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

Impulse Impedance Measurement Methodology in Space Restricted Locations

Adroaldo Raizer
Federal University of Santa Catarina
UFSC
Florianópolis, Brazil
adroaldo.raizer@gmail.com

Vilson Luiz Coelho
Faculty SATC
FASATC
Criciúma, Brazil
vilson.coelho@vlc.eng.br

Thiago Schmoeller
Federal University of Santa Catarina
UFSC
Florianópolis, Brazil
eng.thiagoschmoeller@gmail.com

***Abstract* — This paper presents the analysis results of field measurements of ground resistance and impulse impedance. First, the Current Derivative Method is presented, whose objective is to obtain the R_{LF} steady-state ground resistance value from the transient impedance curve $Z(t)$. Second, it is presented a study about the application of ground resistance measurement methods, for electrodes positioned at reduced distances, in impedance measurements under the same conditions, and it is concluded that these methods do not present satisfactory results. Based on the results, a proposal is presented for the development of a method with orthogonally positioned electrodes that allows field measurements without significant errors, both for ground resistance and for impulse impedance.**

Keywords — Field Measurements, Ground Grid, Ground Resistance, Impulse Impedance.

I. Introduction

The determination of the ground resistance and impulse impedance values in substation ground grids are two of the main factors to be considered during the performance and safety analysis of these systems. The need to obtain low ground impedance values, ensuring protection of the electrical system during surges and faults, as well as touch and step voltage levels tolerable to living beings, make the measurement process indispensable for these analyzes.

Due to the importance of obtaining these data, the sum of the efforts of several studies and research establishes norms to be used when this subject is exposed, among which ANSI/IEEE 81 [1] and NBR 15749 [2]. These standards define, in addition to accepted measurement methodologies and other important features, the minimum (and considerable) distances between the system to be evaluated and the auxiliary voltage and current electrodes. These distances are not always available, depending on the installation location and the dimensions of the grounding system under measurement, as is generally the case for grounding substations in urbanized environments.

For the measurements of ground resistance, some methods and contributions [3 - 9] have been proposed to overcome these obstacles of great distances, among which the Tagg or Slope Method [3], Tagg Extent [4] and PRED [5]. For the case of impulse impedance measurements ($Z_P=V_{max}/I_{max}$), despite the many efforts in this way, a suitable and guaranteed method of results for space restricted sites has not yet been established.

Therefore, based on the constraints of the previously mentioned methods and field data previously obtained in Ref. [10], what is intended in this paper is the analysis and contribution to the development of an appropriate method of impedance measurements of space constrained locations.

II. Theoretical Basis

A. Fall-of-Potential Method or Wenner Method

One of the most widely used methods for determining impulse impedance and ground resistance values is the Fall-of-Potential Method. This method consists in measuring the voltage, resulting from current circulation by the auxiliary current electrode, between the grounding system and the auxiliary voltage electrode [11, 12].

By providing the auxiliary current electrode at a distance *dA* from four to ten times the largest diagonal *D* of the system under measurement, and the auxiliary voltage electrode at a distance *dP* of 62% *dA*, the ratio between voltage and current results in the value of impedance of this system. This auxiliary voltage electrode may be arranged in the same direction or in orthogonal to the auxiliary current electrode [1].

The procedure of this method, which appears to be relatively simple, presents great problems of application in the field due to the great distances involved, mainly in the measurements of large grounding systems. In the substation ground grids, generally with large dimensions, the distance of the auxiliary voltage and current electrodes reaches values in the order of hundreds of meters. There is the possibility of using the transmission lines and ground grids of "nearby" substations, such as conductors and auxiliary voltage and current electrodes, as a possible alternative to overcome these obstacles. However, the application of this technique can result in incorrect data due to external interference, such as coupling with other transmission lines, for example [5].

B. Slope Method or Tagg's Method

As an alternative to the measurement of grounding systems where there is not enough space for auxiliary electrode positioning, in 1970 Tagg [3] proposed an alternative method for measuring at reduced distances, known as the Slope Method. This method is also recognized and recommended by ANSI/IEEE 81 [1].

As in the Fall-of-Potential Method, the method proposed by Tagg also considers that the grounding system behaves like a hemispherical electrode, and that the soil has a uniform apparent resistivity. The difference of the Slope Method is the implementation of a correction in function of plateau slope of the data obtained in field measurements [1]. From a coefficient μ calculated in function of field measurements, the positioning of the voltage electrode in relation to the current electrode is obtained in a table.

Following this methodology, it is possible to obtain the correct resistance value for measurements where it is not possible to respect the minimum distance of the auxiliary electrode of current ($dA \geq 4$).

C. Extent Tagg Method

Extent Tagg Method arose from the perception that some field values resulted in a coefficient μ outside the range determined in the Slope Method ($0.400 \leq \mu \leq 1.599$) [4].

As a way of determining the points where μ is not defined, a third-order polynomial interpolation was performed, based on the values determined by Tagg, resulting in an equation that determines the ratio dP/dA [4]:

$$dP/dA = -0.1242\mu^3+0.2339\mu^2-0.3049\mu+0.738 \qquad (1)$$

Therefore, with the application of the Extent Tagg Method, it is possible to estimate the resistance value even for measurements where the Slope Method is not possible.

D. PRED Method

PRED (*Polynomial Regression from Database*) Method also aims to determine the resistance value in space restricted areas. The difference of this method for the other two methods, presented in II-B and II-C, is in the approach between the variables: whereas the Slope Method and the Extent Tagg Method require three initial measures to determine the slope coefficient μ, the PRED Method establishes, as a function of the dA/D, the measuring point where the plateau value is obtained [5].

$$dP/dA = 0.14 \ln (dA/D) + 0.41 \qquad (2)$$

One of the great advantages of the PRED Method is the determination of the correct measuring point of the voltage electrode dP/dA, which depends on D and dA, even before any field measurements are made. However, if at the point of measurement dP/dA indicated there is a soil discontinuity caused by sandy or stony soil, for example, the measured value obtained at this point is impaired [5].

E. Field Measurements

The field data analyzed in this paper are the result of the study presented in Ref. [10], where field measurements of ground resistance and impulse impedance were performed under different conditions, making the results publicly available and allowing analyzes and contributions for studies in this area.

For this study, briefly, the following results obtained in [10] are used:

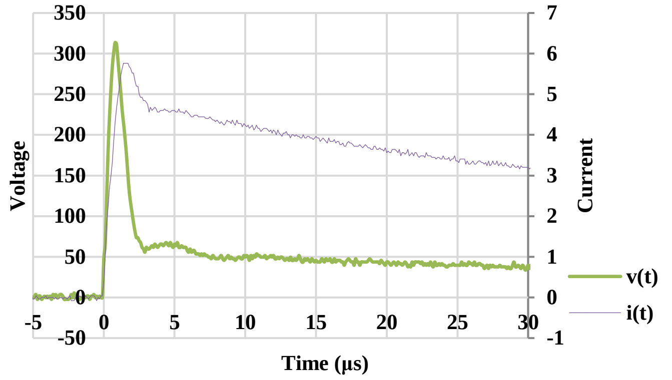

Fig. 1. Voltage $v(t)$ and current $i(t)$ waveforms for 10 m x 10 m grid, $dA = 5D$ e $dP = 0.6\ dA$.

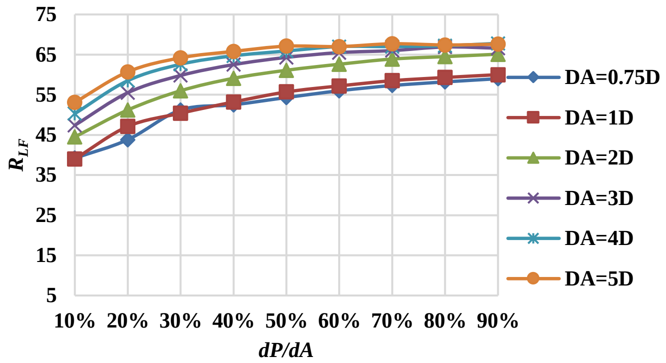

Fig. 2. Ground resistance R_{LF}, 5 m x 5 m grid, auxiliary electrodes in orthogonal.

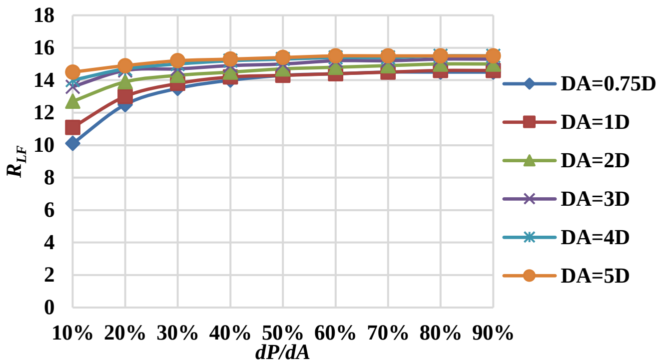

Fig. 3. Ground resistance R_{LF}, 10 m x 10 m grid, auxiliary electrodes in orthogonal.

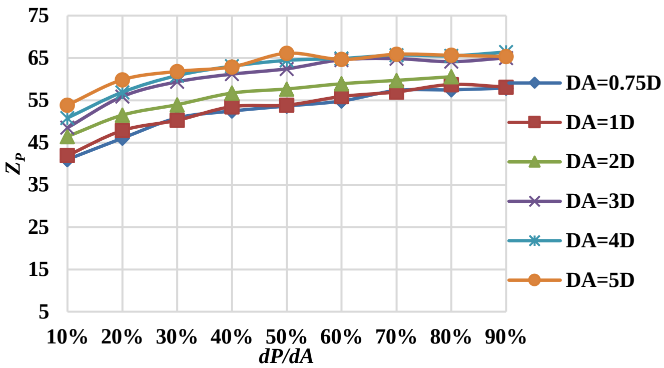

Fig. 4. Impulse impedance Z_P, 5 m x 5 m grid, auxiliary electrodes in orthogonal.

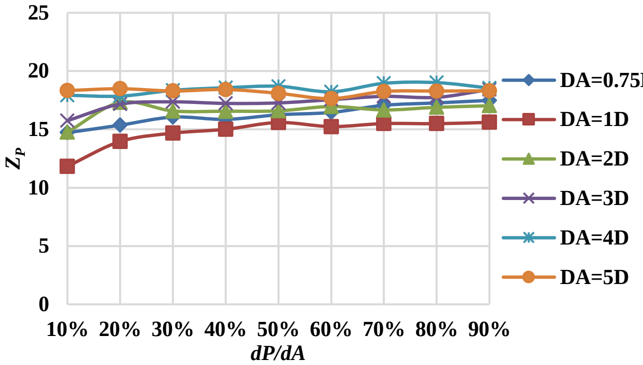

Fig. 5. Impulse impedance Z_P, 10 m x 10 m grid, auxiliary electrodes in orthogonal.

III. Current Derivative Method for Determining Resistance in a Steady-State Within the Transitional Impedance Curve

Ground resistance R_{LF} measurement is used to evaluate the effectiveness of a new system, validating the design and installation, and allowing monitoring of its performance over its useful life.

ANSI / IEEE 81 standard [1] defines that the ratio between voltage and current over time, during a surge in a grounding system, results in the transient impedance curve $Z(t)$. At the instant of time $i(t)$ has its derivative equal to zero ($di/dt = 0$), the voltage ratio $v(t)$ and current $i(t)$ is called the surge impedance Z_S. The impulse impedance Z_P is defined as the ratio between the maximum voltage V_{max} and the maximum current I_{max}, regardless of the instant of time in which they occur. About the moment when the transient impedance $Z(t)$ presents the value of the ground resistance in steady-state R_{LF}, this specification is not present in any of the references researched.

Due to the lack of this information in the literature, the first research done in this study is about the moment when the steady-state resistance R_{LF} can be extracted from the transient impedance curve $Z(t)$.

Fig. 1 shows the voltage $v(t)$ and current $i(t)$ curves injected into a 10 m x 10 m ground grid [10]. The transient impedance $Z(t)$ of this surge is shown in Fig. 6.

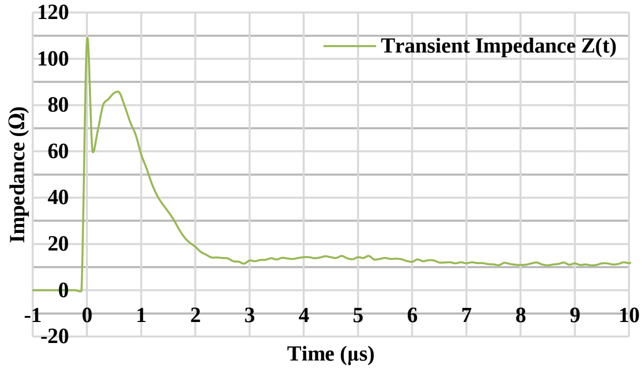

Fig. 6. Transient impedance waveform $Z(t)$ in the 10 m x 10 m grid, dA = 5D and dP = 0.6 dA.

In order to establish a relationship between the transient impedance $Z(t)$ and the ground resistance R_{LF}, an approach based on in the instantaneous percentage variation rate of the current curve $i(t)$, in steps of 1 µs was tested. This variation rate is obtained as shown in (3). Applying this equation to the current curve $i(t)$ of Fig. 1, the current derivative curve is obtained, shown in Fig. 7 (plotted under Fig. 6).

$$i'(t) = [i(t+1) - i(t)] / I_{max} \ [\%] \tag{3}$$

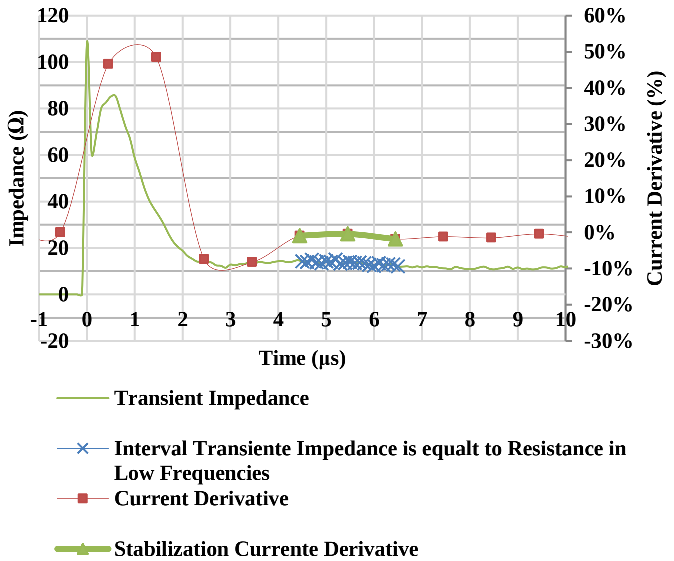

Fig. 7. Transient impedance curve $Z(t)$ indicating moment of stabilization of the derivative of the current, in the grid 10 m x 10 m, dA = 5D and dP = 0.6 dA.

Analyzing Fig. 7, it is possible to verify that the highest rates of variation of the current, both positive and negative, are close to the moment when the peak current of the injected surge occurs. After these high values, the rate of variation tends to decline linearly, with a negative rate of approximately -1%.

In the comparison of the transient impedance curve $Z(t)$ with the derivative curve of current $i'(t)$, it was found that R_{LF} occurs at the first instant of time in which derivative of current $i'(t)$

stabilizes in a linear decay near of -1%. This time instant is also highlighted in the curves of Fig. 7, both in the current derivative curve *i'(t)* and in the transient impedance curve *Z(t)*. For this measure, the R_{LF} value obtained with the earth meter was 14.2 Ω, while the value obtained by the presented method was 13.69 Ω.

A fact that draws attention in the presented approach is that the obtaining of R_{LF} occurs in the first instants of time of the application of the surge, still with considerable values of tension and current circulating through the system.

A. Results from the Application of the Current Derivative Method

Ref. [10] presents the result of field measurements for R_{LF} ground resistance in steady-state. These values were shown here in Fig. 2 and Fig. 3. Applying the Current Derivative Method to the transient impedance field measurements *Z(t)* obtained in [10], the R_{LF} values extracted from the transient impedance curve *Z(t)* are also obtained and shown in Fig. 8 and Fig. 9.

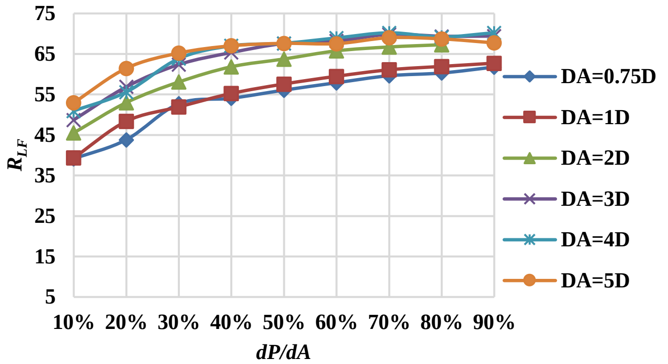

Fig. 8. Ground Resistance R_{LF}, grid 5 m x 5 m, obtained by the Current Derivative Method.

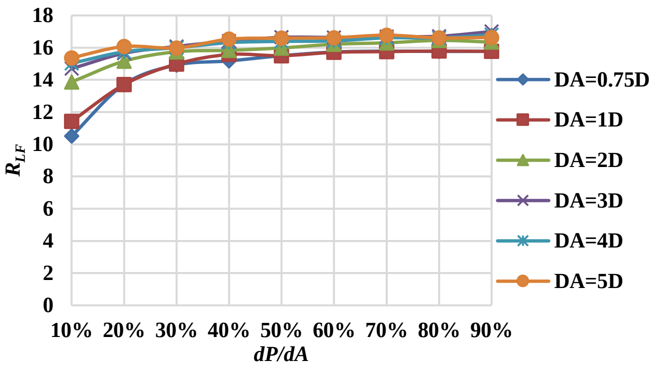

Fig. 9. Ground Resistance R_{LF}, grid 10 m x 10 m, auxiliary electrodes in orthogonal.

Comparing the results between Fig. 2 and Fig. 8, for the ground resistance measurements in the 5 m x 5 m grid, the mean of the relative errors obtained is 3.11%, while the maximum error obtained is 5.82%, which means an absolute error of 3.84 Ω.

In the comparison between Fig. 3 and Fig. 9, the mean of the relative errors is 8.24%, while the maximum error obtained is 11.11%. This error of 11.11% in the value of the ground resistance of the 10 m x 10 m grid, represents an absolute value error of 1.7 Ω.

Therefore, with the presentation of the results for both ground grids, the efficiency of this method for determination of the R_{LF} ground resistance from the transient impedance curve *Z(t)* is proved.

IV. Analysis of Field Measures with Orthonally Positioned Auxiliary Electrodes

A. Application of Measures Methods at Reduced Distances

In section II of this paper, methods of resistance and impedance measurement are presented for locations with no space restriction (Fall-of-Potential Method), and space restricted areas (Slope Method, Extent Tagg and PRED). Fig. 2 and Fig. 3 presented the values of ground resistance field measurements, as well as Fig. 4 and Fig. 5 presented the values of impulse impedance field measurements. These field measurements were performed with the auxiliary voltage and current electrodes arranged in orthogonal, mitigating the effect of the inductive coupling between the conductors of these auxiliary electrodes [1, 13, 14].

The Tab. I presents the results of the application of the reduced distance, Extent Tagg and PRED methods, in cases where the auxiliary current electrode is arranged at a distance *dA* equal to 0.75*D* and 1*D*. The reference value is established by a 3rd degree polynomial interpolation when the auxiliary voltage electrode *dP* is set at 62% *dA*, and *dA* = 5*D* (obeying the conditions of the Fall-of-Potential Method). Tab. II presents the results for ground resistance.

TABLE I. Z_P Results for Measurement Methods with Space Restriction

Grid	*dA*	*Fall-of-Potential (dA=5D)*	*Extent Tagg*	*PRED*
5 m x 5 m	*0.75D*	65.48 Ω	55.98 Ω	51.82 Ω
5 m x 5 m	*1D*		56.43 Ω	53.22 Ω
10 m x 10 m	*0.75D*	18.03 Ω	16.34 Ω	15.98 Ω
10 m x 10 m	*1D*		15.38 Ω	15.28 Ω

TABLE II. R_{LF} Results for Measurement Methods with Space Restriction

Grid	*dA*	*Fall-of-Potential (dA=5D)*	*Extent Tagg*	*PRED*
5 m x 5 m	*0.75D*	67.34 Ω	56.61 Ω	51.92 Ω
5 m x 5 m	*1D*		57.27 Ω	54.01 Ω
10 m x 10 m	*0.75D*	15.48 Ω	14.40 Ω	13.99 Ω
10 m x 10 m	*1D*		14.41 Ω	14.30 Ω

The analysis of the values, presented in Tab. I and Tab. II, shows that the application of these methods for reduced distances returned considerable discrepancies, both for impulse impedance and resistance of plateau.

The probable cause of these discrepancies is related to the development of these methods. They were designed to correct measurements with auxiliary electrodes in the same direction and, with this, it is verified that the direct application of these methods to measurements with orthogonal electrodes does not present satisfactory results.

B. Ground Grids Behavior Analysis and Proposal of Methodology of a Correction Factor

With the need to perform ground impedance measurements with orthogonal auxiliary electrodes [10], and with unsatisfactory results from the application of measurement methods at reduced distances (item IV-A), it was noted the need for establishment of a method of measuring impulse impedance and ground resistance, with orthogonal auxiliary electrodes, for space restricted locations.

Seeking a contribution to the development of this methodology, it is analyzed, at first, only the measures of ground resistance with the electrodes in orthogonal. The data presented in Fig. 2 e Fig. 3 are normalized in *pu*, in relation to the plateau values established by the Fall-of-Potential Method in Tab. II. The normalization equation in *pu* is presented in (4), and the results are plotted in Fig. 10.

$$R\ (pu) = R_m/R_{ref} \tag{4}$$

With:
$R\ (pu)$ = Resistance in *pu*
R_m = Measured Resistance
R_{ref} = Reference or Plateau Resistance

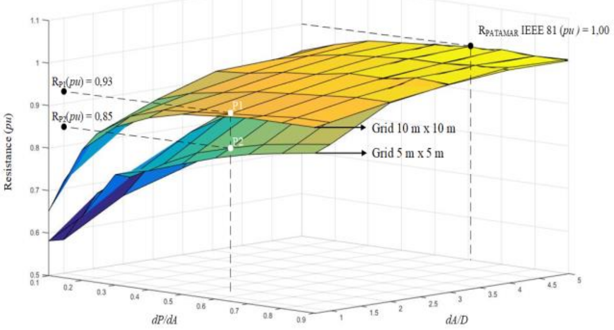

Fig. 10. Behavior of the ground resistance curves in *pu*: 5 m x 5 m and 10 m x 10 m grids.

In this figure, the resistance values are plotted in *pu* of 10 m x 10 m grid, in the upper curve, and the 5 m x 5 m grid, in the lower curve. Also, the plateau point of both grids is shown, in the condition where *dP* = 62% *dA* and *dA* = *5D*, as well as two points (*P1* and *P2*), in the condition where *dP* = 60% *dA* and *dA* = *1D*.

It is observed that both plotted curves have similar behavior in the measurements without space restriction (*dA* greater than or equal to 4*D*), approaching in the plateau value as the *dP* / *dA* and *dA/D* values increase. However, for measurements where *dA* is less than or equal to 3*D*, the behavior of the curves is no longer the same. This is exemplified by the points *P1* for the 10 m x 10 m grid, and *P2* for the 5 m x 5 m grid. While in *P1*, the measured resistance value is 93% of the plateau value, in *P2* the measured value is 85% of the plateau value. Finally, it is still observed that for low values of *dA/D*, especially when *dA* is equal to 0.75*D* or 1*D*, the measurements do not reach the plateau value at any time.

Hence, the analysis of the curves in Fig. 10 shows that, for both ground resistance and impulse impedance, the behavior of the curves does not only vary as a function of the relation between *dP/dA* and *dA/D*, but also as a function of the dimensions of the ground grid, represented by the larger diagonal *D*. This relationship appears to be inversely proportional to the grid size: the smaller the ground grid, the greater the *dA/D* value to obtain the plateau value, and the larger the ground grid, the value of *dA/D* can be reduced.

Based on these findings, data analysis is approached by a different way: as the *dP/dA* and *dA/D* quantities are relative to *D*, when analyzing the values *dP* and *dA* in meters, the third variable *D* is already weighted, simplifying the analysis from three to two variables. These data are shown in Fig. 11.

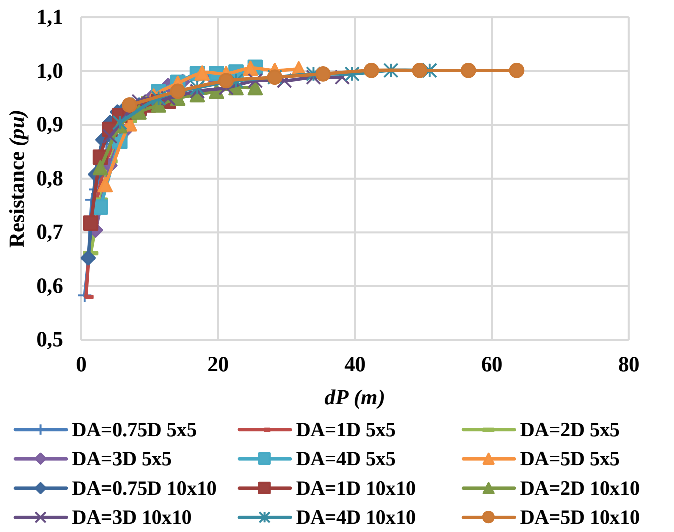

Fig. 11. Ground resistance curves in *pu*: 5 m x 5 m and 10 m x 10 m grids.

Plotting the data in *pu* with *dP* in meters, of ground resistance in Fig. 11, shows very clearly that the measurements now have a very close behavior trend, independent of the dimensions of the ground grid under analysis.

Based on the behavior analysis of Fig. 11, it is possible to obtain the typical behavior of the measurements with orthogonal electrodes, according to Fig. 12.

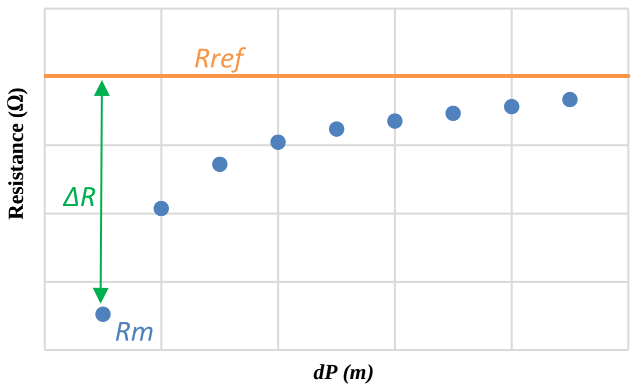

Fig. 12. Typical behavior of the measurements with orthogonal electrodes.

Based on the behavior shown in Fig. 12, it is possible to define a *ΔR* for each of the field measurements. Then, if the value of *ΔR* can be determined, it would be possible to correct the measured value, and obtain the correct ground impedance value. Based on the analysis of the variables previously carried out, it is estimated that the value of *ΔR* can be determined by a relation according to the dimensions *D* of the grounding system, the distances of the auxiliary voltage electrode *dP* and current *dA*, and the measured R_m value.

Since it was presented the possibility of studying the relationships that determine *ΔR*, an analytical study using the Maxwell equations, applied to ground resistance and ground impedance measurements, will allow the determination of the *ΔR* values of each of the field measurements, for any values of *dP* and *dA*, obtaining the plateau value R_{ref}.

V. Discussions and Conclusions

The results discussed in this paper make an effective contribution to the study and research in this area. Not only for the presentation of new results in the study of the transient impedance curve, but also for the analysis and suggestion of a new approach to a method of measuring resistance and impedance with orthogonally positioned auxiliary electrodes.

The Current Derivative Method, which determines the instant of time in which the transient impedance *Z(t)* is equal to the ground resistance in steady-state R_{LF}, is presented as an unprecedented result. The advantage of the application of this method is that it is not necessary to use the earth meter to determine the ground resistance, since this value can be extracted directly from the transient impedance curve *Z(t)*. In addition, the ground resistance R_{LF} is obtained at a time when it is circulating around 70% of the maximum current injected by the surge generator, providing a higher fidelity of the real situation of the grounding system under measurement.

As important as the Current Derivative Method, in item IV the analyzes of the field data of resistance and impulse impedance are presented. Initially, the methods available in the literature for measurements in space restricted systems were applied, where it was found that these methods are not efficient for measurements with orthogonal auxiliary electrodes, precisely because they were developed for measurements with aligned electrodes. From this result, we proceeded to study the behavior of the field data in absolute values for distance, and in relative values for resistance. As a result, a methodology of a correction factor *ΔR* was proposed for each of the field measurements with orthogonally arranged electrodes. In this way, it would be possible to obtain the correct value of a measurement for whatever the distances between the auxiliary electrodes and the grounding system to be measured.

Considering the results obtained so far, it is possible to affirm that this study contributes to the state of the art in this area of research. A methodology is being developed to determine the correction factor *ΔR* for orthogonally positioned electrodes, which will allow impulse impedance measurements in grids located in urbanized regions.

References

[1] IEEE Power and Energy Society, "ANSI/IEEE Std 81-2012 - IEEE Guide for Measurement Earth Resistivity, Ground Impedance, and Earth Surface Potentials of a Grounding System," Nova York, 2012.

[2] ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS, "NBR 15749 - Medição de resistência de aterramento e de potenciais na superfície do solo em sistemas de aterramento," Rio de Janeiro, 2009.

[3] G. F. Tagg, "Measurement of the Resistance of Physically Large Earth-Electrode Systems," *Proceedings of the IEEE,* vol. 117, pp. 2185-2190, Novembro 1970.

[4] A. Raizer, W. Valente Jr., V. L. Coelho and C. Cardoso, "Contribution to Tagg's methodology in the resistance measurement of earth-electrode systems at reduced distances," *XIII SIPDA,* p. 109–115, 2015.

[5] A. Raizer, W. Valente Jr. and V. L. Coelho, "Development of a new methodology for measurements of earth resistance, touch and step voltages within urban substations," *EPSR,* pp. 111-118, December 2017.

[6] A. Lima, J. Paulino, W. Boaventura, I. Lopes, M. Guimarães, W. Chisholm, B. Jamali and F. Bologna, "Transient grounding impedance and transient resistivity measurements using a very short current lead," *EPSR,* pp. 69-75, 2015.

[7] F. Dawalibi, J. Ma, "Extended analysis of ground impedance measurementusing the fall-of-potential method," *IEEE Trans. Power Deliv.,* pp. 881-885, 17 10 2002.

[8] K. Murakawa, H. Yamane, M. Hattori, "Earthing resistance measurement technique without using auxiliary electrodes," *Proceedings of the IEEE International Symposium on Electromagnetic Compatibility,* pp. 213-216, 16 05 2003.

[9] C. Korasli, "Ground resistance measurement with alternative fall-of-potentialmethod," *Proceedings of the Transmission and a Distribution Conferenceand Exhibition-IEEE-PES,* pp. 942-946, 21-24 05 2006.

[10] A. Raizer, V. Coelho and T. Schmoeller, "Ground Resistance and Impulse Impedance Measurements: Results and Major Error Factors," *XV SIPDA,* 2019.

[11] IEEE Power and Energy Society, "ANSI/IEEE Std 80-2013 - IEEE Guide for Safety in AC Substation Grounding," New York, 2013.

[12] ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS, "NBR 15751: Sistemas de aterramento de subestações — Requisitos," Rio de Janeiro, 2009.

[13] J. Ma, F. P. Dawalibi, "Influence of Inductive Coupling Between Leads on Ground Impedance Measurements Using the Fall-of-Potential Method," *IEEE TRANSACTIONS ON POWER DELIVERY,* pp. 739-743, Outubro 2001.

[14] C.Wang, T. Takasima, T. Sakuta, and Y. Tsubota, "Grounding resistance measurement using fall-of-potential method with potential probe located in opposite direction to the current probe," *IEEE Trans. Power Delivery, vol. 13,* p. 1128–1135, 10 1998.