2019 International Symposium on Lightning Protection (XV SIPDA), São Paulo, Brazil, 30th September – 4th October 2019.

Methodologies for Measurement of the Response of Tower-Footing Electrodes of Transmission Lines

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***Abstract*— Methodologies for measurement of the concise parameters that express the quality of the response of grounding electrodes subject to lightning currents, such as the low-frequency and 25-kHz resistances, and the impulse impedance are discussed based on theoretical and experimental results shown in this paper. In particular, the work presents rare experimental impulse-impedance results of tower-footing electrodes obtained by using traditional measurement setup. It also presents results of the impulse response of concentrate electrodes by using both traditional setup and a setup that includes open-ended artificial transmission lines. The results are discussed and the consistency of concise parameters derived from the measurements is discussed.**

Keywords*— *Lightninf response of electrodes; Measurement of the response of grounding electrodes, Impulse impedance of grounding electrodes; Grounding Resistance

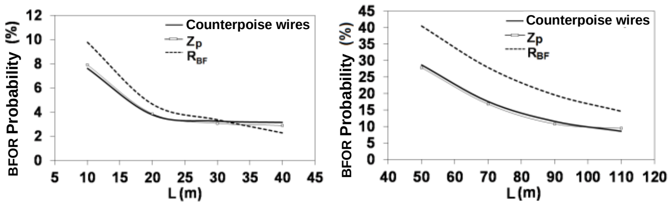
I. Introduction

Most outages of transmission lines (TLs) installed over soils exhibiting moderate and high resistivity [1]–[3] are caused by backflashover, which is a mechanism governed by the lightning response of the tower-footing electrodes [2], [3].

In most cases, the low-frequency grounding resistance R_T has been the parameter used for representing tower-footing electrodes in studies of the lightning performance of TLs. In some cases, the harmonic impedance $Z(\omega)$, determined in specific frequencies f (notably at 25 kHz), has been adopted.Recently there has been a trend for adopting the first-return-stroke impulse grounding impedance Z_{P1st} as a concise representation of electrodes in studies of the lightning response of TLs [4, 5]. This impedance corresponds to the ratio between the peaks of the grounding potential rise (GPR) and the impressed current of a representative first return stroke ($Z_{P1st} = V_P/I_P$).

Recent works demonstrated that using this concise parameter for representing tower-footing electrodes yields practically the same results obtained under the physical representation of electrodes, in terms of backflashover rate. On the other hand, these results are significantly different from those obtained under the low-frequency-resistance representation. Fig. 2 illustrates both aspects.

This work addresses the problems involved in the measurement of the low-frequency resistance, the harmonic impedance at 25 kHz, and the first-return-stroke impulse impedance of tower-footing electrodes and alternatives, and solutions for improving the measurements, considering experimental and simulated results related to the measurement.



(a) (b)

Fig. 1. Example of the lightning performance of transmission lines under different representations of tower-footing electrodes and distinct conditions of soil resistivity, in terms of back flashover rate BFOR (138-kV line): (a) Low (b) and high soil resistivity (300 and 2000 Ωm). Procedure for estimating this rate described in [4]. Adapted from [4].

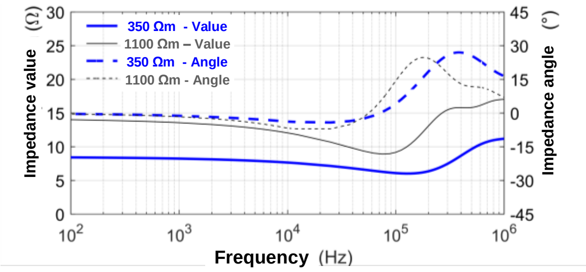
Reference [5] addresses the questions involved in the response of the grounding electrodes of transmission lines subjected to lightning currents, along with the techniques for measurement of representative parameters of this response, following a scientific approach. Differently, this work develops an objective approach for application in engineering.

II. Fundamental Considerations on the Lightning Response of Grounding Electrodes

Only first return strokes are the relevant cause of backflashover in high-voltage TLs and the frequency content of this current can extend to the range of 250 kHz.

Two fundamental characteristics related to the transient response of electrodes are exhibited in Fig. 2, adapted from references [5,17]. Fig. 2(a) shows the frequency diagram of the harmonic impedance of tower-footing electrodes, consisting of counterpoise wires buried in low- and a high-resistivity soils. Fig. 2(b) shows the variation of the impulse impedance and the low-frequency resistance in relation to the length of the electrode and Fig 2(c) shows the general curve of the impulse coefficient I_C, given by the ratio between Z_P and R_T. Note that Z_P is significantly influenced by high-frequency components of current, whereas R_T is defined by the low-frequency components and can be calculated as the ratio between the instantaneous values of the GPR and first-stroke impressing current at their wave tails.

As discussed in [4, 5, 17], in the low-frequency range, Z(ω) is almost constant and equivalent to a resistance (null phase angle). In this range, reactive and skin effects are practically negligible and, practically, no capacitive current flows in the soil. Thus, in this frequency range, the electrodes correspond to an equipotential volume and Z(ω) is equal to R_T. As the frequency is raised, capacitive currents become relevant in the soil (increasing negative impedance phase) and become responsible for decreasing Z(ω) above a few kilohertz. Raising the frequency further makes inductive effects to appear, decreasing the negative impedance phase. First, their interaction with capacitive effects results in additional decrease of the impedance until a minimum value is reached when the impedance phase is close to zero. After that, the magnetic effect prevails (positive impedance phase) and Z(ω) tends to increase continuously, exceeding R_T and becoming larger at higher frequencies. All through this range, the voltage drop along the electrodes becomes significant and the equipotential assumption is no longer valid for electrodes. The described qualitative behavior does not change with the soil resistivity or electrode arrangement, though the decrease of Z(ω) is more significant in high resistivity soils, due to the larger capacitive currents in the soil and the greater frequency-dependence effect of the electric parameters of soil.



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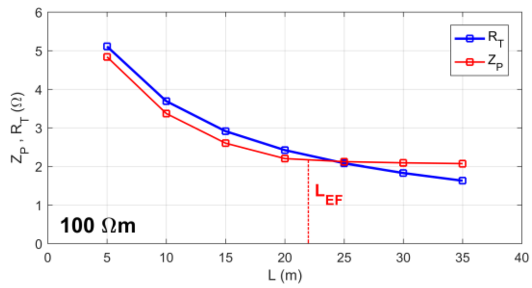

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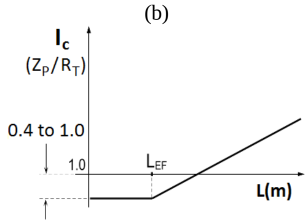


(c)

Fig. 2. Features of the response of grounding electrodes subjected to currents in frequency and time domains: (a) diagram of harmonic impedances Z(ω) of counterpoise wires buried in low and high resitivity soils (L of 20 m for a 350-Ωm soil and L of 50 for a 1100-Ωm soil); (b) Variation of ZP and RLF as a function of the length of counterpoise wires for a 100- Ωm soil; (c) General curve of the Impulse Coefficient IC as a function of the length of counterpoise wires. Adapted from [5] and [17].

On the other hand, as discussed in [7], the curve of the impulse coefficient in Fig. 4(b) denotes some relevant aspects related to the concise parameters Z_P and R_T.

It shows that the effective length (L_{EF}) delimits two regions, in which I_C is first practically constant and, then, increases continuously. As discussed in [6,7], L_{EF} corresponds to the length at which the decrease of the impulse impedance with increasing electrode length is saturated, due to the attenuation of the current wave traveling along the electrode. This attenuation is more pronounced in low-resistivity soils.

Therefore, L_{EF} is shorter in low-resistivity soils and longer in high-resistivity soils [6,7]. For a an electrode shorter than L_{EF}, as its length increases, both Z_P and R_T continuously decrease. This simultaneous decrease continues while the threshold corresponding to L_{EF} is not reached ($L < L_{EF}$) and results in a constant value for I_C, lower than one. The capacitive currents in the soil and, above all, the decrease of soil resistivity due to its frequency dependence are responsible for a Z_P value lower than R_T [6,7]. In high-resistivity soils, I_C can be as low as 0.4, as both capacitive currents and the decrease of soil resistivity are more pronounced.

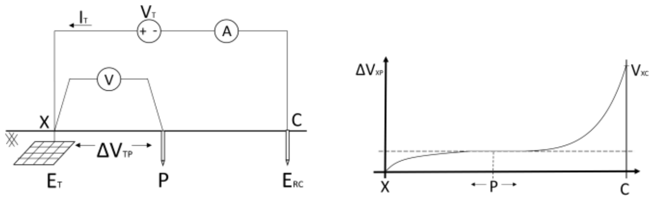
I_C approaches 1 in soils of very low resistivity, as both the capacitive currents and the decrease of soil resistivity tend to be negligible. Despite the variation of Z_P and R_T in the range of electrode length shorter than L_{EF}, their ratio remains practically constant and lower than one. Increasing further the electrode length ($L > L_{EF}$) yields no decrease of Z_P, whereas R_T continues to decrease, as the low-frequency components are not subject to attenuation. Thus, as Z_P remains constant, the decrease of R_T results in increasing I_C values. This coefficient can reach very high values for very long electrodes ($L >> L_{EF}$).

III. On The Methodologies for Measurement of the Response of Tower-Footing Electrodes

The response of tower-footing electrodes is usually measured by applying the traditional fall of potential method, considered the most reliable technique [8], [9].

The general idea of this method consists of impressing a current on the electrodes under test E_X, making it to circulate in the ground towards an auxiliary current-return electrode E_{RC}, and detecting the corresponding grounding potential rise (GPR) it yields in relation to the remote earth. The response is expressed as the ratio between the GPR and the impressed current.

The circulation of current in the ground yields a difference of potential (ΔV_{XP}) between the electrodes under test (at position X) and the points along the line XC connecting this position to the position C of the auxiliary current-return electrode. Fig. 5(b) exhibits a typical profile of the mentioned difference of potential as the voltage probe is displaced over the ground along the line XC, considering a long distance XC between the electrodes E_X and E_{RC}, as obtained from the setup indicated in Fig. 3(a).



(a) (b)

Fig. 3. Setup for measuring the response of electrodes subject to the impression of current (a) and the distribution of potential over the ground along the line connecting electrode EX under test and the auxiliary current-return electrode ERC (b). Adapted from [5] and [17].

The potential rise of the electrode under test E_X in relation to the remote earth (GPR) corresponds to difference of potential ΔV_{XP} specifically between this electrode and a position P over the flat region that separates this potential rise from the potential rise of the auxiliary current-return electrode. What ensures the existence of this flat region is a significant distance XC. Large distances XC ensure that no mutual effects exist between electrodes E_X and E_{RC}. If there is no flat region, then it is no longer possible to detect the potential rise of the electrode E_X.

In an attempt to detect the existence of the flat potential region, the voltage ΔV_{XP} between the tower-footing electrode E_{TF} and the auxiliary voltage probes driven in the soil is detected for three positions of P (XP equal to 0.55XC, 0.65XC, and 0.75XC), corresponding to a 10% variation in relation to XC. For each position, the measuring instrument provides the ratio between the measured voltage ΔV_{XP} and impressed current I_T, which corresponds to a resistance.

As the current remains the same in the three consecutive measurements, if the flat potential region exists, the instrument will exhibit similar values of resistance. In this case, the detected voltage corresponds to the potential rise of E_{TF} and the average of the measured resistances corresponds to the low-frequency tower-footing grounding resistance R_T. If the measured resistances are significantly different (differences larger than 3% to 4%), this means that no flat potential region exists. To solve this problem, the auxiliary current-return electrode has to be displaced to longer distances (for instance, 2 times the distance XC) and the whole measuring procedure has to be repeated, until the three measured resistances exhibit similar values.

It is worth mentioning that the disseminated idea of using a distance XP equal to $0.62 \cdot XC$ is a frequent cause of errors in the measurement of R_T, as, in most conditions, it is not able to ensure that the measurement is performed at the border of the zone of influence of the electrodes under test, notably in the measurement of long counterpoise wires.

There are practical problems involved in the specific measurement of the grounding response of LTs tower-footing electrodes, which makes this measurement unfeasible or very difficult. Firstly, in order to prevent buried electrodes laid along the line direction from interfering with the measurement results, the leads used in the tests have to be laid along a direction orthogonal to that of the line. Second, in the case of extensive grounding electrodes, as is the typical case of the Brazilian LTs, the recommended distance between the tower and the auxiliary current return electrodes has to be very long to ensure the existence of the flat potential level. Frequently this distance has to exceed 200 m. Another general problem concerns the need to allocate a substantial part of the potential applied by the test voltage over the area of influence of the grounding electrode under test. Due to the typical grounding impedance of the current-return electrodes much lower than that of the electrodes under test there is a trend to concentrate almost all the applied voltage over the area of influence of the first. To mitigate this problem, it is recommended using a large number of connected driven rods as auxiliary current return electrodes (from 5 to 10 rods driven at least 70 cm in the soil).

If the measurement uses low-frequency instruments, the shield wires have to be disconnected from the tower (or, when possible, buried electrodes have to be disconnected from the tower). Without that, the measured resistance would not correspond to R_T, but to the parallel of the grounding resistance of a set of towers connected by the shield wires.

The specific constraints of the former type of measurement has led to using high-frequency instruments (usually 25kHz), which, allows performing measurements without disconnecting shield wires. Due to a pronounced skin effect at these frequencies, the shield wire's longitudinal impedance value would be much higher than R_T and the portion of current flowing to nearby towers could be neglected.

On the other hand, measurement in this frequency range amplifies the coupling effect between the current and voltage measurement cables. To overcome this problem, it is recommended to place the auxiliary electrodes of current and the voltage probes in opposite directions, along a line, which is orthogonal to the TL direction.

Nevertheless, even in this case, depending on the value of the tower footing impedance, a parcel of the current impressed to the tower can be dispersed to adjacent tower, corrupting the results of measurement. Table I shows the expected errors in the measured resistance at 25 kHz on transmission lines with 1 or 2 shield wires, as detailed in [5].

TABLE I. EXPECTED ERRORS IN THE MEASURED TOWER-FOOTING RESISTANCE

Freq. (kHz)	Shield wires	Error** (%)		
		RT* = 10 Ω	RT = 20 Ω	RT = 40 Ω
25	1	-4	-8	-25
	2	-5	-14	-54

*RT = GPR/$I_{TOWER\text{-}FOOTING}$ – Grounding resistance of central tower

**Error (%) = (R25kHz - RT)/RT*100, where R25kHz = GPR/I_{TOTAL}

The measurement of the impulse grounding impedance (Z_P) presents similar difficulties. In fact it requires even more attention to the electromagnetic coupling effects between the measuring leads and between them and buried electrodes, due to the high-frequency components of the impressed impulse current that extends to above 200 kHz. However, it is worth remarking that the impulse response of electrodes is much more representative of the condition of electrodes subjected to lightning, as suggested by the curves of Fig. 1. In addition, an important restriction has already been overcome, which consisted in the lack of instruments dedicated to the realization of this type of measurement. New instruments have been developed specifically for this type of application, such as the one presented in [13]. Thus, there is a current trend for this kind of measurement for qualifying the lightning response of tower-footing electrodes. Considering the mentioned difficulties, the arrangement indicated in Fig. 4 was configured to consistently measure the impulse response of tower-footing electrodes.

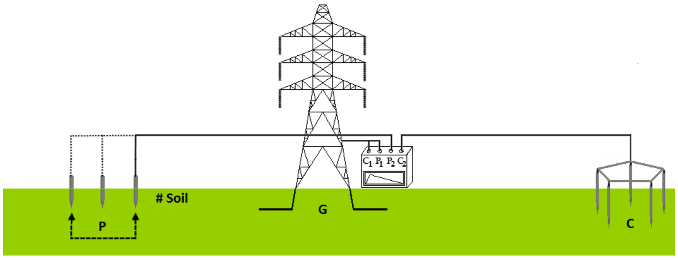


Fig. 4. Setup for measurement of tower-footing impulse grounding impedance to provide (for measuremt of tower-footing impedance of guyed towers, impressing current at the central mast connected to the anchhors by lead wires at ground level is recommended). Adapted from [5].

In this kind of measurements, it may be required to perform an impedance matching to avoid the possibility of current wave reflections at the auxiliary current-return electrodes. If the value of its impedance is too high, the problem can be mitigated by using a large number of auxiliary current-return electrodes to reduce this impedance. On the other hand, if it is too low, an additional resistance R can be included between the current lead and the ground termination for matching their impedances. The value of resistance R can be obtained by a trial-and-error procedure, to determine which value minimize reflections.

A general interesting feature supported by theory and experiments consists of the relation "$R_T > R_{25kHz} > Z_P$". The difference can be very significant in high-resistivity soils due the strong effects of the frequency dependence of electrical parameters of soil [10-12] and also the substantial capacitive currents in the soil.

IV. Experimental Results and Analysis

Due to the complexity of measurement of the impulse response of tower-footing impedance, results of this kind of measurement are extremely rare in the literature. This work presents results taken from a significant number of measurements performed by the authors in different TLs, which are illustrated specifically for a 230-kV line installed in flat and low-altitude region in Brazil. Most towers of the line are guyed towers, but the result explored here concerns specifically the free-standing tower shown in Fig. 5. A differential aspect of this measurement is the local low-resistivity soil. All results previously published by the authors (e.g., in [5] and [17]) refers to high-resistivity soils.

In the impulsive measurements, a handmade portable 0.6-kV peak voltage impulse generator was used. In the experiments, a current wave with a 5-μs front time was impressed on the tower base. The current-return electrodes were placed at 200-m distance from the tower. The exact position of the voltage probe P was found by displacing it from a distance of 90 m until the variation of the GPR was ceased, indicating that the remote earth had been reached.

Fig. 5. View of the freestanding tower (no. 251) and surroung environment of transmission line where measuremnts were peformed: 230-kV TL in Brazil.

The impressed current wave was recorded along with the corresponding GPR. Furthermore, the tower-footing grounding resistance was also measured by using a 25-kHz instrument. In both types of measurements, the shield wires remained connected to the tower. Fig. 6 presents the results of the measurements, including the harmonic impedance calculated by using Fourier Transform. Relevant aspects of these results are discussed below.

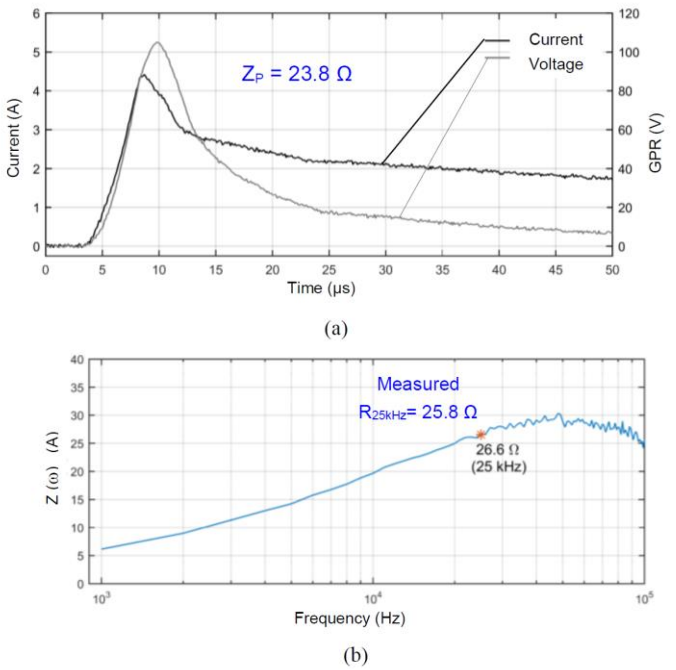


Fig. 6. Results of impulsive measurements obtained for tower 251 of the 230-kV TL: (a) recorded waves of GPR and current and (b) calculated diagrams of tower-footing harmonic impedance.

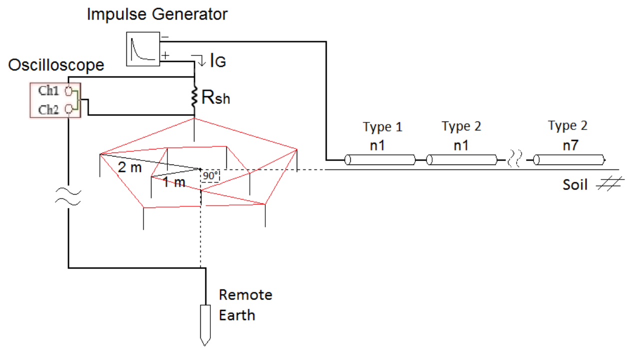
Note that the measured tower-footing impulse impedance of 23.8 Ω is not so different from the calculated 25-kHz grounding resistance with the commercial instrument, using the same setup (26.6 Ω), exhibiting an error of about 12%. Considering the expected relation "$R_T > R_{25kHz} > Z_P$", this percentage is expected to increase substantially comparing the impulse impedance with the low-frequency resistance.

The curves in the diagram of impedance show very interesting results. First, the measured and calculated 25-kHz resistance are quite similar (25.8 against 26.6 Ω). In particular, the harmonic impedance is expected to decrease continuously with increasing frequency in the typical range of frequency of first strokes, while the electrode remains shorter than the effective length. However, what the curve shows is a continuous increase of the harmonic impedance until a few hundreds of kilohertz. This behavior derives from the significant part of the current of the low-frequency components that flows to the shield wires, as the skin effect is not important at this range. As the frequency increases, the longitudinal impedance of these wires increases as well, and the part of current flowing to the ground increases.

Though it is not shown here, two experimental observed during measurements results deserve to be mentioned. First, as expected, the value of R_{25kHz} obtained by the measurement performed with the auxiliary current-return electrodes positioned in the same direction (current and voltage measuring leads laid parallel over the ground) exhibits huge errors in relation to that measured with the leads laid in opposite sides (error larger than 200%). Second, even when the leads were laid in opposite sides, using distance XC shorter than 200 m between the tower and auxiliary current-return electrodes led to significant errors (for instance, the error was of about 20% for XC=150 m). These two results illustrates how important is to observe the recommendations of Section III for ensure reliable results of measurement of tower footing electrodes.

On the other hand, the last result remarks an important constraint related to this kind of measurement, consisting of the need of very long distances XC, which is a serious problem when developing measurements under unfavorable environmental conditions, what is quite common. This stimulates developing solutions to mitigate this constraint. In this respect, using the so called open-ended artificial transmission line (OATL) is a promising technique. The use of this methodology is still under development and has not been applied for arrangements of long counterpoise wires.

Anyway, Fig. 7 illustrates how promising it is by presenting some recent results developed for concentrate electrodes, which were taken from [18]. The impulse impedance measured using OATL (52 Ω) is quite similar to that obtained using the traditional methodology of measurement (53 Ω). Furthermore the grounding resistance of 56 Ω estimated in Fig. 3(c) at the range of 25 to 35 µs is also quite similar to that measured with low frequency instruments (57 Ω). Although the results are limited to concentrate electrodes, their excellence stimulate to continue exploring the application of this technique to make it feasible for very long electrodes. This would represent a huge advance on the measurement of the impulse response of tower-footing electrodes.



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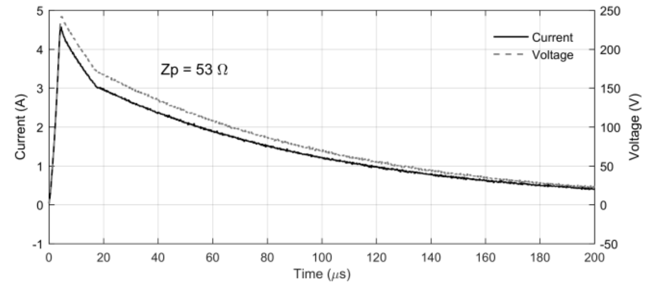

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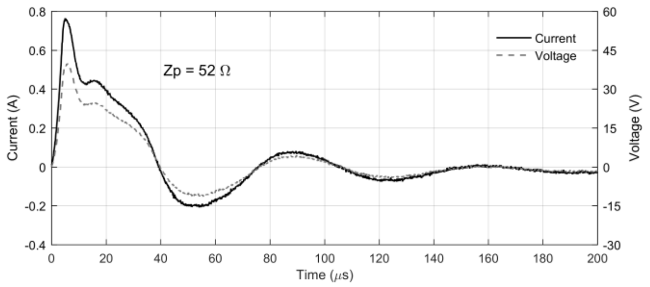

(c)

Fig. 7. Setup for measuring the impulse response of grounding electrodes by using open-ended artificial line, comprising 8 units, each one consisiting of a long copper wire wrapped around a ½ inch PVC pipe, 3 m long. Impulsive waves with patterns of lightning-current waveforms are impressend on the electrodes under test by the impulse generator installed between the electrodes under test and the open-ended transmission line. Both the current and developed potential rise are recorded. Experimental results for the low resitivity soil (200-Ωm low frequency soil resitivity): (a) Coorresponding measured GPR and current impressed on electrodes using the traditional setup of Fig. 4; (b) the same, using the open-ended artificial transmission line. Adapted from [18].

V. Conclusion

The measurement of concise parameters R_T, R_{25kHz}, and Z_P of tower-footing electrodes subject to lightning currents was addressed. The practical problems involved in implementing this measurement was discussed along with corresponding solutions.

Although the low-frequency resistance is not able to express the lightning response, which would be properly expressed by the first-stroke impulse grounding impedance, it is feasible to determine Z_P from R_T by using the impulse coefficient I_C, whose values for specific soil resitivity can be determined from expressions provided in the literature, for instance in [4], [7].

Even so, the measurement of R_T in the typical conditions of Brazilian lines is a laborious task, as it requires disconnecting shield wires from the tower. This has led to the use of commercial 25-kHz instruments, which do not require the shield wire to be disconnected. But, even in this type of measurement, significant errors can be expected when the grounding resistances/impedances of the tower under test are high.

Currently, impulsive impedance measurement of tower grounding without disconnection of shield wire is feasible by following the measuring arrangement in Fig. 4. In this case, the errors of measurements are acceptable, as illustrated by the experimental results of Fig. 6.

However, even this type of measurement presents a serious constraint related to the need of very long distances between the tower and the auxiliary current-return electrodes.

This is the reason why the authors believe that measuring the first-stroke impulse impedance by using OATL, such as in the case of concentrate electrodes whose results are presented in Fig. 7, is a very promising and feasible methodology to overcome the constraints involved in this kind of measurement and to allow reliably qualifying the lightning response of tower-footing electrodes.

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