with propagation effects. Considering such lightning currents, buried metallic electrodes cannot be considered equipotential volumes and the grounding response can no longer be approached as that of a pure resistance. The discussion of these aspects are contemplated in some recent publications [3,4].

Figure 1 illustrates a typical first return stroke lightning current impressed to an arrangement of electrode consisting of 70-m-long counterpoise wires buried 0.5 m deep in a 2000 Ωm soil and corresponding GPR curve.

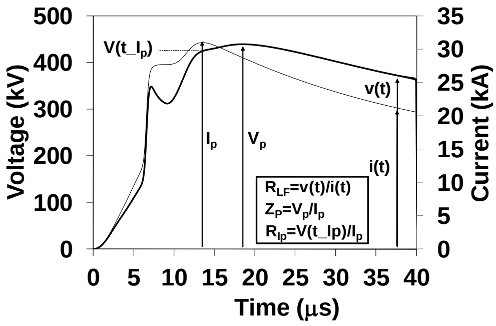

Figure 1. Response of counterpoise wires 70-m long buried 0.5 m deep in a 2000-Ωm soil subjected to a representative first-stroke lightning current, along with their concise representations Z_P and R_{LF}. Calculated Z_P , R_{LF} and R_{IP}: 14.2 Ω , 18.9 Ω, and 13.7 Ω.

Note that the waveforms of GPR and impressed current are relatively similar, but the peak values of GPR and current are not simultaneous due to reactive and propagation effects in the soil. In Figure 1, the current wave is in advance in relation to the GPR, and this denotes the prevalence of capacitive effect.

Concise representations of the response of electrodes, namely the impulse impedance Z_P, the low frequency resistance R_{LF} and the impulse resistance R_{IP} are also indicated. The first parameter is defined as the ratio of peaks of the GPR and impressed current, $Z_P=V_P/I_P$. In general, the ratio of instantaneous values $v(t)/i(t)$ is known as transient grounding impedance. R_{LF} is given by this ratio at the waves' tail and R_{IP} is given by this ratio at the time of the peak current, presumably when the time derivative of current would be null.

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In spite of the current-and-voltage peak shift, Z_P is a very useful parameter for lightning protection applications and the authors advocate its use in applications related to the lightning performance of transmission lines. There are two main reasons for that. First, though the impulse impedance varies with the front time and waveform of current, once a representative waveform of first-stroke current is used, this impedance practically does not vary in the real range of front-times of first strokes. Second, it allows determining promptly the maximum GPR yielded by a first stroke current for any value of I_P.

One fundamental characteristic of Z_P is that it can be either higher or lower than R_{LF}. Accurate simulations [1,5] developed with elaborated electromagnetic models, such as the HEM [6], have already shown this behavior. The most important, this statement was proved by experimental works. Reference [1] shows that a same grounding grid, consisting of 20 4x4-m^2 meshes (16mx20m) buried 0.5 m deep in two different soils (160 and 2000 Ωm), subjected to impulsive currents of about 3.8/200 µs shows impulse impedance of 11 and 22 Ω and low-frequency resistance of 4.3 and 54 Ω, respectively for the low and high resistivity soils. This corresponds to a ratio Z_P/R_{LF}, known as Impulse Coefficient of 2.6 for the low resistivity soil and 0.41 for the high resistivity soil. This demonstrates the statement above.

The results above are discussed in [1]. The typical curve of Impulse Coefficient I_C (given by the ratio Z_P /R_{LF}) of Figure 2 is a good reference for explaining this behavior. Considering a short length of electrode, while this length is increased, the values of corresponding Z_P and R_{LF} are decreased until a threshold length (effective length L_{EF}). In the range of length shorter than L_{EF}, I_C is lower than one, due to the effect of capacitive currents in the soil, but, overall, due to the frequency dependence of soil resistivity and permittivity. Both parameters decrease with increasing frequency [7]. Increasing further the electrode length while R_{LF} continues to decrease, Z_P remains constant. Thus, I_C begins to increase and can reach very high values for long electrodes.

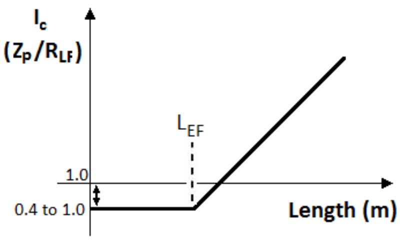


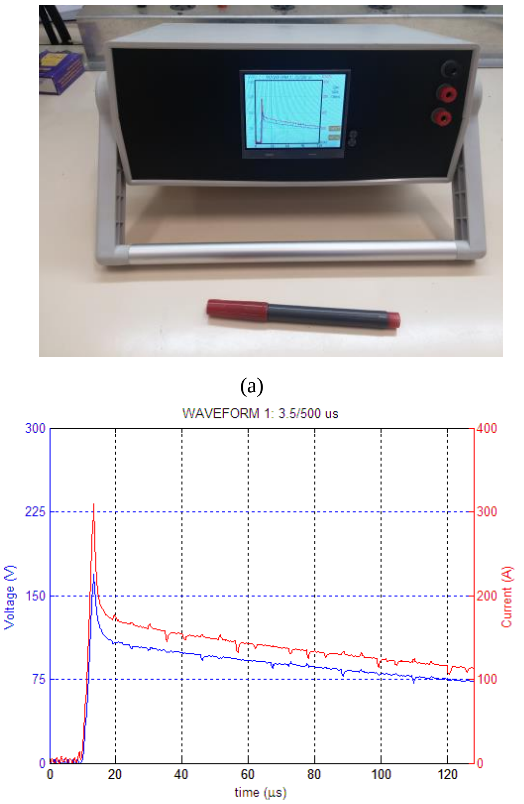
Figure 2. Typical profile of the impulse coefficient I_C as a function of the electrode length. Adapted from [1].

The estimates of Z_P from R_{LF} have to take this aspect into account. Long electrodes (L>>L_{EF}) have always a value of R_{LF} much lower than that of Z_P and a low value of R_{LF} does not imply a low value of Z_P. Thus, a low value of R_{LF} does not imply necessarily an improved lightning response of the grounding electrode, since even with its low value, the impedance for a first-stroke current could have a much higher value.

In spite of such aspects, due to the difficulties to measure Z_P in practical conditions, the measured R_{LF} is still used for qualifying the grounding-electrode response in lightning-related applications. In this case, it is prudent to estimate the parameter Z_P from the measured R_{LF} and I_C, using expressions provided in literature, such as those given for counterpoise-wires in [1].

In this respect, it is also important to notice the present availability of *Grounding Impedance meters*, such as that shown in Figure 3, which was developed recently to perform such kind of measurement [8]. The internal impulse generator (0.5 and 1.6 kV) of this low cost and portable DSP-based instrument is able to impress impulsive currents with typical time parameters of lightning currents on grounding electrodes. The device stores the corresponding current/GPR waves and provides the value of Z_P in addition to an estimate of R_{LF}.

It is worth remarking the relevance of preventing coupling effects among the leads used in the measurement of Z_P and the electrodes, which can interfere a lot in the results of measurements. Reference [9] discusses this question and develops some recommendations on this aspect, notably, the need to observe orthogonality between the leads carrying the current impressed on electrodes and the leads for measurement of the grounding potential rise.



(b)

Figure 3. View of grounding impedance measuring instrument. Both current and GPR waves, values of Z_P and R_{LF} are stored and displayed on the LCD screen.

III. DEVELOPMENTS

This work discusses the impact of using concise representations of the lightning response of tower footing electrodes on the performance of transmission lines, based on the developments and results of reference [1,2] and on some specific complementary results. The analysis took as reference the characteristics of a real 230-kV transmission line, whose CFO is 1200 kV and tower-footing electrodes consist of the counterpoise arrangement as indicated in Fig. 4. The influence of the adjacent towers was not considered to focus on the tower response, and all line conductors were impedance matched 30 m from the tower.

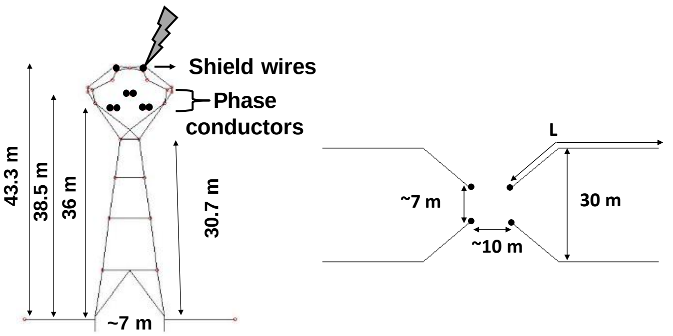


Figure 4. Representation of the tower configurations of the 230-kV line (a) and the tower-footing arrangement consisting of four counterpoise-wires (radius 0.75 cm) of length L buried 0.5 m deep in soil and 3-m long vertical rods (radius 5 cm) to represent the buried metallic components of the tower foundations.

The overvoltage developed in response to the impression of a representative first-return-stroke current [10] that reproduces the median peak and time parameters measured at Mount San Salvatore Station [11] was simulated using the HEM model [6].

Figure 5 represents the results obtained for the GPR and the overvoltage across the upper insulator of the line due to the impression of the current directly on the electrodes and on the top of the transmission line, respectively. The simulations considered three different conditions for tower-footing representation, the physical representation of electrodes and their concise representation by Z_P and R_{LF}.

Considering the GPR curves, it is clear that the response of the counterpoise wires is approximately governed by Z_P in the first microseconds (at the wavefront). After the peak this response transits in a way that at the wave tail it becomes governed by R_{LF}. The curve of GPR obtained by the representation of tower footing electrode as the parameter R_{LF} and those obtained as the physical representation practically match at the wave tail.

This result was shown to hold in simulations involving a wide range of soil-resistivity values, once usual length of counterpoise wires was used for each tested resistivity, meaning length shorter than L_{EF}.

The wavefront of the overvoltage calculated under the physical representation of the counterpoise wires practically coincides with that obtained under their representation by the Z_P as shows in Figure 5. For these representations, the peak-voltage values V_P are practically the same (difference about 3%). This means that, when using the voltage-time curve, the backflashover condition is practically the same for both physical and Z_P representations.

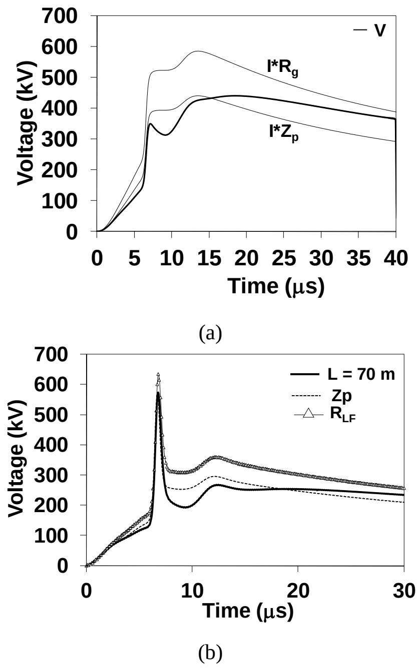


Figure 5. Simulated voltages obtained under different representations of the tower-footing electrodes: physical representation and those by parameters R_{LF} and Z_P. (a) GPR of the tower-footing electrodes subjected to the median first-stroke current. (b) Overvoltage experienced across the upper insulator string. Configuration of tower and electrode arrangement of Figure 4. Counterpoise wires 70-m long and 2000 Ωm soil. Frequency dependece of soil parameters taken into account according to expressions by Visacro-Alipio [12].

On the other hand, it is clear that using the R_{LF} representation leads to much higher values of grounding potential rise and overvoltage amplitude (including peak value) in relation to those obtained under physical representation. Therefore, the backflashover rates would also be much higher than that obtained under physical and R_{LF} representation of electrodes.

The comments of the four paragraphs above are valid in general, once usual lengths of counterpoise wires are used for each resistivity. This qualitative behavior has been confirmed by measurements of the impulsive response of counterpoise arrangement of electrodes developed for a few specific resistivity values using the Grounding Impedance Meter of Figure 3.

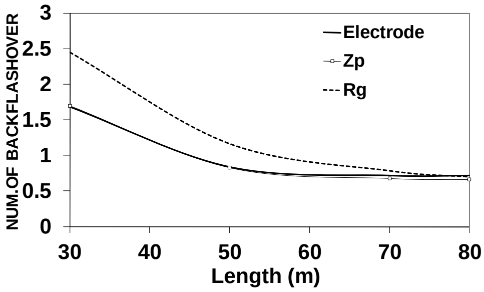
However, it is worth noting that at low frequencies the differences in the GPR, overvoltage across insulators and backflashover rates tends to decrease, since the response given by both Z_P and R_{LF} representation of electrodes tends to approach that given under the physical representation.

Actually, what does really interest in this work is the impact of concise representations of the response of electrodes on the lightning performance of the line. In this respect, the same type of simulation developed to obtain the overvoltage across insulators in Figure 5(b) was repeated systematically, varying the electrode length for soils of different resistivity value. Results similar to those obtained in [1,2] were developed, though corresponding to different conditions, notably different tower and grounding configurations.

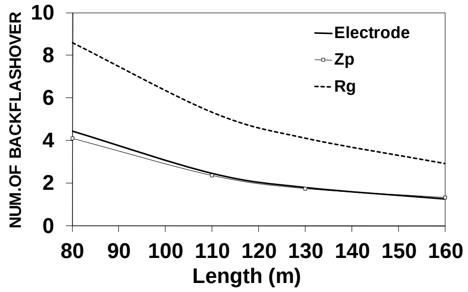
Considering the calculated overvoltages waves, the Disruptive Effect Model (DE) [13] was used to determine the critical currents leading the insulators to backflashover for each tested condition. Using the IEEE cumulative probability distribution of first-stroke peak-currents [14], the percentage of lightning currents expected to exceed I_{PC} (corresponding to the percentage of lightning currents striking the tower leading to backflashover) was determined, following the traditional procedure describe in [15,16].

IV. Results and Analysis

Figure 6 shows the results obtained for two different values of soils resistivity, in terms of backflashover rate of the line. The electrode length was varied in each case in a range required to ensure moderate and low values of grounding impedance. For the sake of simplicity and to focus on the impact of the concise representations of tower-footing electrodes, a same number of lightning strikes to the line was assumed (60 flashes/100 km/year).



(a)



(b)

Figure 6. Backflashover outages rates (/100 km/year) calculated from different representations of the tower-footing electrodes. Soil resistivity of: (a) 1000 and (b) 4000 Ωm. [NL = 60 flashes/100 km/year]

The results of Figure 6 denote that the lightning performance of the 230 kV line obtained under the physical representation of tower-footing electrodes practically match that obtained under the Z_P representation for both soils. On the other hand, the results obtained under R_{LF} representation is extremely conservative. The only case the later does not hold is for very long electrodes in Figure 6 (a). Note that in that case (1000 Ωm soil) the counterpoise length is longer than L_{EF} (60 m for first stroke current). The longer length was purposely included to denote that the reduction of R_{LF} based on the increase of electrode length beyond L_{EF} does not affect the line performance, which remains governed by Z_P value (it remains constant).

Similar results were obtained for soils with different resistivity values, though the difference in the performance under different representations tends to decrease, once counterpoise length shorter than L_{EF} are used. It is worth mentioning that soil ionization effect was disregarded in the present evaluation. Taking it into account would contribute to further improvement of the performance of the line provided by the Z_P representation. On the other hand, it is worth mentioning that, considering counterpoise arrangements of electrodes (typically long) this contribution would apply only for the very high amplitude lightning currents. Due to the uncertainties in the values recommended in literature for the critical electric field in the soil, the authors prefer to ignore this effect when dealing with counterpoise arrangements of electrodes, in a little conservative approach.

V. Conclusions

The results developed in this work are consistent with those obtained in [1,2] and complement them for different conditions of transmission lines. In this respect, they contribute to enlarge the generality of the conclusions of such references.

Basically, the lightning performance of transmission lines obtained under the physical and Z_P representations of tower-footing electrodes are very similar. On the other hand, the performance obtained under the R_{LF} representation is extremely conservative, meaning that the backflashover rate is much higher than that obtained under the other representations. The concise representation of grounding electrodes by Z_P allows a consistent assessment of the lightning performance of transmission lines.

Due to the simplicity of the Z_P representation, this conclusion is worth to be applied in procedures to determine the lightning performance of lines based on simulations carried out on EMTP-type platforms. To apply this representation, the authors suggest using the values indicated in the graphs or calculated by the expressions provided in reference [1] for a wide range of soil resistivity and of length of counterpoise wires.

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