A DIDACTIC GENERAL APPROACH OF GROUNDING BEHAVIOR  
FOR LIGHTNING CURRENTS

Silvério Visacro
LRC - Lightning Research Center, UFMG - Federal University of Minas Gerais
Av. Antônio Carlos 6627 - Pampulha - 31.270-901 - Belo Horizonte - MG - Brazil
Phone/Fax: +55.31.34994872    e-mail: LRC@cpdee.ufmg.br - visacro@cpdee.ufmg.br

Abstract: This paper is intended to present a comprehensive and objective approach for the behavior of grounding electrodes submitted to lightning currents.

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1. Introduction
When submitted to lightning currents, the grounding electrodes present a very particular behavior. The author has been working with this subject since a long time ago. Teaching this topic in graduate courses, he has perceived that, very frequently, a lack of basic concepts in the engineering personnel involved in lightning protection, regarding the grounding behavior. These concepts are fundamental for understanding most of problems involved in lightning protection and to provide solutions for them. In this paper, the author would like to share his experience in this field by presenting a comprehensive and simplified approach of grounding behavior for lightning current, as a contribution to change such picture.

2. Basic considerations on Gronding behavior
In order to enable a better understanding of the concepts developed in the following sections, a brief simplified description of grounding behavior is presented, in a circuital perspective [1].

Basically, grounding is composed by three components: (i) the metallic conductors that connect the system to electrodes, (ii) the electrodes and (iii) the earth surrounding the electrodes. The last one is the relevant component. In order to consider the nature of grounding general behavior, one have to consider that any termination to earth presents resistive, capacitive and inductive effects. An equivalent circuit, shown in Figure 1, represents such effects for only a "piece" of a grounding system, considering a length of electrode and the portion of earth around it.

The current injected into the electrode has two different components. It is partially spread into soil (leakage transversal current, \( I_T \)) and partially transferred to the remaining electrode length (longitudinal current, \( I_L \)). The longitudinal current establishes internal losses in the conductor and a magnetic field in the region inside and outside the conductor. Considering the associated energy, this effect may be translated by means of a series RL branch, in the equivalent circuit (R: resistance, L: inductance). Both parameters are responsible by a voltage drop along the electrode during current flow.

On the other hand, the leakage current establishes an electric field in the soil (a medium with resistivity \( \rho \) and permittivity \( \epsilon \)). This determines the flow of conductive and capacitive currents through this medium. The ratio between conductive and capacitive currents in the soil does not depend on the electrode geometry, but only on the relation "\( \sigma/\omega\epsilon \)" (\( \sigma=1/\rho \) and \( \omega=2\pi f \) is the angular frequency). The associated energy may be represented in the equivalent circuit by means of a branch with parallel conductance and capacitance (\( G, C \)).

Figure 1 - Current components in the soil
This description applies only to the specific "piece of grounding" represented by the simplified circuit. In order to consider the whole grounding configuration, also the electromagnetic couplings that accounts for the mutual effects among elements has to be computed (capacitive, inductive and resistive ones). So, the knowledge of the entire grounding behavior requires the solution of a series of interconnected circuits (each one of them similar to the presented one), taking into account mutual effects among them. The solution of this entire equivalent circuit
expresses the impedance, seen from the current injection point. It translates the relation between the potential developed at the electrode (in relation to a remote point) and a given applied current. In an electromagnetic perspective, the grounding behavior may be expressed by means of such a grounding impedance.

In most applications, it is very usual to refer to a grounding resistance and not to a grounding impedance. This should be attributed to the fact that, the reactive effects are negligible for such applications. These conditions are very common for slow phenomena, whose representative frequencies have low values, as short-circuits in power systems. In these cases, a constant potential approach is valid for the electrodes and the resulting configuration for the equivalent circuit is reduced to a set of conductances (or equivalent resistances) positioned in parallel and including resistive mutual effect among them. Therefore, the value of grounding resistance, \( R_T \), is quantified by the ratio between the developed potential (referred to a distant point) and injected current:

\[
R_T = \frac{V_T}{I_T} \quad (1)
\]

Nevertheless, in a general approach, the grounding configuration should be represented by an impedance. In the frequency domain, for each specific frequency, a Complex Grounding Impedance may be accurately determined, as the solution of the grounding equivalent circuit \([Z(\omega)]=V(\omega)/I(\omega)]\), at the specific frequency into consideration. In time domain, for impulsive waves like that one associated to lightning currents, it is very usual to represent the grounding behavior by the Impulsive Grounding Impedance, \( Z_P \). This parameter refers to the ratio between the peaks of the developed voltage and current.

\[
Z_P = \frac{V_P}{I_P} \quad (2).
\]

In spite the usual non-simultaneous occurrence of such peaks, this representation has a very attractive aspect. It allows obtaining the maximum voltage developed at the current injection point simply from the product of \( Z_P \) by the current peak value. This is very appropriate for sensitivity analysis purposes.

Of course, this impedance is very dependent on the current waveform and front time parameters. Figure 2 illustrates this aspect and shows the response of a same grounding electrode for two different current waves.

The ratio of voltage and current peaks is larger for the fast wave \((1.75 \ \Omega=4.2 \ \text{kV}/2.8 \ \text{kA})\) comparing to the slow wave \((1.43 \ \Omega=4 \ \text{kV}/2.8 \ \text{kA})\). In spite the variance of impulsive impedance as function of front time, the ratio between the instantaneous values of voltage and current are practically constant along the wave tail, for both waves \((\sim 2 \ \Omega)\). In this time range, this ratio approaches the low frequency resistance of the grounding configuration.

### 3. Fundamental concepts: explaining grounding behavior for lightning currents

#### 3.1 Introduction

In a general approach, in order to describe the grounding behavior, two main aspects should be contemplated: (i) the soil behavior on conditions determined by the imposing electromagnetic phenomenon; (ii) the correct expression of electromagnetic coupling among the whole grounding components, including propagation effects.

The first aspect depends only on soil properties, but the second one is very influenced by the geometric configuration of electrodes. The computation of both aspects consists on a very complex task. In the following paragraphs, both aspects are commented, but only those fundamental concepts of objective interest for the present approach are considered.

#### 3.2 Current Composition and Frequency Dependence of Soil Parameters

Most works that deal with grounding behavior consider the earth to be a predominantly conductive medium. As a consequence, displacement currents (capacitive) are disregarded. This assumption is reasonable only for slow occurrences (short-circuit and so on). For fast phenomena, such as lightning current, capacitive current may reach the same magnitude of resistive one, mainly for high resistivity soils. Experimental data show that the ratio between conductive and capacitive currents in the soil widely varies in the frequency range that is representative for lightning currents \((0.5 < \sigma/\omega< 10^3)\) [2,8]. Figure 2 shows the voltage-current characteristic measured for a soil sample submitted to an impulsive current \((1.2/50 \mu\text{s double-exponential})\). The voltage wave is applied between two coaxial cylinders spaced by a compact soil sample and a low amplitude current flows between them.
This curve was built from registered current and voltage waves. For each instant of time \(t_i\), the simultaneous voltage and current values were taken from curves that represent such waves in time domain (such as those of Figure 2) and were placed together in the VxI curve. As it may be verified, the resulting curve corresponds to the response of a parallel RC circuit to an impulsive current. The derivative (in the VxI curve) allows getting a rough idea of the soil impedance, as it is obtained from the ratio between voltage and current variations \(\Delta V/\Delta I\). A double exponential current presents its maximum derivative at the first instants and this derivative decreases to the null value when the curve reaches its crest. So, at first instants, as the rising current has its maximum derivative, the capacitive branch is responsible for decreasing the total impedance of the equivalent circuit. This explains the minimum derivative at the VxI curve, in this period. As total current increases the impedance of the capacitive branch is increased and, so, the derivative on the VxI curve. The straight dashed line expresses the resistive behavior of that soil at the low frequency range. The slope of this line just corresponds to the low frequency resistance between the coaxial conductors. The curve denotes very clearly the relevance of capacitive effect for lightning currents.

For most application conditions, the magnetic property of soil is similar to that of air (magnetic permeability: ~\(\mu_0\)). However, those parameters responsible by conductive and capacitive currents (respectively the electrical conductivity and permittivity) are strongly frequency dependent [2]. Experimental data obtained for determined soil categories show the soil resistivity to decrease to around its half value when frequency rises from \(10^2\) to \(2.10^6\)Hz. The computation of this effect would imply reducing grounding impedance. The order of the relative permittivity is observed to decrease from \(10^2\) to \(10^3\) in the same range [2]. As no accurate general formulation is provided in literature for expressing the frequency dependence of soil parameters, the effect is usually neglected. In a conservative approach, the soil resistivity value is assumed as that one measured by conventional measuring instruments, which employ low frequency signal. In the same approach, the soil relative permittivity is assumed to vary from 4 to 81, according to soil humidity.

3.3 Field distribution and propagation effects in the soil

When current or voltage waves are applied to a long conductor buried into the soil, the corresponding electromagnetic wave propagates along the conductor. This system works as a transmission line embedded in a lossy medium. While the wave is propagating, energy losses promote the attenuation of its amplitude. On the other hand, the frequency components of the wave present different propagation velocities and are submitted to different levels of attenuation. Such attenuation increases with frequency and with soil conductivity, in the same way the energy losses do. In summary, the current and voltage waves that propagate along the electrode have their amplitude attenuated and are also submitted to distortion along the propagation direction, with diminishment of the front wave slope. These aspects are illustrated in Figure 3.

![Attenuation of current and voltage wave along electrode](image)

As the electrode length is limited, such behavior should be superposed to another one, which translates the divergent nature of the field associated to the current that flows from the electrode to remote earth. Figure 2 illustrates this aspect, by means of curves that show the distribution of electric scalar potential in the soil. For concentrated electrodes (short compared to typical wavelength of imposing signal), this divergent behavior prevails.

![Divergent behavior of field](image)

As a consequence of attenuation, the current that is dispersed to soil along the electrode presents a non-uniform density. The linear current density \((A/m)\) decreases along the electrode. The concept of effective length of electrode (or effective radius for grids), which was very clearly introduced by Gupta [3], is just derived from such considerations. It corresponds to a limiting electrode length. Longer lengths are not able to reduce grounding impedance value. This behavior is explained just by the fact that from this limiting length on, the current is already so much attenuated that, in spite of conductor length availability, practically no more current is injected into soil. The effective length decreases with soil conductivity and frequency rise. This is explained as both parameters are responsible by increasing the losses in the soil and, so, the attenuation of current and voltage waves that propagate along electrodes. This is easily perceived if a transmission line approach is adopted for the electrode imbedded in the soil. The attenuation constant \((\alpha)\) corresponds to the real component of propagation constant \((\gamma)\). It clearly increases with frequency and conductance: \(\gamma=\alpha+j\beta = [(R+j\omega L)(G+j\omega C)]^{1/2}\). This conductance is proportional to soil conductivity.

In frequency domain, the value of effective length is very clearly defined for each frequency. Nevertheless, for impulsive currents, which involve a large spectrum of frequency components, the definition of this parameter is a little more complex. In this case, it is usual to assume this parameter as that electrode length that corresponds to the minimum impulsive impedance. Larger electrode lengths
are not able to reduce this limiting impedance value. Of course, this definition includes a dependence on front time parameters of current wave.

3.4 Effect of current density

In practical conditions, for a wide domain of current intensity, the soil presents a linear behavior. This means that the ratio between the amplitudes of applied voltage and resultant current is constant. However, for concentrated electrodes and very intense applied current, the current density at the soil near electrode surface can reach very pronounced values. The corresponding electric field in the region may exceed a critical limit. Above it, an ionization process takes place in the soil and electrical discharges are established in this medium. The, so-called, critical electric field \( (E_{CR}) \) ranges from 0.2 to 1.7 MV/m, depending on soil resistivity and humidity. The phenomenon keeps some similarity to Corona Effect, depending on soil resistivity and humidity. The phenomenon dynamics is already equalizing along electrode length. For slow occurrences (low frequency), it could be correctly described by an analytical approach, deriving the transient grounding behavior. This partially explains the usual misunderstandings concerning the interpretation of grounding behavior. In this respect, it is remarkable the usual overestimation of ionization process, as source of grounding impedance reduction for impulsive current.

The analytical approach, employed in the past for describing transient grounding behavior, was very limited for computing all these effects. Fortunately, the huge computational advance, regarding memory capability and processing speed, allowed the development of very efficient numerical approaches based on field equations to substitute the analytical approach. In the beginning of nineties, several consistent computational models were presented in literature for calculation of grounding transient behavior \([5,6,7]\). The models formulated by such approaches have developed and nowadays they allow computing all the referred effects.

4. Practical remarks

These previous simple considerations are sufficient for remarking some important practical aspects and to emphasize the significance of certain concepts, for the specific interest of this text.

First, as a principle, the grounding behavior has the nature of an impedance and only for very particular imposing phenomenon conditions (low frequency), it could be properly represented by a resistance. The very usual reference to a "dynamic resistance" to describe the transient grounding behavior should be avoided, as actually it hides the real nature of grounding behavior. For lightning currents, the grounding behavior is quite different from that of a resistance, even when non-linear behavior is disregarded. In this respect, a question immediately arises: "Why the term Grounding Resistance is the usual reference for problems involving lightning protection instead of Grounding Impedance?". This seems a reasonable practice that is derived from the practical restrictions to measure grounding impedance in field application conditions. For ordinary engineering personnel, this is a quite complex task. On the other hand, the measurement of grounding resistance is a feasible task for such personnel and the knowledge about this parameter and about the electrode configuration may allow developing estimates for the grounding impedance value. As a second aspect, the usual assumption of potential equalization along electrode length is only a reasonable approach for slow occurrences (low frequency) or for very short electrode length. For transients and high frequency occurrences, the propagation effect and voltage drop, due to inductive and internal resistive effects, establishes...
significant potential differences along electrodes. Therefore, for lightning currents, the potential varies along the grounding electrodes and the metallic connections among buried conductors does not assure the potential to be equalized. In this respect, it is prudent to avoid connecting electrically linked equipments (connected by aerial loops, such as cable shielding) to electrodes at different points of the grounding grid. This may generate destructive loops of current.

It is possible to describe the grounding response when a current wave is injected into the soil through electrodes by means of two parameters: the grounding potential rise (GPR) and the voltage distribution over soil surface at electrode vicinities. They constitute the main parameters to be observed in the grounding design. For lightning current waves, the practical interest concerns the knowledge about the critical conditions, which are usually translated by the crest value of developed voltages. In this case, very commonly, the grounding impedance is approximated by the Impulsive Grounding Impedance, $Z_{p}$.

As previously mentioned, this parameter refers to the ratio between the peak values of the developed voltage and current waves ($Z_{p}=V_{p}/I_{p}$). The attractive aspect of such representation is that it allows immediately determining the maximum GPR (always verified at the current injection point) simply from the product of $Z_{p}$ by current peak value. This possibility is very appropriate for lightning protection evaluations. As a principle, the value of impulsive grounding impedance is quite different from the low frequency resistance, mainly due to the reactive effects (capacitive and inductive currents) and also to the frequency dependence of soil parameters. However, in some cases it is possible to estimate the impedance from this resistance, which is the usually measured parameter. If the effective length is not exceeded and no ionization process is verified, certain references indicate the impedance to be a little lower than the low frequency resistance ($Z_{p} \approx 0.7 \cdot R_{LF}$) [9].

Other aspect that deserves attention concerns the concept of the Effective Length of Electrode, previously explained. Longer electrode lengths have their grounding impedance limited to that value found for effective electrode length. As mentioned, for lightning currents, this impedance is usually approximated by the impulsive one ($Z_{p}$). This concept is very important when attenuation of current wave along electrode is significant. This is the usual case for long electrodes or even for short ones (in this case, when they are buried in low resistivity soils). The Effective Length is not a constant parameter for a given electrode configuration buried into a determined soil. Naturally, current waves with different time parameters correspond to different effective lengths. Fast waves, whose representative frequency components are typically high, have shorter effective length, as they are associated to more pronounced attenuation effects in the soil. Only as a rough reference, for soils whose resistivities have the values 100, 1000, 2000 and 5000 $\Omega\cdot$m, the effective length has respectively the order of 10m, 30m, 50m and 80m, considering a fast current wave (1.2/50$\mu$s) [9]. For slower waves (for example, 5/70$\mu$s) the values are a little larger. Nevertheless, when determining the length of electrode to be employed, it is not a efficient practice to achieve the effective length, as the contribution of the third part final of electrode to the current distribution is very reduced. Therefore, it seems reasonable to adopt the cited values, even for slower lightning current waves.

Concerning this effect, three main practical aspects should be observed. First, for grounding applications concerned with lightning protection, it is waste of resources to employ longer electrodes than the effective length. This is the usual case for counterpoises cables connected to transmission line tower footings.

Second, special care is recommended for those applications where the grounding impedance value is estimated from measured grounding resistance. This the typical case for transmission lines where the values of tower footing resistance are limited to determined value (very usually 20 $\Omega$ or 30 $\Omega$, in Brazil). A limiting value of grounding resistance is observed with the expectation that this would imply on limiting the grounding impedance value. Not always, a reduced value for grounding resistance implies a reduced value for grounding impedance. When the electrode length is increased, its resistance is decreased. This behavior holds even after the effective length is overpassed. Therefore, this resistance may reach very low values, while the grounding impedance value is limited to that value obtained for the effective length. In this case a false expectation of reduced value for impedance may be generated.

The third aspect concerns the relevance on defining the position of earthing connection to the electrode. Even for the same electrode configuration, the impedance value may largely vary according to the position of earthing connection to buried electrode. This is illustrated in Figure 7 for two different configurations, that consider electrodes longer than the effective length for the particular soil where it is buried.

For the horizontal electrode, if the earthing connection is done in point A (electrode extremity), a determined value of grounding impedance is found. When the connection is done in point B (at the mid point), the impedance is decreased to about its half value. This is explained as, in

![Figure 7 – The influence of the position of earthing connection to electrode on grounding impedance.](image-url)
the second case, the current "sees" two parallel impedances, whose individual value is similar to the grounding impedance of first case.

For the grid, when the earthing is connected to a corner, a determined value is found for grounding impedance. As the connection is changed to the grid center, this value is reduced to almost its fourth value. Approximately the same behavior would be expected, if aerial conductors were employed to distribute the lightning current, placing the earthing connection at the four corners.

Of course this effect is very pronounced only for those cases the electrode extent overpass the effective length. As soil resistivity is increased, the impedance diminution would be decreased, once the current wave attenuation becomes lower (corresponding to larger values for electrode effective length).

Regarding the recommendation of values for grounding impedance, as a principle, it is desired to obtain a value as low as possible. However, in special cases, which involve the distribution of large currents (such as associated to atmospheric discharges) imposed to a system with several earthing terminations, it may be of interest to increase the impedance of one of these terminations. This can constitute a way to influence the distribution of currents through the system. Undesirable interference effects of surge currents in the region close to one termination may be avoided by such practice. Of course, as the overall potential rise is determined from the product of impedance by current, in such applications, safety precautions should always be considered. One practical example of such situation refers to the surge transference from the medium voltage distribution network to the consumer facilities, which are fed by the low voltage line. When a voltage wave (for example, associated to a lightning induced overvoltage or a distant direct strike) reaches the protected distribution transformer, the surge arresters operate and the associated current is drained to the soil. It is also partially transferred to the low voltage network through the neutral and phase cables. If the grounding impedance of a close consumer entrance is lower than that of the transformer, the surge current tends to be drained to the consumer grounding. Unless the consumer facilities are protected, it may be submitted to dangerous levels of voltage.

The main factor that influence in the decrease of grounding impedance is the extension of the area covered by the electrodes of the grounding system. However, for fast phenomena the field attenuation makes the increase of dimension over determined extension not effective in decreasing grounding impedance (effective length concept). The action to reduce grounding impedance, in this case, should be concentrated to the proximity of current injection point, in order to increase capacitive and conductive current in this region. As cited before, the position of earthing termination may be important. Also, the number of earthing connections may influence and the use of aerial cables to distribute the current to different earthing connections may play an important role on reducing the grounding impedance value, when long electrodes are involved. For the specific condition of a layered soil, whose second layer presents a low resistivity value (in comparison to that of the first one), the employment of rods to reach such layer can have also a significant influence.

The ionization process is able to contribute to reduce grounding impedance value, but only for very concentrated (short) electrodes and very high values of lightning current. For large extension of electrodes the effect is not able to affect the impedance value. This is the usual case for transmission lines. Only in order to have a rough idea about the amplitude of this effect, a reference is done to the results of an experimental work [8] that considers an horizontal electrode (0.05 m radius) buried in a 800 Ω.m resistivity soil. The effect is not verified until the density of current per unit length reaches 200 A/m. In order to promote a reduction about 10% on grounding impedance value , the current density should overpass 600 A/m. Considering a four legs 20m long electrode configuration (horizontal radial or counterpoises) placed in this soil and disregarding attenuation effect (I_{efetivo} ≅ 30m), as a simplification, the onset of ionization process would require a 16kA crest current value (80m length of buried electrode). A 48 kA current would be required to diminish the grounding impedance value around 10%.

5. References


