Space Charge and Soil Ionization: An Electro-kinetic Approach

Ricardo R. Diaz and **Jose N. Silva**
High Voltage & Power Transmission Institute
National University of Tucuman
Av. Independencia 1800, 4000 Tucuman, Argentina

ABSTRACT

This paper proposes an electro-kinetic model of soil ionization for concentrated electrodes submitted to impulse currents. This approach allows a better understanding of the dynamic response of earth rods. Since current density attains a sufficient value around the electrode, ionization appears in the soil and produces a transient reduction of the grounding resistance. Experimental results, obtained under well-controlled conditions in laboratory, indicate that the injected energy is the most important parameter in the transient resistance reduction, rather than the crest value of impulse currents. The meaning of this resistance reduction is interpreted by the electro-kinetic model that calculates the resistance-time variation by computing the energy required to arrange a distribution of space charge around the electrode. A practical conclusion of this energy-depending interpretation for grounding electrodes, is that with ionization it would be attended a significant and durable reduction of the transient resistance for long impulse currents.

Index Terms — **Ionization, space charge distribution, electro-kinetic, transient resistance, grounding electrodes, lightning current.**

1 INTRODUCTION

GROUNDING systems are designed for protection of equipment and humans against over-voltages, providing a preferential way for evacuation of phase-to-ground faults or lightning stroke currents. Since many years, protective and operation devices in electric power systems have incorporated electronic technology sensitive to fast electromagnetic perturbations and deep grounding resistance variations.

In general, when direct lightning currents are flowing through grounding systems this surge response depends on electrode geometry and the soil electrical parameters. With high currents in grounding systems, strong electric fields produce ionization of the soil around the buried electrodes. Ionization provokes the time-dependent reduction of transient resistances in grounding systems. The resistance reduction can be very pronounced during several tens of microseconds. Nevertheless, this effect can be advantageous for insulation coordination in highly resistive soils, reducing the frequency-dependent inductive effects, which impair grounding performance by increasing impedance during fast rise-time currents. The non-linear resistance of earthed electrodes associated to ionization is important since it allows material and cost saving in the installation of grounding systems.

Dynamic models predicting the non-linear surge-current characteristics of concentrated earth electrodes were published [1-3] many years ago. In order to improve model accuracy, the determination of the ionization gradient value of each soil is critical. Based on experimental results, several articles [4-8] have been published concerning the analysis of soil ionization gradients, the effect of impulse polarity, soil conductivity and cell geometry.

Different approaches of soil ionization have been proposed: a circuital method applied to grounding systems having simple or composed configurations [9]; a current-dependent resistance model based on arc equations similar to those applied to the arc interruption in circuit breaker [10]; a simulation model based on the finite-element method [11]; a hybrid frequency-time domain methodology applied to coupled systems [12].

The composed dynamic performance of earthed electrodes by both the non-linear and the frequency-dependent effects due to soil ionization and inductive behavior has been analyzed in [13]. The transmission line theory has been applied to study the ground impedance of buried horizontal wires submitted to lightning or switching transients [14]. An exhaustive analysis of the inductive characteristic of rod electrodes was proposed in [15], including the analytical expression of the critical length.

In previous articles [16-17] the authors have presented the laboratory results using a scaled model of grounding rods. The measurements show a sound correlation between the injected energy of the current surges and minimum transient resistance of the grounding system. From these experiments, the energy

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appears as the most significant electrical parameter conditioning the transient grounding resistance, even more than the current peak value.

The aim of this paper is to propose a physical model based on an electro-kinetic formulation of the discharge progression in soils around a buried rod. This model, which computes the space charge distribution around the electrode, can explain the correlation observed [16] between injected energy and transient grounding resistance by a causality relationship between energy and resistance. This is a new point of investigation in soil ionization phenomena; in the past researchers tried to find a relation between soil ionization and injection current wave shape, peak value, rise time and so on, but never came upon a very good correlation between these parameters and the transient resistance of grounding systems.

The ionization process in soils is more complex than in gases and the parameters associated to inception and progression of discharges were previously studied [4-6]. Field measurements of the grounding transient resistances are not easily obtained under lightning strokes. The study of the ionization process in soils presents many difficulties because of the limited accessibility to discharge parameters from experiments. The lack of experimental data showing the effects of impulse currents parameters (wave shape, peak value, rise time, etc.) on the transient resistance in real grounding systems, caused measurements to be performed on an equivalent system with well controlled electrical and soil conditions.

The proposed physical approach is based on the numerical analysis of experimental results obtained in a cylindrical test cell with a vertical rod submitted to current impulses with several amplitudes and front-tail time values, under controlled conditions [16-17]. The test cell was a 1 m scaled model of buried rod, which was designed with the purpose of reproducing the current density and electric field distributions, that actual grounded rods under lightning stroke currents experience. The earth electrode was shorter than the critical length [15], diminishing the inductive behavior for the spectrum frequencies of the current impulses. In order to obtain current density and electric field distributions similar to those produced by long vertical buried rods; the design of the equivalent grounding system was closely based upon discharge parameters in soils [5].

2 EXPERIMENTS

A short description of the experimental set up is presented below.

2.1 THE EQUIVALENT GROUNDING SYSTEM

An equivalent grounding system (EGS) was built in laboratory with a vertical rod electrode, R_1=0.003 m radius, buried L=1 m long in sand of conductivity σ=2.8 mS m^{-1} in a PVC tank of 150 cm diameter with a coaxial grounded electrode of external radius R_2= 0.63 m. The total weight of the cylindrical test cell was about 3,000 kg. Discharges on the buried tip of the rod were avoided by crossing the bottom side of the tank with a bushing [16] and screening the tip rod with an air insulated metallic sphere of 20 cm diameter. This device preserves the cylindrical symmetry of the ionization around the rod. Figure 1 shows the impulse test circuit.

The measured resistance of the cell was 300 ohms; no difference has been detected for positive or negative voltage polarity at low voltage (<2 kV). The soil sample was sand principally composed of quartz (83%) and limestone (7%), and potassium feldspar, calcium carbonate, biotite and mica in comparable amounts.

The current impulses were produced with a Marx generator of 35 kJ working as a current source. Currents were measured in the external grounded electrode with a current monitor of 1 Hz to 20 MHz of bandwidth. Voltages between rod and ground were measured with a resistive divider and the waves were recorded with a digital storage oscilloscope of 8 bits, 1 GS/s, 100 MHz.

The crests of the applied current impulses were comprised between 5 and 1760 A with impulse front times around 7 to 15 µs and tails between 20 and 50 µs. Some additional tests were carried out with negative current impulses of 40/70 µs in order to verify the physical model. With these strokes the current density J on the rod surface was in the same order (9.5 A/cm^2) as that of a buried rod, 2.5 m long and 2.54 cm diameter, submitted to lightning strokes of up to 19 kA.

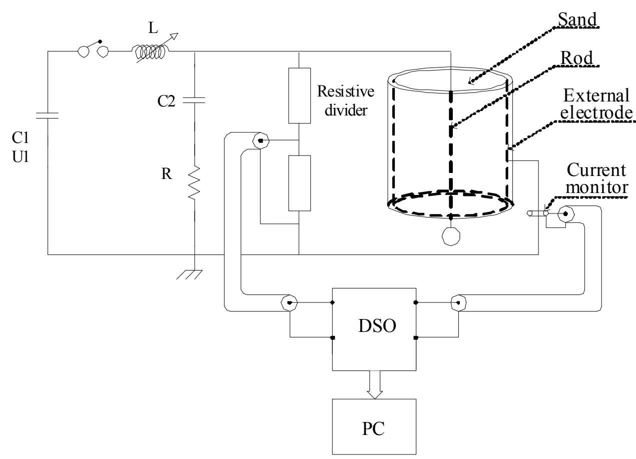

Figure 1. Test circuit and cylindrical cell.

The EGS was designed to represent a rod buried in the soil from an electrical point of view. The electric field E around the buried electrode can be calculated by the well known equation:

$$E = J / \sigma \quad (1)$$

The radial electric field distribution of the buried rod is unchanged in the axial coordinate because of the accurate design of the system [16, 17]. The radial distribution around the inner electrode is comparable to the radial distribution of a long rod of 2.5 cm diameter with zero potential 30 m away. From this comparison we can assume there is electric strength equivalence between the EGS and a buried long rod. Furthermore this design with cylindrical symmetry consents a simplified mathematical modeling.

2.2 TRANSIENT RESISTANCE

When a strong current impulse is applied or when the soil resistivity is high enough, the electric field and the potential on the rod increase, but not following a linear behavior, then voltage is not proportional to current. The current impulse peak is delayed with respect to the voltage peak and then the transient resistance, intended as the instantaneous ratio between voltage and current, changes with time presenting a relative minimum after some tens of microseconds. This dynamic behavior has been also quantified by the alternative concepts of impulse impedance, ground impedance or impulse grounding impedance [18-21], especially for large electrodes. To clarify this expression, it would be important to remark differences between magnitudes defined as “impedance” and “resistance”. Traditionally impedance is a complex operator acting over complex amplitudes of voltage and current, which is defined in time-harmonic regime. The impedance operator is frequency dependent and can strictly only be applied to linear systems. Instead resistance is a parameter typically associated to the relation between voltage and current at a specified time. The transient performance of a concentrated grounding electrode is fully quantified using this relationship at each instant of time, and this is the meaning assigned to the transient resistance concept in this article.

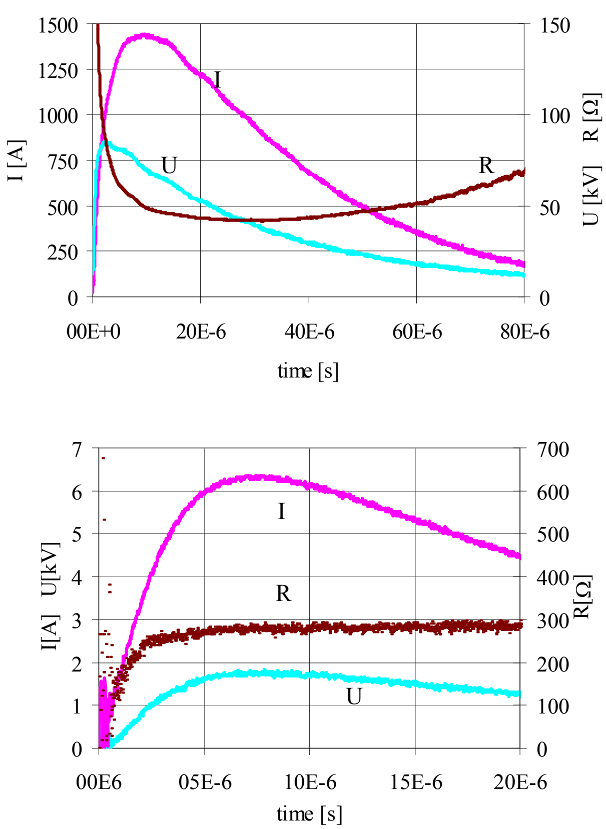

Figure 2. Current, voltage and resistance as a function of time. Without (I_{max}= 6.4 A) and with ionization (I_{max}=1410 A).

Figure 2 shows an example of the EGS measured voltage and current.

Comparing both pictures it is possible to distinguish a variable resistance in the time, the transient resistance, which can be calculated as:

$$R(t) = U(t) / I(t) \quad (2)$$

The measured current and voltage waves with ionisation are in good agreement with those measured in actual rods, as discussed in [16].

Figure 3 shows the resistance as a function of time for several impulses of current, the minimal resistance values are delayed for higher currents. It is remarked that a reduction of 50% is already attained for current density J lower than 1 A/cm^2 (188.5A). No resistance reduction has been measured for current densities lower than 0.2 A/cm^2 (38 A). In general no appreciable differences were observed between positive and negative polarity.

If the derivative of the transient resistance r_t= dU/dI is calculated from a diagram (U, I) or (U, J), negative values are observed just before the lower values of the transient resistance R(t). An interpretation of this behaviour is the ionization phenomena in the soil.

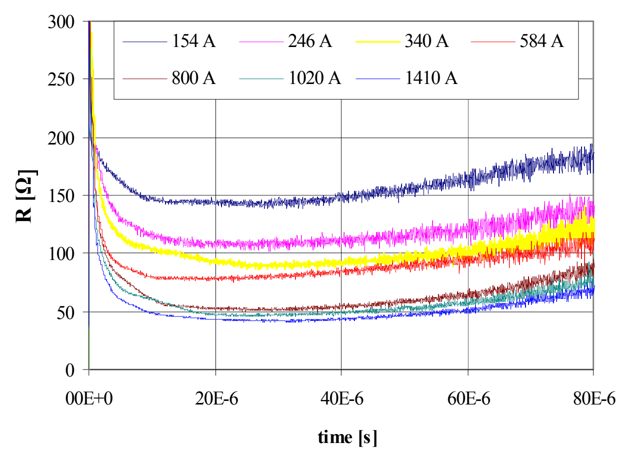

Figure 3. Resistance as a function of time for several current densities, with ionization (10/40 μs current surge).

Figure 4 shows the diagram (U, J) for currents between 154 and 1410 A. Negative values of transient resistance r_t are evident at time t_4, just before the minimum of resistance R_m, as can be observed for the example of 1020 A.

From this diagram it is possible to appreciate the hysteresis loop which area is proportional to the energy absorbed by the test cell.

2.2 PEAK CURRENT AND ENERGY

The instantaneous power injected into the EGS can be calculated from:

$$P(t)= U(t) . I(t) \quad (3)$$

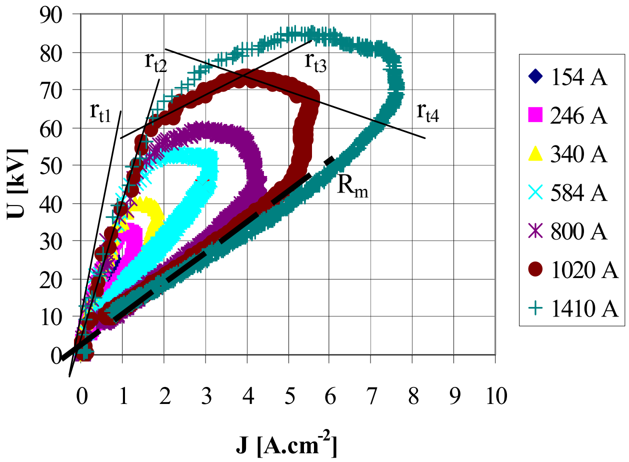

Figure 4. Characteristics voltage/current density for σ=2.8 mS m^{-1}. Current crest value I_{max} as parameter, derivative of transient resistances r_{ti} at different times t_i (i = 1 … 4).

The energy W injected up to the time of the minimum of resistance t_m is:

$$W(t_m) = \int_0^{t_m} P(t)\,dt \quad (4)$$

At first sight, it is valid to suppose that the reduction of the transient resistance depends on the electric field in the soil. As the electric field increases with current density, shown by equation (1), a relation between the peak current and the minimal value of transient resistance should be expected. In a previous work [16] a poor correlation was shown between the minima of resistance R_m measured for several current impulses as a function of the crest value I_{max}. Only for the same current waveform there would seem to exist a good correlation.

Figure 5 presents the minimums of transient resistance as a function of energy injected in the EGS up to the time t_m. In this case there is a better correlation when considering all current surges together. Moreover, a fitting equation can be proposed:

$$R_m = -33 \ln(W(t_m)) + 280 \quad (5)$$

Where: R_m = Minimal transient resistance (Ω)
W = Injected energy (J)

The electrical breakdown condition is close to 4000 J and the impulse current wave becomes distorted. For low energy the resistance draws out to 280 Ω; but a further analysis of the linear to non-linear transition is necessary.

2.3 ANALYSIS OF EXPERIMENTAL RESULTS

The voltages and currents measured in the EGS show that in the laboratory it would be possible to reproduce the lightning currents and voltages in concentrated grounding electrodes with high current density.

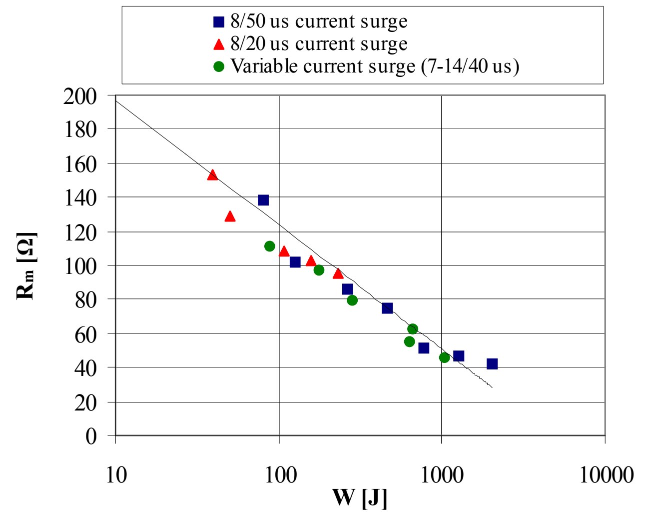

Figure 5. Measured minimal transient resistance as a function of injected energy (both polarities).

When the applied current impulse presents low amplitude, the current peak leads to the voltage peak and the behaviour corresponds to the response of a parallel-connected RC circuit. Instead of high current impulses the resulting curves show that the voltage peak is advanced with respect to the current peak and a pronounced reduction of the transient resistance appears clearly. This is a physical evidence of soil ionization. In [16] it was proved that this effect results from a non-linear behaviour. In consequence, ionization can be clearly put forward in the EGS like in actual grounding systems submitted to large currents.

From Figure 5, it is clear that there is a correlation between the injected energy in the EGS and the minimums of transient resistance. On the basis of the experimental results, the dynamic resistance reduction can reasonably be associated to streamers formation and pre-breakdown phenomena. Thus the assessed association between discharges and injected energy would be related with the concept that energy is employed to form ionized channels before breakdown [22] and this energy depends on material properties and channel geometry.

3 MODELING

In order to evaluate the causality relation between transient resistance and injected energy, a simplified physical formulation of the discharge channel growth is proposed, in which the energy is spent mainly to deploy a distribution of space charge.

3.1 PHYSICAL FORMULATION

In order to formulate the electro-kinetic model, several hypotheses are proposed. Resistance reduction is attributable to the formation of a discharge channel; this channel evolves as ionized plasma in function of its growth. The total injected energy W(t) in the EGS can be associated to two electrical phenomena. The first one helps to build the discharge channel by accumulation of space charges with energy $W_d(t)$ and the second one produces energy loss $W_s(t)$ in the resistive sand.

In that case the following energy balance equation must be satisfied:

$$W(t)= W_d(t) + W_s(t) \tag{6}$$

Ionization appears when the electric field around the electrode reaches the ionization critical gradient E_c [5]. A value of 8 kV/cm has been considered for computation. After formation of an ionized channel the mean gradient falls to $E_b=u(t_b)/(R_2 - R_1)$, measured at the time of breakdown t_b. From a short series of experimental data obtained in the test cell this field value E_b was estimated equal to 0.4 ± 0.1 kV/cm.

Figure 6 shows a sketch of the ionization region in the EGS. The cylindrical volume, coaxial with the inner electrode (R_1), is the region in which ionization takes place (discharge zone). In the space between the outer boundary of this region and the external electrode (R_2) no ionization occurs because $E<E_c$ (no-discharge zone).

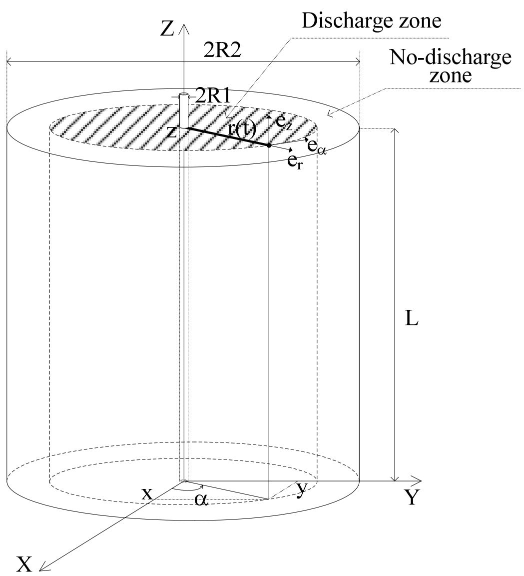

Figure 6. Ionized region into the test cell.

Considering cylindrical coordinates, the local electric field in the EGS can be formulated:

$$\vec{E} = \vec{e_r}\frac{\partial u}{\partial r} + \vec{e_\alpha}\frac{1}{r}\frac{\partial u}{\partial \alpha} + \vec{e_z}\frac{\partial u}{\partial z} \tag{7}$$

3.2 DISCHARGE ZONE

The charge employed to build the discharge channels is a fraction of the total injected charge and, in first approximation, it is proportional to the ionized volume. In order to simplify the calculation it will be assumed a uniform cylindrical expansion of the ionized volume with time variations of radius, then ionization rise in elemental volume dv:

$$dv= 2\ L\ \pi\ r(t)\ dr \tag{8}$$

The electro-kinetic energy required to develop the discharge channel depends on the injected charge and the local potential at such time. Considering a cylindrical symmetry for the volume V(t), this energy [23] can be expressed by the following equation:

$$\begin{aligned} W_d(t) &= \frac{1}{2}\int_{V(t)} \rho_c(r)\ u(r)\ dv = \\ &= \frac{1}{2\ R_2^2}\int_0^t U(t)\ r(t)^2 I(t)dt - \frac{1}{3\ R_2^2}\int_0^t E_d(t)\ r(t)^3 I(t)dt \end{aligned} \tag{9}$$

$\rho_c(r)$ is the charge density inside the volume in which ionization takes place, it can be calculated considering the amount of charge injected inside the discharge zone; r(t) is the radial length of the ionized volume; u(r) is the potential produced by contribution of the charge distribution and the applied voltage at each point r and it is a function of time along the discharge channel considering the voltage drop:

$$u(t) = U(t)-E_d(t)\ r(t) \tag{10}$$

$E_d(t)$ is the mean electric field in the channel; τ is the mean time constant, which is assumed to be equal to 3 μs by trial and error:

$$E_d(t) = E_b+(E_c-E_b)\ \exp(-t/\tau) \tag{11}$$

The resistance $R_d(t)$ in the discharge volume can be estimated from:

$$R_d(t) = \int_t E_d dr(t) / I(t) \tag{12}$$

3.3 NO-DISCHARGE ZONE

The injected charge flows in the sand zone where the electric field is lower than the critical value E_c. Again assuming a cylindrical symmetry, this energy loss can be expressed with the following formulation:

$$W_s(t)= \frac{1}{2\pi\sigma L}\int_0^t I(t)^2 \ln\frac{R_2}{r(t)}dt \tag{13}$$

The resistance $R_s(t)$ in the non-ionized zone is then calculated with:

$$R_s(t) = \frac{1}{2\pi\sigma L}\ln\frac{R_2}{r(t)} \tag{14}$$

The resistance values R(t) as a function of time are calculated from the computed discharge length r(t) solving the transcendent equation (6) at every time step. The total resistance R(t) in the EGS can be calculated by the addition of $R_d(t)$ and $R_s(t)$ and compared with the measured values by equations (2) and (5) in order to evaluate the accuracy of the model.

$$R(t) = R_d(t) + R_s(t) \tag{15}$$

3.4 COMPUTATION

Table 1 presents some computed results of minimal transient resistance and energy for negative polarity. The corresponding measured values are included for comparison; in this Table a large range of wave shapes are presented. The time-to-crest and the tail-time of the impulses are shown between brackets.

Table 1. Measured and computed resistances for several impulse waveforms.

	Current and voltage parameters		Measured		Computed	
	I_{max} (T_1/T_2) [A, µs]	U_{max} (T1/T2) [kV, µs]	W(t_m) [J, µs]	R_m [Ω]	W(t_m) [J, µs]	R_m [Ω]
Case 1	246 (10/40)	32 (4/35)	140 (20)	108	124 (22)	140
Case 2	584 (10/40)	53 (4/35)	320 (20)	75	410 (20)	95
Case 3	656 (15/50)	69 (7/45)	880 (24)	90	650 (21)	105
Case 4	888 (15/50)	78 (7/45)	1450 (29)	74	1335 (21)	92
Case 5	1170 (15/50)	89 (7/43)	2350 (33)	55	2040 (24)	72
Case 6	1410 (10/40)	84 (3/30)	2100 (28)	42	1654 (20)	57
Case 7	1640 (40/70)	97 (8/24)	3700 (60)	8	3030 (64)	46
Case 8	1760 (40/70)	98 (8/24)	3795 (60)	5	3380 (65)	42

Table 1 shows additional impulse wave shapes whose resistance and energy were measured and computed with the model presented. Cases 1, 2 and 6 correspond to the measured resistances presented in Figure 3 and Figure 4.

Figure 7 shows an example of computed resistances R(t), R_d(t) and R_s(t) of case 6. This calculated curve R(t) can be compared with the measured transient resistance shown in Figure 3, corresponding to 1410 A.

Figure 8 presents the computed dynamic resistance R(t) for the cases of Table 1. It can be noted that the time to minimal resistance t_m and the reduction length change with the impulse rise and tail times. The period in which the resistance is strongly reduced can be long, in the order of tens or hundreds of microseconds, depending of the applied current wave shape and peak value. On the basis of this observation, for lightning protection a grounding system confronted to multiple flashes could present a very low resistance for subsequent strokes. This reduction remains more time for long current waveforms, and the effect is depicted comparing cases 4, 5 and 6.

The predicted behavior of cases 1, 2, 4, 6 and 8 (see Figure 8) can be compared with the experimentally determined resistances (see Figure 3 and Figure 9).

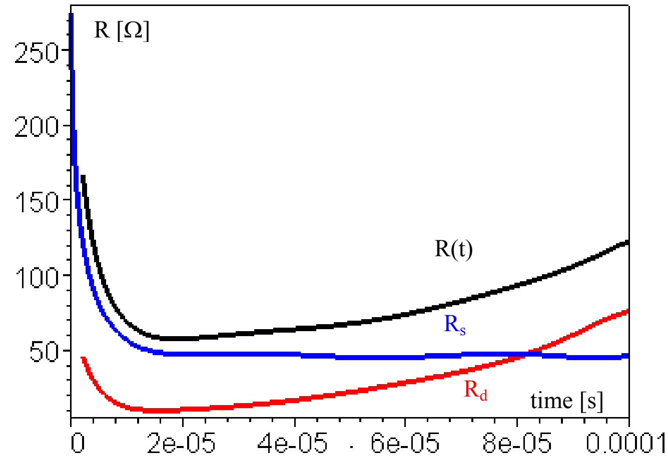

Figure 7. Computed transient resistance. Case 6 (1410 A).

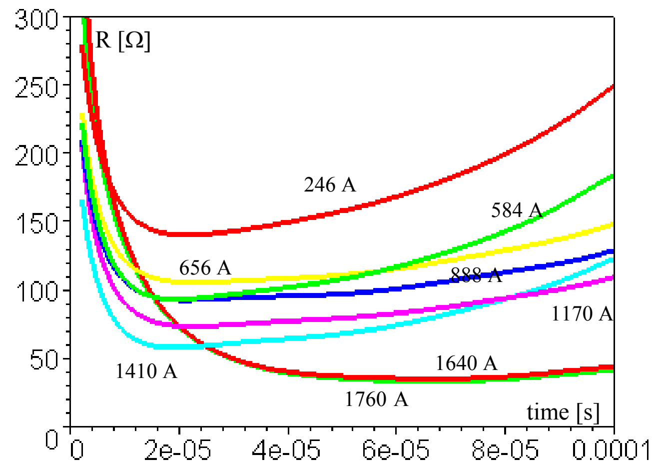

Figure 8. Computed transient resistances for the cases of Table 1.

4 DISCUSSION

Figure 9 shows the measured resistance for three different impulse waveforms: 10/40 µs for case 6 (similar to cases 1 and 2); 15/50 µs for case 4 (similar to cases 3 and 5); 40/70 µs for case 8 (similar to 7). The transient resistances evidence diverse features influenced by the impulse parameters. The overall calculated resistance-time characteristics show satisfactory accordance with the experimental measurements up to the recorded time (80 µs), although there are differences in absolute values.

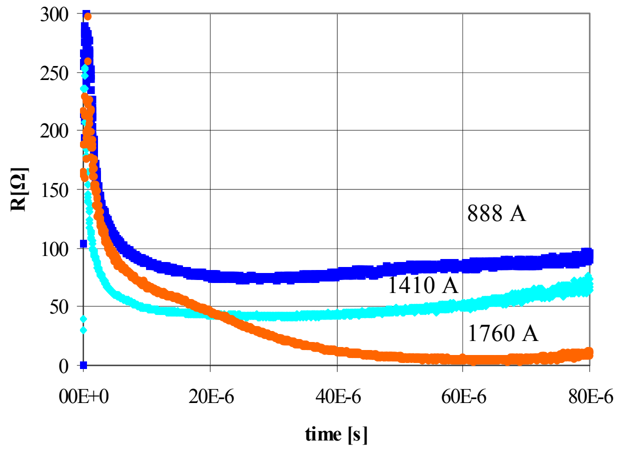

Figure 9. Measured transient resistances for three current waveforms: 10/40 μs (1410 A), 15/50 μs (888 A), 40/70 μs (1760 A). See Table 1.

The calculated values of R_m are presented in Figure 10 and a comparison with the measured results in the same figure evidences an acceptable qualitative agreement. The interpolation of the calculated values gives the following equation:

$$R_m = -29 \ln(W(t_m)) + 280 \tag{16}$$

This expression is comparable to equation (5).

The differences between the calculated and measured values of R_m in Table 1 are among 15 and 38 Ω. This difference can be a consequence of the simplifications introduced in the model for an easy computation and may be examined in future research:

- The discharges propagate into a cylindrical volume instead of occurring in many long and short channels, which is a more realistic assumption.
- No energy loss for ionization was introduced in the model. Only the necessary work to arrange the space charge in the discharge zone was computed. It can be reasonably assumed that soil ionization consumes additional energy for transforming neutral molecules in electrons and ions.
- The ionized volume is associated to a unique mean electric field instead of admitting differenced regions, with diverse gradient and velocity.
- No thermodynamic considerations were assumed in the model. Probably the discharge channel presents significant thermodynamic properties, strengthened by the presence of the soil with no negligible thermal conductivity.
- The current intensity determines the inception field E_c (see equation (1)) around the electrode at the beginning of ionization, but no other current-field influence is supposed during discharge propagation. However it could be reasonably assumed that the current intensity favors the ionization development increasing the field ahead of the discharge channel.
- Generation of steam by heating water in the sand has not been included in the energy balance and may become significant with soils of high conductivity.

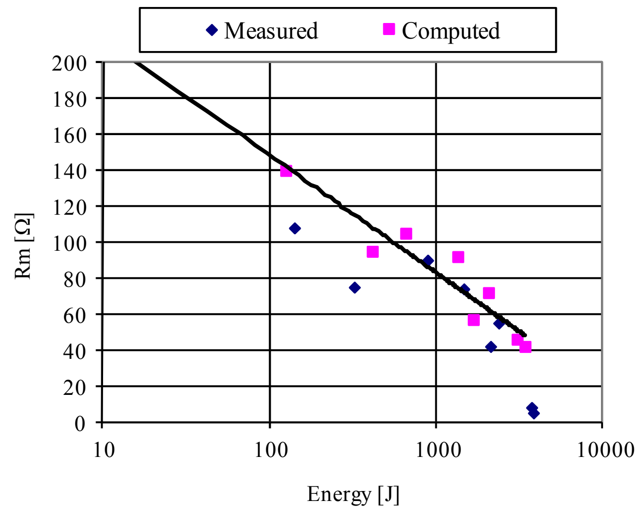

Figure 10. Measured and computed minimal transient resistance as a function of injected energy (negative polarity). See Table 1.

5 CONCLUSIONS

The equivalent grounding system proposed in this contribution was able to reproduce pre-breakdown phenomena in earthed rods submitted to high-density current. This scaled model made possible accurate measurements and calculations in order to investigate the non-linear behaviour on grounding concentrated electrodes under lightning currents.

The measured and computed results showed logarithmic relationships between the minimal values of transient resistance and the injected energy in the grounding system, independently of the impulse polarity.

The minimum of transient resistance arrives after some tens of microseconds, when normally the frequency behavior of the grounding system is gone reducing the transient mitigation effect of ionization on the fast rise-time currents. The duration of the resistance reduction depends on the applied current waveform and peak value. This length of time can attain hundreds of microseconds.

The electro-kinetic model presented in this paper offers a useful approach to explain the energy effect and discharge development. An acceptable agreement was found between predicted and measured values for several impulse waveforms.

Under the present experimental conditions, the injected energy appears as the most important electrical parameter, even more than the crest value of impulse currents, conditioning ionization effects and transient resistance evolution. Consequently, lightning current impulses with long front and tail times would produce greater reduction of grounding resistances than short time impulses. The general validity of these conclusions should be extended to other soil conductivities and electrodes, including composed grounding systems.

The model presented in this article intends to be a comprehensive approach of the phenomena of ionization in soils. This may provide the physical basis of a self-consistent model to predict the transient resistance of grounding systems only from the current impulse parameters.

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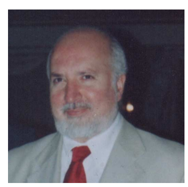

Ricardo R. Diaz (M’88–SM’02) was born in Argentina in 1955. He received the engineer degree in electrical engineering from the National University of Tucuman, Argentina, and the doctorate degree in high voltage engineering from the University of Padua, Italy. From 1983 to 1985, he was with the research staff of the Direction des Etudes et Recherches of Electricité de France and Les Renardières Group (Physics of Discharges). from 1986 to 1988, he was with the Laboratoire d´Electricité, University of Pau, France. Currently, he is full professor of high-voltage at the National University of Tucuman and member of the Argentine Research Council (CONICET). His main research activities are electrical discharges, electrical insulation, h-v measurements and testing.

Jose N. Silva was born in Argentina in 1971. He received the engineer degree in electronic engineering from the National University of Tucuman, Argentina, in 1999. Currently, he is a lecturer and engineer at the High-Voltage & Power Transmission Institute, National University of Tucuman. His main fields of work are h-v measurements and testing.