Simplified representation of tower-footing electrodes for assessment of the lightning performance of transmission lines using EMTP-based platforms

S. Visacro, F. H. Silveira, M. H. M. Vale

***Abstract*— The use of simplified models to represent tower-footing electrodes in the assessment of the lightning performance of transmission lines was analyzed. After discussing basic aspects of the response of such electrodes subjected to first-return-stroke lightning currents, an electromagnetic model was applied to determine the lightning response of the line pursuing obtaining equivalent circuits. In the tested cases, using simply the tower-footing impulse impedance practically match the performance of line obtained using the physical representation of the electrodes.**

***Keywords*: Lightning, Grounding, Transmision lines, Backflashover, Lightning performance of transmission lines, EMTP, Representation of tower-footing electrodes.**

I. INTRODUCTION

LIGHTNING is a frequent cause of transmission line failures. In most cases, it is responsible for more than 50% of non-scheduled line outages. These failures occur when lightning strikes to the line and the overvoltages resulting across line-insulators exceeds their withstand.

Different mechanisms might cause such failures, but the so-called backflashover largely prevails in lines installed in regions of soils with high and moderate resistivity. This mechanism can occur when the current of a lightning strike to a tower (or to shield wires at tower vicinities) flowing towards the ground finds a high tower-footing grounding impedance. In this case, very high grounding potential rises are developed and transmitted to the tower top. High overvoltages can be experienced between the tower top and each one of the phase conductors, whose average potential is zero. If such voltages overpass the insulators' withstand, backflashover takes place [1].

Therefore, the assessment of the lightning performance of transmission line involves the evaluation of the overvoltages developed across insulators strings, in response to lightning strikes to the line [2]. Different approaches can be used to assess this performance by means of computational simulation. Electromagnetic-field approaches are able to yield accurate results, though their use is complex and the corresponding processing is very time-consuming. This scenario has been responsible for the users' preference for application of EMTP-type platforms in the analysis of the lightning performance of lines. When using EMTP-type approaches, the proper representation of tower-footing electrodes is fundamental to ensure consistent simulated results. This requires the availability of simplified models for representing grounding electrodes, by means of equivalent circuits or parameters. This representation has to be not only accurate, but simply as well, in order to prevent increasing excessively the simulation time.

The authors have been investigating this issue and have found some very interesting results, apparently of practical interest in engineering applications. Their preliminary results are discussed in this paper.

II. BASIC CONSIDERATIONS

In terms of assessment of the lightning performance of transmission lines, the primary response of tower-footing electrodes consist of their grounding potential rise GPR when subjected to lightning currents. Indeed, the ultimate response of interest consist of the overvoltage developed across insulators due to strikes to the line, which intrinsically contemplates the response of electrodes. In most cases, only the response to first return strokes' currents are of interest [2], since their median peak current is about three times higher larger than that of subsequent strokes [3,4].

A consistent representation of the tower-footing electrodes would basically require the lightning response of this representation to match that of the real electrodes buried in the soil. In other words, their GPR should be the same when subject to the same current waveform. Some works have been addressing this issue, proposing the synthetizes of equivalent circuits, which would be able to reproduce the transient response of electrodes. For instance, this type of approach was developed in [5], though referring to equivalent circuits of simpler arrangements of grounding electrodes.

Any proposal in this direction have to consider the nature of the transient behavior of tower-footing electrodes subjected to impulsive currents. In this respect, the curves of Fig.1, presenting the median current of a first return stroke impressed on a typical arrangement of tower-footing electrodes of Fig. 3 and the corresponding GPR, consist of an interesting resource for discussing this aspect.

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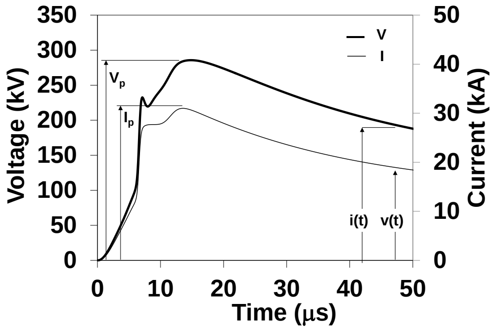

Fig. 1. Response of the tower-footing electrodes (arrangement of Fig. 3) to the impression of a median first return stroke current [6,7]: Peak current of 31,1 kA, Front times td10 and td30 of 5.6 µs and 3.8 µs, maximum derivative of 24 kA/µs and duration of 75 µs (time to half-peak) [8,9]. Counterpoise length of 50 m. Soil resistivity of 600 Ωm and frequency dependence of soil resistivity and permittivity given by the Visacro-Alipio expressions [10].

Note that, while in the waves' tail the ratio of the instantaneous values of GPR and current tends to a constant value equal to the electrodes' low-frequency grounding resistance R_{LF}, at the wave front and the region just after the peak, the value of this ratio varies, being significantly lower than R_{LF} [11]. This ratio of instantaneous values is known as transient grounding impedance [12].

Such qualitative behavior holds true in the range of electrodes length L shorter than the so-called effective electrode length L_{EF}, which results from the attenuation of the current propagating along the electrodes due to electric losses associated to the flow of current in the soil. In this range, increasing L results in decreasing the transient impedance and the grounding resistance. After L becomes larger than L_{EF}, increasing further L no longer results in reduction of the transient impedance at the wavefront, though the resistance continues to decrease. As discussed in [11], L_{EF} is longer in high resistivity soils and shorter in low resistivity ones. This attenuation, responsible for decreasing L_{EF}, is also stronger for fast-varying currents and negligible for slow-varying currents.

In real conditions, counterpoise wires are always shorter than L_{EF} for first stroke currents. This results from the fact that, in real applications, basically a single factor governs the design of tower-footing electrodes: pursuing a low value of the tower-footing grounding resistance. In low resistivity soils, it is possible to achieve such low value with electrodes shorter than L_{EF}. In high resistivity soils longer electrodes are required to achieve such value, but still it is shorter than L_{EF}, which is quite longer in this case [13].

Usually, resistances values below 20 Ω are pursued. For instance, considering the tower-footing arrangement of Fig. 3, in a 100 Ωm soil, a resistance of 5 Ω can be obtained with counterpoise wires of 5 m, for an effective length of about 20 m. In a 1000 Ωm soil, a resistance of 15 Ω can be obtained with counterpoise wires of 40 m, for an effective length of about 60 m.

As discussed in [14], there are two reason for the value of the instantaneous ratio lower than R_{LF} at the wave front: the effect of capacitive currents in the soil, and the reduction of the soil resistivity in relation to the low-frequency resistivity, due to a strong frequency dependence of the electrical parameters of soil.

Several parameters are proposed to characterize in a simplified way the electrode response in the region comprising the wavefront. The authors consider that the impulse grounding impedance Z_P, given by the ratio of the peaks of the GPR and impressed first-stroke current ($Z_P = V_P/I_P$) is a consistent simplified representation [11].

As a rule, the response of the electrode would be somehow intermediate between that given representing the electrodes by a constant circuit parameter corresponding to the impulse impedance Z_P and to the low-frequency resistance, R_{LF}, both considered a real number. In the first microseconds, the response should be approximately governed by Z_P, while at the wave tail it would be governed by R_{LF}. This trend is clearly denoted in the curves of Fig. 2.

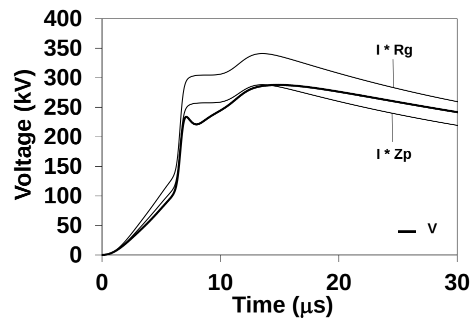

Fig. 2. Comparison of the response of the tower-footing electrodes of Fig. 3 subjected to the median first-stroke current of Fig. 1 (curve V) and those obtained assuming the representation of the tower-footing by the concentrate parameters R_{LF} and Z_P. Length of counterpoise wires L of 50 m and soil resistivity of 600 Ωm.

Note the transition in the curve of GPR obtained using the physical representation of the electrodes between the initial part of the curve corresponding to the response representing the electrodes simply by Z_P and the final part of the curve tending to the response for their representation by R_{LF}. At the wave tail the GPR curve finally coincides with the latter.

III. Developments

A. Introduction

Following the concepts discussed above the authors used to begin investigating the synthesis of equivalent circuits, which would be able to reproduce the lightning response of typical arrangements of tower-footing electrodes, notably that of the counterpoise-wires represented in Fig. 3. As a rule, the pursued equivalent circuit would have to develop a response to first return stroke currents, which would tend to those given by Z_P and R_{LF} respectively at the boundaries corresponding to the beginning and tail of the waveform.

Soon, it has been recognized how difficult is to find a general equivalent circuit able to reproduce this response, considering different values of soil resistivity and different counterpoise-wires' length. Furthermore, it is known that the backflashover occurrence is not governed only by the response of the electrodes but by a balance between the overvoltage resulting across insulators (under the influence of the electrodes' response) and the insulator withstand. Several other factors contribute to this balance.

This led to idea of analyzing the impact of the tower-footing representation directly on the backflashover condition instead of simply investigating the matching of grounding potential rise of physical representation of electrodes and simplified representations. A methodology to develop this idea is presented below.

B. Methodology and tested conditions

In the developments, the Hybrid Electromagnetic Model (HEM) [15] was systematically used to simulate first-stroke GPR and overvoltage experienced across string insulators of a real 138-kV transmission line due to direct strikes to the tower, considering the physical representation of tower-footing electrodes and other simplified representations, for comparison. The line, consisting of three phases distributed in a triangular configuration and a single shield wire, has a CFO of 650 kV. Details of the tower configuration and of tower-footing arrangement are indicated in Fig. 3. Since the tower-footing representation is the focus of the problem, adjacent towers were not considered, in order to prevent side effects on the results: all line conductors were impedance matched 30 m from the tower. The lightning current waveform is that represented in Fig. 1.

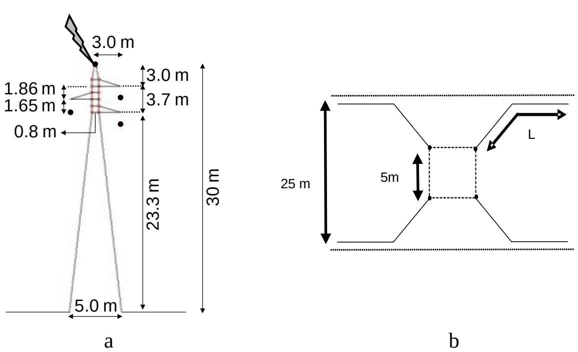

Fig. 3. Representation of the tower configurations of the 138-kV line (a) and the tower-footing arrangement consisting of counterpoise-wires of length L buried 0.5 m deep in the soil (radius of 0.75 cm) and vertical rods (3 m long and radius of 5 cm) to represent the buried metallic components of the tower.

Considering different values of soil resistivity and distinct length of counterpoise wires L, the GPR and the overvoltage developed across the line's insulator strings were simulated in each case, considering the physical representation of tower-footing electrodes. Curves of GPR and of overvoltage similar to those of Figs.1 and 4 respectively were obtained in each case. In addition, in a first step to explore the required features of equivalent circuits, two other limiting conditions were simulated: that assuming the representation of tower-footing electrodes by a single concentrate circuit element equal to R_{LF} and also to Z_P.

The Disruptive Effect Model (DE) was used to determine the critical peak current leading the insulators to backflashover in each case and condition. Details of this model are found in [17,18]. Following the same procedure and using the same parameters of [19], the criterion to assess the backflashover occurrence consists of comparing the magnitude of the *integral DE*, given by (1-2), and the *Critical Base DE*, given by (3) and calculated from the line critical-flashover overvoltage *CFO*. *DE* is integrated in the interval t_o-t, in which the instantaneous value of the voltage across insulator *v(t)* is higher than V_0, as illustrated in Fig. 4. When *DE* exceeds *DEb*, backflashover takes place.

$$DE = \int_{t_0}^{t} \left[v(t) - V_0 \right]^{1.36} dt \qquad (1)$$

$$V_0 = 0.77 \cdot CFO \qquad (2)$$

$$DE_b = 1.15 \cdot CFO^{1.36} \qquad (3)$$

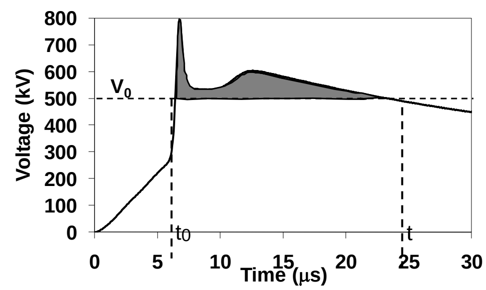

Fig. 4. Stylized representation of the DE method for determining the critical current leading the insulators to backflashover.

Fig. 4 illustrates the integrated interval in the process to determine the critical peak current of a representative first stroke current. According to this method, for a given set of conditions of the line comprising its configuration, dimensions, soil resistivity and electrode length, the peak current is increased continuously and so the overvoltage across insulators. Once the conditions are preserved, the same occurs with the overvoltage waveform. When the backflashover condition is achieved, meaning that the integral DE becomes larger than DE_b, the associate peak current corresponds to the critical peak current.

Considering the critical peak current I_{PC} in a cumulative peak-current distribution [20] allows determining the percentage of lightning currents expected to exceed I_{PC}, which corresponds to the same percentage of lightning currents striking the tower leading to backflashover.

If the number of strikes to the line N_S is known, the expected number of backflashover is promptly calculated simply multiplying the percentage above by Ns.

IV. Results

In a case study, the methodology mentioned in the previous section was applied to the line represented in Fig. 3, considering a moderate and a high resistivity soils, respectively of 600 and 2000 Ωm, and variable length of counterpoise wires.

The IEEE peak current distribution [20] was used in evaluations. A same number of lightning strikes to the line, 40 flashes/100 km/year (5 flashes/km^2/year × 0.08 km × 100 km) was assumed. The expected backflashover rates were determined, considering the physical representation of tower-footing electrodes and their representation by Z_P and R_{LF}. All towers were considered equal and installed in a same soil.

The calculated low-frequency resistance R_{LF} and impulse impedance Z_P were determined for tower-footing electrodes installed in both soils. To obtain these parameters, simulations were developed considering the counterpoise wires of Fig. 3(b) subjected to the median first-return-stroke current represented in Fig. 1, varying the length L in the ranges 20 to 60 m and 50 to 110 m, respectively for a 600- and a 2000-Ωm soils. In each simulated case, a pair of waves corresponding to the impressed current and resulting GPR was determined. For each pair of curves, Z_P was calculated as the ratio between the peak values of the GPR and current, and R_{LF} was calculated as the ratio of the instantaneous values of GPR and current at 50 µs. Tables I and II show the calculated parameters obtained for electrodes shorter than the effective length.

TABLE I
CALCULATED IMPULSE IMPEDANCE AND LOW-FREQUENCY RESISTANCE OF THE TOWER-FOOTING ARRANGEMENT OF FIG. 3(B) COMPRISING COUNTERPOISE WIRES OF LENGTH L BURIED IN A MODERATE RESISTIVITY SOIL

L (m)	Z_P (Ω)	R_{LF} (Ω)	Difference (%) $[(Z_P - R_{LF})/ R_{LF}]\cdot 100$
20	12.6	14.5	-13.1
30	9.3	11.0	-15.5
40	7.4	8.9	-16.9

TABLE II
CALCULATED IMPULSE IMPEDANCE AND LOW-FREQUENCY RESISTANCE OF THE TOWER-FOOTING ARRANGEMENT OF FIG. 3(B) COMPRISING COUNTERPOISE WIRES OF LENGTH L BURIED IN A HIGH RESISTIVITY SOIL

L (m)	Z_P (Ω)	R_{LF} (Ω)	Difference (%) $[(Z_P - R_{LF})/ R_{LF}]\cdot 100$
50	19.5	25.0	-22
70	14.7	19.5	-25
90	11.7	16.0	-27

Note that the magnitude of the impulse impedance is always lower than that of the resistance and the difference becomes more pronounced in the high resistivity soil. This occurs because both effects responsible for decreasing the impedance, namely the capacitive currents in the soil and frequency dependence of soil resistivity and permittivity are stronger in high resistivity soils. An exception to this behavior is shown for the 60-m-long counterpoise wires buried in the 600-Ωm soil. This is the only case in which the electrode length is very close to the effective length L_{EF}.

From the waveform of the overvoltage across line insulators obtained in each case, the critical current was determined. From the peak current distribution, the percentage of backflashover was estimated to determine the expected number of outages for an assumed number of 40 flashes striking the line per 100 km per year. Tables III and IV show the outage rate calculated for a moderate and a high resistivity soil.

TABLE III
ESTIMATED NUMBER OF BACKFLASHOVER (138 KV LINE – 600-ΩM SOIL)

L (m)	Number of backflashover (per 100 km per year)		
	Physical representation	Representation by Z_P	Representation by R_{LF}
20	4.96	5	6.56
30	2.8	2.8	3.88
40	1.96	1.88	2.6

TABLE IV
ESTIMATED NUMBER OF BACKFLASHOVER (138 KV LINE – 2000-ΩM SOIL)

L (m)	Number of backflashover (per 100 km per year)		
	Physical representation	Representation by Z_P	Representation by R_{LF}
50	11.48	11.16	16.2
70	7.04	6.72	11.16
90	4.64	4.32	7.84

Fig. 5 depicts the variation of the outage rates as a function of the length of counterpoise wires for both soils and allows comparing better the results provided by the different representations of the tower-footing electrodes.

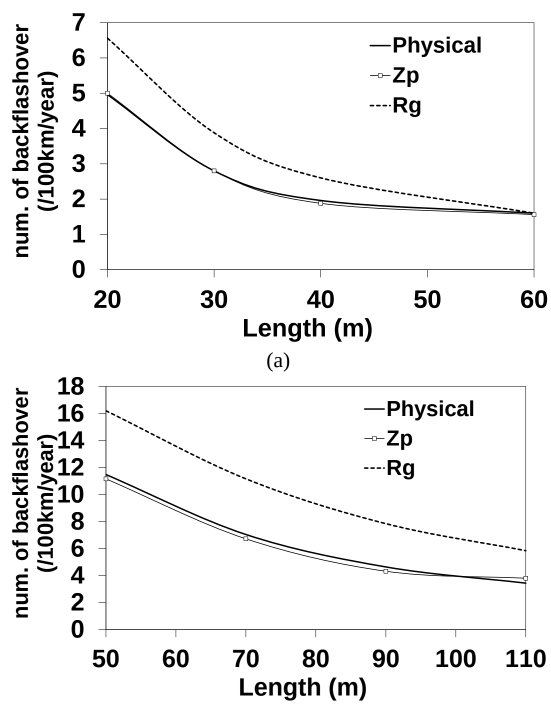

Fig. 5. Comparison of the outages rates calculated from the different representations of the tower-footing electrodes. Soil resistivity of: (a) 600 and (b) 2000 Ωm.

What the results of estimated outage rates above show is that, though the representation of tower-footing electrodes by R_{LF} leads to an extremely conservative result (meaning that backflashover would occur most frequently than in real cases), the backflashover frequency found under the tower-footing representation by Z_P is very similar to that of real electrodes, in all cases.

Surprisingly, after a considerable number of simulations, considering different conditions of line parameters, this finding still showed to hold true, suggesting the adequacy of using this type of simplified representation instead of the physical representation for a consistent assessment of the lightning performance of transmission lines.

V. Discussions and Conclusions

Though the generality of the finding of this paper still requires deeper and more extensive evaluations, such as those developed in [22], the result described above was found to hold true, considering very different conditions of line parameters, soil and electrode length (for counterpoise wires shorter than L_{EF}).

The confirmation of this result suggests the possibility of replacing the physical representation of the tower-footing electrodes in EMTP-type simulations simply by their impulse grounding impedance Z_P to obtain accurate estimates of the lightning performance of transmission lines, in terms of blackflashover rates. No complex equivalent circuits is required.

Though this possibility seems very attractive for engineering applications, it leads to another question. How to determine the tower-footing impulse impedance of transmission lines in practical conditions?

Presumably, there are several options to determine this impedance. First, using electromagnetic models, such as the HEM, it could be accurately calculated from the systematic simulation of typical arrangements of tower-footing electrodes, considering different length and different values of apparent soil resistivity. The results could be tabulated and make available for users in general [22]. A simpler solution would be to determine Z_P from the measured or calculated low-frequency resistance: assuming that the electrode arrangement and dimensions or the apparent soil resistivity are known it is possible to estimate Z_P from R_{LF} using simple commercial or self-developed software based on a constant electric potential approach [22]. Furthermore, presently special instruments are available for measuring directly the first-stroke impulse grounding impedance in field conditions, such as the one described in [21].

The preliminary results of this work look very promising to simplify and improve the evaluations of the lightning performance of transmission lines, though they still require complementary investigation to assess the extension and generality of their validity.

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