Differences on the response of transmission lines subjected to the currents of negative and positive lightning flashes: influence of ground terminations

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***Abstract*-- The differences on the lightning response of transmission lines, whose towers are subjected to the impression of pulses of current of first negative return strokes and of positive flashes, are determined by computational simulation. It is shown that the amplitude of the resulting transient overvoltages across insulators per unit of impressed current is much larger for negative return strokes. As most of the traditional procedures for assessing lightning performance of transmission lines ignore these differences, their results can exhibit significant errors.**

***Keywords*: Transient response of towers subjected to lightning currents, Lightning overvoltages of transmission lines, Currents of negative and positive flashes, Lightning response of grounding electrodes, Lightning performance of transmission lines.**

I. Introduction

THE main mechanism responsible for lightning-related outages of transmission lines (TLs) is the backflashover that is basically governed by the tower-footing impedance. The occurrence of this mechanism depends on the balance between the amplitude of the lightning overvoltage stressing the insulators and their electrical withstand [1,2]. The transient response of the TL components subject to an impressed lightning current, notably of the tower-footing grounding electrodes, and the consequent distribution of currents among the components greatly influence the amplitude of the overvoltages resulting from strikes to the TL [1,3].

In particular, the response of TLs subjected to the incidence of negative cloud to ground (-CG) flashes is well known and is considered in a large number of works. As discussed in [2], there is even an arsenal of mitigating measures to minimize the occurrence of related backflashovers. However, the specific response of TLs subjected to currents of positive flashes is very poorly addressed in literature.

In fact, the peak value and the waveform of the high-intensity pulses of lightning currents, including their rise and decay times, are the parameters of major influence on the resulting overvoltages of the TL [4]. In this respect, one has to consider that these parameters are typically quite different in the currents of first negative return strokes (RSs) and of positive flashes [5]. In particular, the respective transient responses of tower-footing electrodes exhibit very significant differences and, due to the influence of tower-footing impedance on the occurrence of backflashover, this is expected to make different the respective lightning response of the TL, as well [6].

Most of the procedures for assessing the lightning performance of TLs use enlarged cumulative peak-current distributions, such as those of IEEE [7] and CIGRE [5, 8], and distributions of time parameters of first negative RS obtained from measurements at instrumented towers.

Most of the peak current data of those distributions were obtained from magnetic links [5,6]. As these devices are not able to discriminate the event responsible for the peak current, these enlarged distributions include samples of currents of positive flashes. Although the data of -CG return strokes largely prevail (typically, they correspond to more than 90% of the flashes terminating at the ground [7,8]), the vast majority of the samples above 100 kA of these distributions are from positive flashes [5]. This explains the much higher probability of peaks above 100 kA in enlarged distributions in relation to the pure distributions of negative RS from instrumented towers, such as those of Berger [9,10]. The waveforms of the pulses of currents of positive flashes exhibit peculiar features, notably a very slow front (median front time of about 30 µs against about 4 µs for 1st negative RSs) and very long decay time (median time to half-peak of about 500 µs against about 70 µs for 1st negative RSs) [11]. In this text, they are simply referred as positive currents, as it is not clear whether they are associated with return strokes. There is no consensus on the charge transfer mode leading to the occurrence of the measured pulses of current of positive flashes [12-14]. The 26 positive current waves measured by Berger [9] were first assumed to result from upward lightning [10] and, later, from two different mechanisms [5].

In this scenario, the results of lightning performance of TL obtained following these traditional procedures are expected to exhibit significant errors. This work explores the impact of the differences in the positive and negative lightning currents on the tower performance, by analyzing the response of the TL components subjected to the representative waveforms of both currents and investigating how their responses contribute to the resulting overvoltages across TL insulators.

II. Methodology of Development

To yield the results of this work, the transient response of a 138 kV TL, subjected to the impression of currents of a representative negative 1st RS and a positive flash on the top of their towers, was simulated, as indicated in Fig.1, by using the Hybrid Electromagnetic Model (HEM) [15].

This frequency-domain model, described in CIGRE Brochure 785 [16], has been widely employed to determine voltage and current distributions in lightning-related problems. It takes the coupling effects among electrodes and components into account. In particular, the application of this model for calculating the lightning response of electrodes is found in [3, 17], where a detailed approach of the transient response of electrodes is developed. The specific application to tower-footing electrodes is found in [1,6]. And the application of the model to determine the response of transmission-line overvoltages due to direct lightning strikes is found in [1,2,6,15]. The main advantage of this model is the high accuracy of the results it provides, as proved by comparison with experimental results and results simulated using other advanced electromagnetic models. As other frequency-domain models the main constraint is the long processing time. This makes the model less efficient in comparison with distributed-circuit-approach models, though the use of the latter requires modeling per-unit length impedance of the TL and their results are less accurate. In particular, addressing problems involving non-linear effects using HEM requires very time-consuming procedures.

The results of distribution of currents and voltages at the simulated system, determined using HEM, could have been produced using other electromagnetic models.

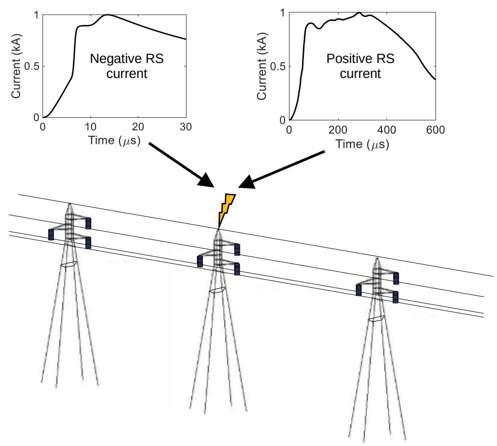

Fig. 1. The simulated event, consisting of a lightning strike to a tower, impressing the current of both events on the top.

Fig. 2 illustrates the geometrical arrangement of the simulated tower. The spans of the two adjacent towers flanking the stricken tower were 400 m long. Note the triangular disposal of the phase conductors and the 30 m high single shield wire of the TL, whose adopted critical flashover overvoltage (CFO) was 650 kV. The figure also depicts the arrangement of the tower-footing electrodes, consisting of buried counterpoise wires of length L.

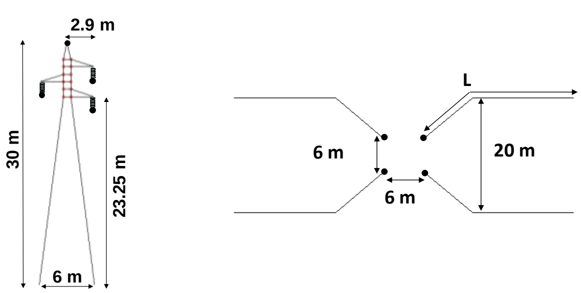

Fig. 2. Simplified geometrical arrangement of the towers of the 138 kV TL (a) and the arrangement of the counterpoise wires (b).

In applications, reaching a threshold value of tower-footing resistance is always pursued by controlling the length of the grounding electrodes. There is a trend to obtain larger resistance with increasing soil resistivity with typical adopted practices. For instance, frequently 80 m long counterpoise wires are used in 3000 Ωm soils, resulting in a grounding resistance of 24 Ω, whereas 25 m long electrodes are used in 300 Ωm low-resistivity soils, resulting in 5 Ω. In this work, realistic values of L were considered for the tested conditions of soil: 25, 50 and 80 m, respectively for 300, 1000 and 3000 Ωm soils. The frequency dependence of the electrical parameters of soil was considered according to the Alípio-Visacro Model [17].

The towers were modeled in HEM by a set of conductive segments in the air, including the crossarms and bracings, according to their physical geometry. The level of detail of the geometric representation of the tower required for ensuring accuracy of the results was determined in previous simulations using the HEM. The radius of the shield wires and phase conductors were considered 0.4 and 1.13 cm, respectively. The TL conductors were extended and impedance-matched 30 m beyond the two adjacent towers.

Two current waves were supposed to be impressed on the tower top. The double-peaked waveform shown in Fig. 3(a) is representative of 1st RSs of the negative flashes measured at Mount San Salvatore (MSS) [9]. This waveform exhibits all the main features of negative 1st RS currents, including the concave wavefront, the abrupt rise from the half to the full peak (first one) and a second peak higher than the first. In addition, it reproduces all the median parameters of amplitude and time, along with the maximum time derivative of the measured currents [18,19]. Due to the lack of data of high-intensity pulses of current of positive flashes with statistical significance, the waveform shown in Fig. 3(b) of a real positive current measured at MSS, exhibiting a front time T_{D30} of 40 μs, was used for representing the waveform of positive currents [10].

The sequence of developments followed in the calculating procedure is summarized next. Direct lightning strikes, impressing the currents of Figs. 3(a) and 3(b) on the tower top, were simulated for the mentioned tower-footing condition, assumed the same for the stricken and adjacent towers. The current and voltage waves resulting at strategic positions of the transmission line considered of interest for the present analysis were determined and are depicted in Figs. 3 and 4.

III. Results and Analyses

The approach for yielding the results of this work focused on developing the understanding of the mechanisms responsible for the specific features of the voltage response of the TL subjected to the negative RS and positive currents.

A. *The distribution of the currents in the TL resulting from the negative and positive flashes*

Fig. 3 depicts the first simulated results, consisting of the distribution of the waves of current along the simulated physical system. To focus on the analysis of the effect of the current waveforms, the results were all developed assuming the impression of a 1 kA normalized peak current.

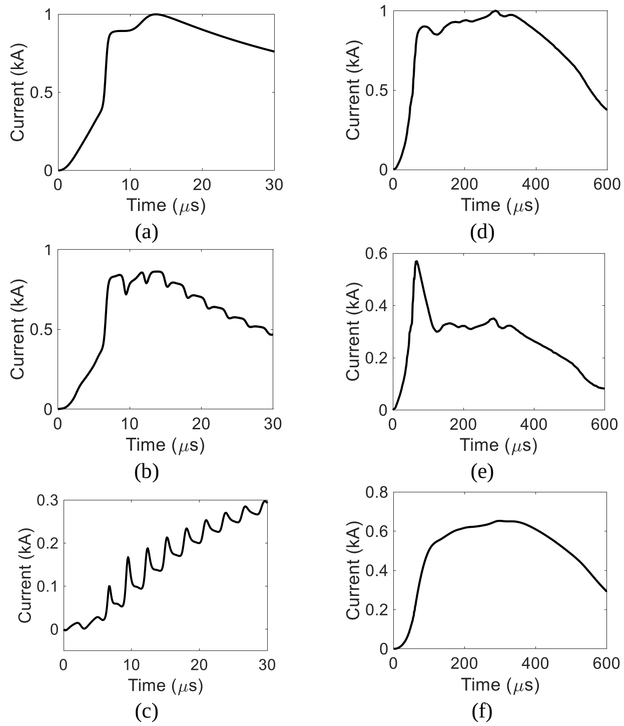

Fig. 3. Simulated currents waves impressed on the tower top: (a) 1st -CG return stroke and (d) positive pulse of front time T_{D30} of 40 µs. Respective currents injected into the ground (b, e)) and flowing to the shield wire (c, f). Low-frequency grounding resistance R_{LF} of the stricken and adjacent towers: 11 Ω. The negative signal of the 1st RS current was reversed.

A first observation about the distribution of currents shown in Fig. 3 concerns the consistency of the results. At any instant, the sum of respective values of current entering the ground and flowing along both sides of the shield wire equals the instantaneous value of the impressed current wave.

The change in the shape of the current waves penetrating the ground in relation to those impressed on the tower is noticeable. Referring to the waveform of the 1st negative RS current, the change is moderate: it loses the second higher peak and exhibits apparent oscillations that, in fact, correspond to the effect of multiple wave reflections at the adjacent towers. On the other hand, the waveform of the positive current penetrating the ground suffers a drastic change of shape. The wavefront comes to exhibit a hook-like shape with the appearance of a pronounced peak, whereas the tail preserves the general original shape. It seems that the peak results from a smaller tower-footing impedance at the wave front that drains the current to the ground. This smaller impedance results from the decrease of soil resistivity for the high frequency components associated with the wavefront. This contrasts with the larger inductive reactance of the shield wire for these high frequencies.

In terms of amplitude of the current waves, at the wavefront, most of the impressed current of the negative RS flows to the ground (about 90% of the peak current), whereas the percentage is lower for the positive current that exhibits much longer front time (about 56% of the peak). This picture results from the difference in the frequency content of the waveforms. The diminution of the highest limit of frequency components with increasing front time is responsible for decreasing the shield wire impedance, resulting in larger current drained through this wire and smaller current flowing to the ground for the positive current. This effect prevails over the decrease of the tower footing impedance with decreasing front time (for the tested currents and usual length of counterpoise wires), resulting from the decrease of soil resistivity with increasing frequency.

After the slope following the peak of the positive current injected into the ground, only less than 40% of the instantaneous value of the impressed current flows to the ground and a little more than 60% is drained to the shield wire. Although it is not shown in the figure, a similar picture tends to occur for the 1st negative RS after the time to half peak.

This picture determines an important difference in the way the lightning current sees the ground terminations of the TL. For 1st negative strokes, practically only the grounding electrodes of the stricken tower are seen, as they drain almost the entire current in the time interval that defines the occurrence of insulation failure. Differently, for the positive current, the tower-footing electrodes of adjacent towers drain a significant part of the current, contributing to reduce the overall ground impedance of the TL seen by the lightning current.

B. Lightning overvoltages in the TL resulting from the impressed negative and positive current waves

Fig. 4 complements the simulated results for the case of 50 m long counterpoise wires buried in a 1000 Ωm soil and shows the distribution of voltages resulting along the simulated physical system, due to the impression of the two current waveforms. This specific condition was used as reference for the analyses of overvolatges. Note that, though the voltage is given in kV, the results were developed assuming the impression of a 1 kA normalized peak current. Thus, in fact, the results should be expressed in kV/kA.

To understand the results of Fig. 4, it is worth noting first that, in general, the voltage resulting at the tower top is given by the sum of the tower-footing GPR (grounding potential rise) and the voltage drop along the tower, due to the flow of the impulsive current towards the ground. This is clearly illustrated for the voltage waves of the 1st negative RS: the curve in Fig. 4(c) is given by the sum of the curves of Figs 4(d) and 4(e). The same applies to the respective curves of Figs 4(h), 4(i) and 4(j), for the positive current.

In addition, the overvoltage across insulators results from the difference of the voltage at the tower top and the instantaneous value of the voltage at the phase conductor (considering both the power frequency voltage and the voltage induced at the phase conductor by the flow of the lightning current along the TL). According to the position where the specific insulator is suspended at the tower, the result may vary slightly in relation to that at the tower top. In particular, the overvoltage across the superior insulator in Figs. 4(b) and 4(g) were obtained by the difference of the voltage at the tower top in Figs. 4(c) and 4(h) and the respective voltage induced at the superior phase conductor (not shown here), as the power-frequency voltage was not considered in the results of this paper. Note their peak value of about 17 and 4.3 kV against the respective overvoltage at tower top of about 24 and 5.3 kV.

The qualitative analysis of the two above paragraphs is general and do not depend on the waveform of current.

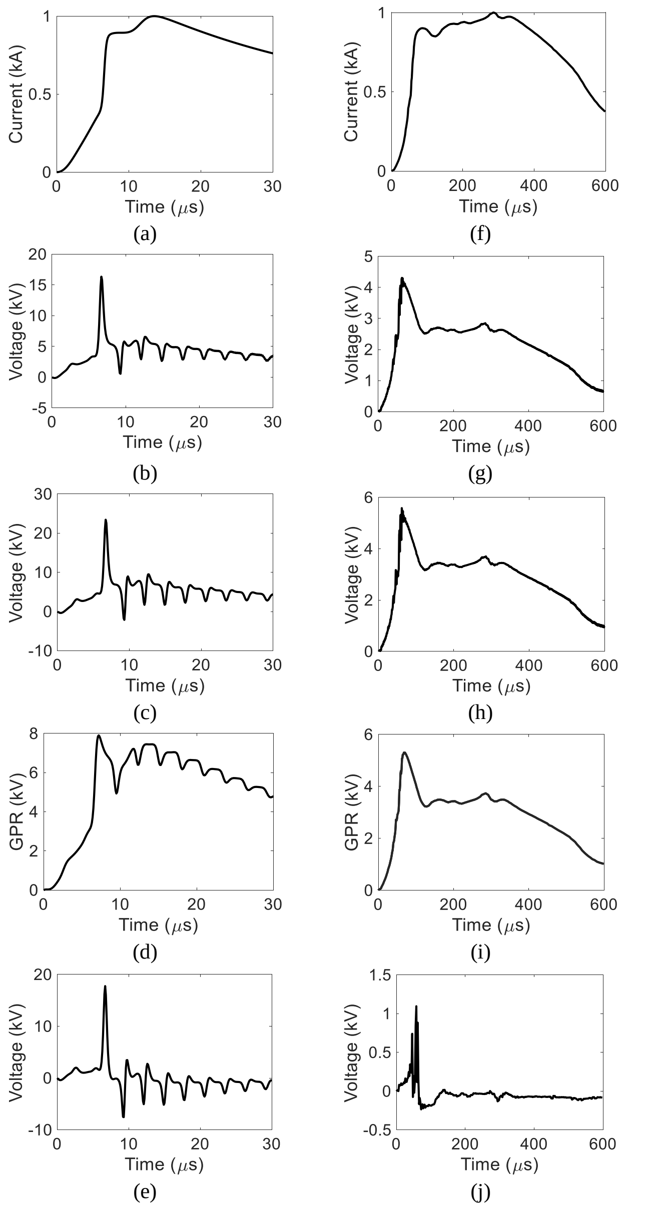

Fig. 4. Impressed current waves of a 1st negative RS (a) and a positive flash (f) and respective voltages, developed due to the impression of the currents on the tower top: (b and g) overvoltage waves across superior insulator; (c and h), overvoltage at the tower top; (d and i) tower-footing potential rise – GPR; and (e and j) voltage drop along the tower. Case: 50 m long counterpoise wires buried in a 1000 Ωm soil (R_{LF} = 11 Ω). To improve the visual conditions for comparison, the negative signal of the 1st RS voltages was reversed.

Considering the results in the second row of Fig. 4, corresponding to the overvoltage wave across the superior insulator, note that both the peak value and the average value at the wave tail (in the interval after the slope following the peak and the time to half-peak) are significantly larger for the negative stroke. The peak voltage of the negative RS (T_{D30} of 3.8 µs) is about 4 times higher than those of the positive current (T_{D30} front time of 40 µs). The approximate average value of voltage in the wave tail of the positive current is about 2 times smaller than that of the negative RS.

What explains this behavior is the difference in the distribution of currents for the two waveforms of current shown in Fig. 3, resulting from their different frequency content. The larger currents flowing to the shield wire for the positive current (in both the wavefront and wave tail) is responsible for the corresponding lower value of both the voltage drop along the tower and GPR. This results in lower overvoltage amplitudes at the tower top and, therefore, across insulators.

In particular, note the great contribution of the voltage drop along the tower for the 1st negative RS (peak voltage of about 18 kV) for the rvoltage peak at the tower top of about 23.5 kV. The time displacement of the peak of the wave of voltage drop along the tower and that of the GPR prevents the overvoltage at the top to reach even a higher peak value. Without this displacement a value of about 26 kV would be reached (adding 8 kV peak of the prevailing resistive GPR to 18 kV peak of the purely inductive voltage drop along the tower).

In contrast, the voltage drop along the tower and the GPR of the positive current are much lower, with respective peak values of about 1 and 5 kV, that result in overvoltage at the tower top and across insulators of about 5.5 and 4.3 kV.

Results of the same type of Fig. 4 were developed for soils of low and high resistivity (300 and 3000 Ωm) as well. They are shown in Figs 5 and 6, respectively.

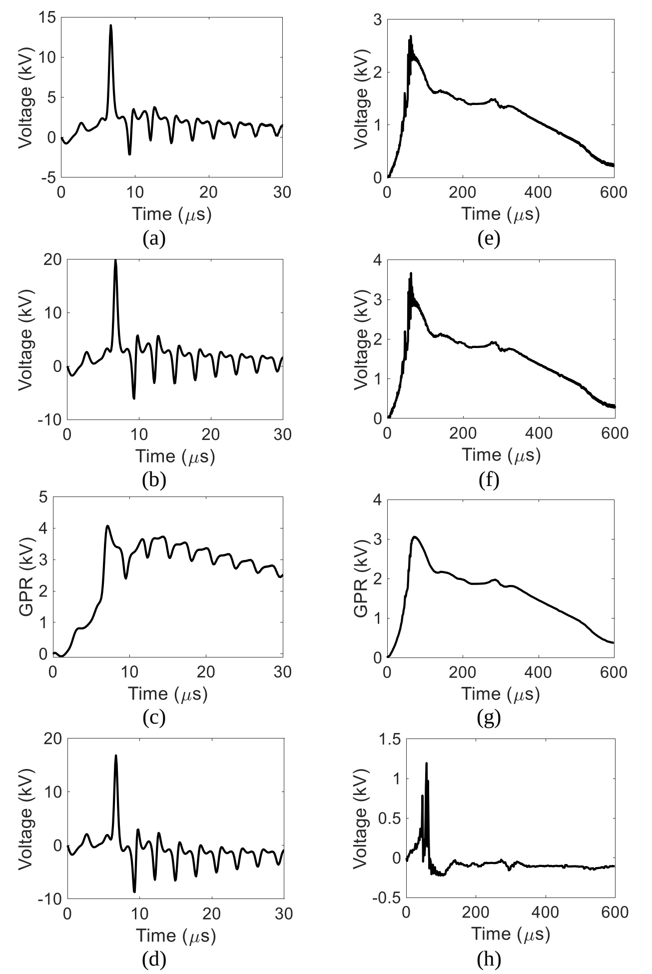

Fig. 5. Voltages (on the left and right), developed due to the impression of the currents of the 1st negative and a positive RSs of Figs. 4(a) and 4(f) at the tower top: overvoltage waves across superior insulator; (a and e), overvoltage at the tower top; (b and f) tower-footing potential rise - GPR and (c and g) voltage drop along the tower. Case: 25 m long counterpoise wires buried in a 300 Ωm soil (R_{LF} = 5 Ω). To improve the visual conditions for comparison, the negative signal of the 1st RS voltages was reversed.

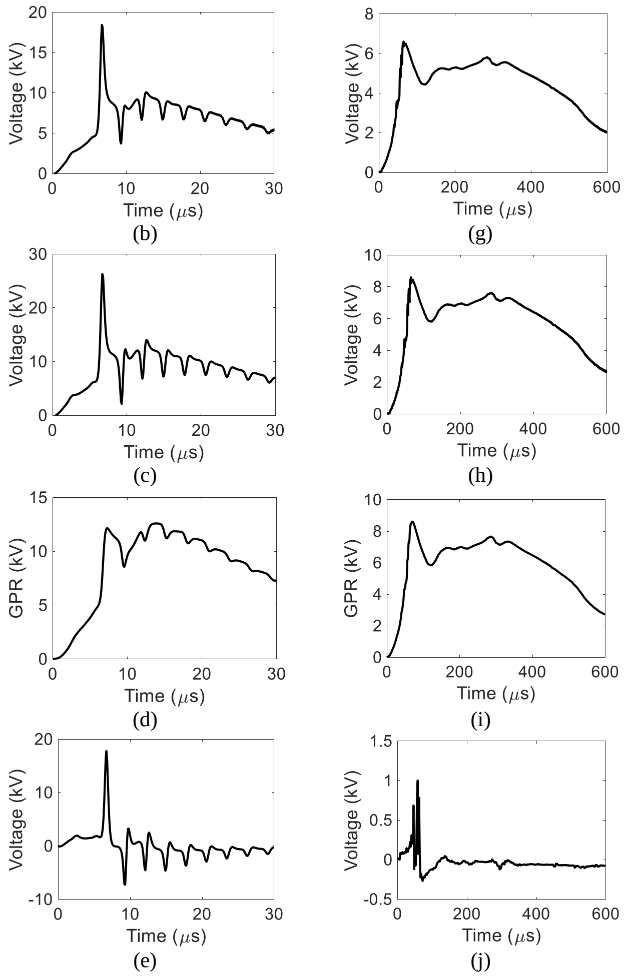

Fig. 6. Voltages (on the left and right), developed due to the impression of the currents of the 1st negative and a positive RSs of Figs. 4(a) and 4(f) at the tower top: overvoltage waves across superior insulator; (a and e), overvoltage at the tower top; (b and f) tower-footing potential rise - GPR and (c and g) voltage drop along the tower. Case: 80 m long counterpoise wires buried in a 3000 Ωm soil (R_{LF} = 24 Ω). Aiming to improve the conditions for comparison, the negative signal of the 1st RS voltages was reversed.

The comparison of the results in Figs. 4, 5 and 6 show that the general analyses following Fig. 4 remains valid for the conditions of soil and electrodes of Figs. 5 and 6. However, it allows detecting that the results for the positive current are more sensitive to the variation of tower footing impedance: the relative variation of the overvoltage across insulators is significantly larger for the positive current (peaks of about 2.5, 4.2 and 6.5 kV, respectively for the soil resistivity of 300, 1000 and 3000 Ωm, against peaks of about 14, 16 and 18 kV for the negative current of the 1st RS). In part, this results from the much larger voltage drop along the tower for the negative current due to their higher frequency components. The contribution of the GPR for the overvoltage across insulators is much more important for the positive currents.

A general comment concerns the effect of the number of towers flanking the stricken one required in the simulations. The application of HEM showed that, for the negative currents the overvoltages obtained using two adjacent towers were practically the same obtained using a larger number of towers, for instance four and six towers. As expected, for the positive currents, the peak voltages were practically not affected. However, in the time interval following the slope after the peak value, a decrease of voltage amplitude was observed. As the time interval that influence the flashover occurrence precedes this interval of amplitude decrease, using two adjacent towers plus impedance match of TL conductors beyond them showed to be appropriate for the present analysis.

IV. Discussion of the Impacts of the Results

In summary, what the results of Section III reveals is that the relative amplitude of the overvoltage resulting across insulators of TLs due to direct lightning strikes of 1st negative strokes are considerable larger than that of the positive currents.

The analysis showed that the distribution of the current among the TL components in each case is responsible for this result. The part of the impressed current flowing to the shield wires is relatively larger for the positive current, due to both the smaller impedance of the shield wires and larger tower footing impedance, in relation to respective impedances resulting from the negative return stroke, whose current exhibit higher frequency components. The ground termination seen by a first return stroke hitting the tower is practically that corresponding to the footing impedance of the tower, whereas the positive current sees a set of ground terminations that include the grounding impedances of the adjacent towers.

This conclusion showed to be general for the towers installed over soils of resistivity ranging from 300 to 3000 Ωm, corresponding to tower-footing low frequency resistances of 5, 11 and 24 Ω, respectively. The distribution of currents between the stricken tower and the shield wire varies when the tower-footing conditions are different and, therefore, the absolute values of currents and voltages become different. However, the relative difference in the distributions of currents found for the impression of the negative RS and positive currents remains quite similar and so the relative differences in the overvoltages across insulators.

The same is expected to occur when considering TLs with towers of different geometry. For instance, higher towers tend to be subjected to larger voltage drop due to the flow of the lightning current toward the ground. The contribution of this larger voltage component tends to increase the absolute overvoltage across insulators. However, this effect is similar in relation to both tested currents and do not affect their relative difference in the distribution of currents flowing to the ground and shield wires. The same occurs with the respective overvoltages.

Specifically, the quantitative results were obtained for a representative waveform of current of 1st negative RS (with median parameters of the currents measured at MSS, including the front time) and the waveform of a particular real current of a high intensity positive flash. The largest negative 1st RS measured by Berger had a peak current lower than 90 kA, whereas measured positive pulses exhibited peaks above 200 kA. In general, there is a clear correlation between the peak current and the rise time, though numerical expressions for such correlation were developed only for negative first return strokes. Applying these expressions to currents of 200 kA yields a front time of about 10 µs, which is not compatible with the typical front times of high positive pulses of current exceeding 100 kA, whose values are much longer, above 30 µs (e.g., T_{D30} of 40 µs in the positive current in this work). Anyway, the value of the front time of the largest negative RSs tends to approach that of the smallest pulses of high intensity of positive currents. However, the shape of their waves is quite different, overall in terms of the time to half peak that is extremely longer for the positive pulses of current.

To assess the impact of the difference of the lightning response of the tower in the TL performance, one has to apply a flashover criterion to the calculated overvoltage waves across insulators, which contemplates the effect of both the amplitude of the voltage stress and its duration, considering the insulator withstand. It was shown that the relative overvoltage amplitude is significantly larger for the 1st negative RS, whereas the overvoltage duration is significantly longer for the high intensity pulses of current of positive flashes. The prevalence of one of these competing features of the currents of the two different events defines the event yielding the larger probability of backflashover. However, determining this prevalence is only possible after applying the flashover criterion in the specific conditions of test.

V. Conclusions

In the conditions defined in the assessments of this work, it was found that the relative amplitude of the overvoltage resulting across insulators of TLs due to direct lightning strikes of 1st negative strokes are considerable larger than that of the positive flashes.

This results from the difference on the distribution of the incident lightning current among the stricken tower and shield wires. The smaller impedance of the shield wires and larger tower footing impedance for the positive current (in relation to the respective impedances for the negative return stroke) make the drain of positive currents to shield wire relatively larger, resulting in lower overall impedance seen by the incident lightning current. Whereas the grounding electrodes of adjacent towers drain only a small part of the negative currents, they drain a very significant part of positive currents.

To assess the impact of these results in the TL performance, the effect of two opposite factors has to be quantified, the significantly larger amplitude of the overvoltages of negative RS and the longer duration of the positive pulses of lightning current, in the light of the probability of occurrence of each one of these events.

What is important to remark is that the results presented here reveal the inconsistency of the traditional practice adopted in procedures for calculating the lightning performance of transmission lines that considers values above 100 kA in cumulative peak current distributions (presumed as pertaining to positive pulse of currents), with waveform and front time distributions typical of 1st negative RSs [20].

As presently no reliable distribution of front time of positive flashes with statistical significance is available, pursuing the development of such distribution by means of extensive measurements is recommended. Nevertheless, even without such distribution, when considering the contribution of the peak currents above 100 kA in calculations of the lightning performance of TLs, it seems reasonable to modify this traditional procedure, replacing the waveform and front time of these currents by representative parameters of positive currents.

The authors expect that the developments and suggestions of this work can contribute to improve the results of the assessment of lightning performance of TLs.

VI. Acknowledgment

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VII. References

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