THE INFLUENCE OF THE SOIL PARAMETERS DEPENDENCE WITH FREQUENCY ON IMPULSE GROUNDING BEHAVIOR

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Abstract - This paper investigates the influence of the soil electrical conductivity and permittivity dependence with frequency in grounding response to lightning currents. Simulated results for soil with frequency variation of its parameters show: i) a significant reduction of the amplitude values of the transient voltages and impulse impedance; ii) an increase of the expected effective length of electrode; iii) a significant reduction of the impulse coefficient with values, in some cases, below unity. These effects are more relevant for high-resistivity soils and are due to the pronounced capacitive effect observed when the soil parameters dependence with frequency is included in simulations.

1 INTRODUCTION

The grounding systems are an important element for good electrical systems performance, mainly when they are subjected to faults. Their basic function is to disperse the current of fault to earth without causing any potential differences or induced voltages that might endanger people or damage equipments. Grounding performance and design at low frequencies are well established and described in classical books and international standards [1], [2]. However, when subjected to lightning currents, grounding electrodes present a very particular behaviour, usually referred as grounding impulse behaviour [3].

Recently, several computational models to evaluate the grounding performance to high-frequency currents have been developed based on different approaches [4]-[7]. These powerful tools play an important role in the investigation of the grounding impulse behaviour, since they allow performing different analysis to relate the grounding performance and some typical variables (soil resistivity and permittivity, grounding dimensions, etc.) [8]. Therefore, such tools have been widely applied in the grounding analysis to understand and improve its performance to lightning currents.

Further, in the grounding study, it is of major importance the adequate soil modelling [9]. In the most part of works, which deal with lightning transients in grounding, the soil electrical conductivity and permittivity are usually assumed to be constant, equal to its low-frequency values and frequency independent. However, measurements of the soil electromagnetic behavior show that both parameters are strongly frequency dependent [9]. Experimental data obtained in [9] for a large number of soil samples indicate an increase of the soil conductivity and a reduction of the relative permittivity when frequency rises from about 100 Hz to 2 MHz [9]. This important effect is usually neglected, likely due to historical and cultural reasons or even due to ignorance. Nevertheless, depending on the soil characteristics at low frequency and the type of transient occurrence, important differences in the results of grounding simulations may be found, if the soil parameters dependence with frequency is disregarded. The main objective of this work is to elucidate such differences. For this, it is investigated the influence of the soil parameters variation with frequency in the computation of some very fundamental grounding quantities related to its impulse performance, namely transient voltages, impulse impedance, impulse coefficient and effective length.

This paper is organized as follows. Section 2 describes the electromagnetic model used for representing the grounding electrodes. Section 3 discusses in brief the formulation proposed in [10] for expressing the frequency variation of soil parameters, which is used in the analysis presented herein. The influence of such variation in grounding impulse behaviour is then analysed in Section 4. Finally, Section 5 presents the conclusions.

2 ELECTROMAGNETIC GROUNDING MODEL

The grounding model employed in simulations performed in this work is based on the Hybrid Electromagnetic Model (HEM), described in detail in [5], with some suitable modifications [7]. Simulations are performed in frequency-domain in order to include the frequency dependence of the soil parameters. The time-domain response is then obtained by application of an inverse Fourier transform.
The grounding system is represented by a set of cylindrical electrodes. Each electrode is source of a transversal current $I_T$ and longitudinal current $I_L$. The current $I_T$ generates a divergent electric field at a generic point. Considering each pair of electrodes, this current promotes capacitive and conductive couplings (self and mutual ones). The current $I_L$ generates a nonconservative electric field and a magnetic field at a generic point. Considering each pair of electrodes, this current promotes inductive and resistive couplings (self and mutual ones). The superposition of both transversal and longitudinal effects of the current sources leads to the final electromagnetic equations, which describe the grounding transient behaviour [5], [7]. The application of Moment Method numerical technique and modified image theory leads to final results [7].

3 SOIL MODELLING

In this work is used a formulation for expressing the frequency dependence of the electrical soil parameters (electric conductivity $\sigma$ and electric permittivity $\epsilon$), originated from measurements of several soil samples of Brazil, covering very different soil types and geological structures [9]. The measurements were performed in a frequency range of 100 Hz to 2 MHz. From a statistical analysis of the experimental results, the following formulation was obtained for $\sigma$ and $\epsilon$ frequency dependence computation [10]:

$$\sigma(\omega) = \sigma_0 + \Delta \sigma \left( \cot \left( \frac{\pi}{2} \alpha \right) \right) \left( \frac{\omega}{2 \pi \times 10^6} \right)^{\alpha} \quad (1),$$

where $\sigma_0$ is the electric conductivity at low frequency, $\omega$ is the angular frequency and $\Delta \sigma$ and $\alpha$ are statistical parameters, which are responsible for the frequency dependence of soil conductivity and permittivity. In this work it is used median values for $\Delta \sigma$ and $\alpha$, which are, respectively, 11.71 S/m and 0.706. The soil magnetic permeability is assumed to be equal to the vacuum magnetic permeability and frequency independent [9]. Further details regarding fitting of soil parameters and the experimental setup can be found in [9].

4 RESULTS

The evaluated grounding configuration corresponds to horizontal electrodes, buried on 0.5 m depth, with radius 1 cm and of different lengths, from 5 to 80 m.

Two soil models were adopted, that is: Soil 1 – soil represented by only its low-frequency electric conductivity $\sigma_0$ (three representative values considered in this work: 10, 2 and 1 mS/m) and relative permittivity equal to 15, both parameters frequency independent. Soil 2 – soil with the inclusion of frequency variation of its parameters and the same previous low-frequency values of conductivities. In simulations, the effects of the soil ionization are disregarded.

The electrode excitation was obtained by the injection of a typical double exponential current wave of 1 kA and 1.2/50 $\mu$s. In all simulations, the current injection was made in the electrode beginning point.

4.1 Transient voltages

To evaluate the influence of the soil parameters variation with frequency on the transient voltages in grounding, it is considered a 60 m long horizontal electrode, buried in both Soil 1 and 2, with $\sigma_0=10$, 2 and 1 mS/m. Fig. 1 illustrates the amplitude $|Z(\omega)|$, Fig. 1(a)), and the angle $\theta(\omega)$, Fig. 1(b)), of the harmonic grounding impedance $Z(\omega)$. The harmonic impedance is frequency independent and equal to the low frequency ground resistance $R$, in the low frequency (LF) range, for both Soil 1 and 2. Nevertheless, as frequency rise, a different behaviour of $Z(\omega)$ is observed, depending on the soil model. Results for

![Fig. 1 - 60 m horizontal electrode. (a) Amplitude and (b) Angle of the harmonic grounding impedance](image-url)
Soil 1 exhibit an inductive behaviour and the amplitude of $Z(\omega)$ becomes larger than $R$, being this effect more relevant for more conductive soils. These results are in accordance with some classical ones, for example, those presented by Grcev in [11]. On the other hand, when the soil parameters dependence with frequency is considered (Soil 2), the capacitive effect become relevant, especially for high-resistivity soils ($\theta(\omega)<0$, Fig. 1(b)]. The capacitive effect plays an important role in the grounding performance and it is responsible for the reduction of $|Z(\omega)|$. Indeed, as may be observed in Fig. 1(a), the frequency dependence of the soil parameters leads to reduction of the amplitude values of $Z(\omega)$ in the high frequency (HF) range.

The transient voltages at the injection point, for both Soil 1 and 2, and $\sigma_0=10$, 2 and 1 mS/m, are illustrated, respectively, in Figs. 2, 3 and 4. Results for Soil 2 exhibit an appreciable reduction of the overvoltage values. Also, the voltage wave has its front shape distorted, with the reduction of the front-wave slope. Both features become more pronounced for high-resistivity soils, as may be observed in Figs. 3 and 4. Along the wave tail it is observed a similar behaviour above a certain instant of time, which depends of $\sigma_0$ being larger for less conductive soils (about 0.8, 15 and 25 $\mu$s for, respectively, $\sigma_0=10$, 2 and 1 mS/m).

The obtained results for the transient voltages are in perfect consonance with that obtained for the harmonic grounding impedance. First, the influence of the soil parameters variation with frequency, in reducing the overvoltage values, is more pronounced in less conductive soils. Similarly, the great reductions of the amplitude of the harmonic impedance are observed for high-resistivity soils. Second, the main differences are observed in front wave region, which are associated with the HF components. It may be understood, since the harmonic grounding impedance present similar behaviour, for both Soil 1 and 2, in the LF range, and significant differences in the HF range.

4.2 Impulse impedance and effective length

When an impulsive current wave is injected in a long grounding electrode, the corresponding electromagnetic wave propagates along the electrode [3]. While the wave is propagating, it has its amplitude attenuated and also distorted with a reduction of the front-wave slope along the propagation direction. As a consequence of attenuation, the current that is dispersed to ground along the electrode presents a nonuniform distribution with the decrease of the linear current density (A/m) along the conductor [3]. The concept of effective length of electrode is just derived from such considerations. It is a limiting electrode length from which grounding impedance reductions are not observed [3]. It occurs due the fact that the current wave attenuation to this limiting length is strong so that the current dispersion to ground from this point is negligible.

Fig. 5 shows the ratio of the attenuation constant for soil 2 ($\alpha_2$) and soil 1 ($\alpha_1$), with $\sigma_0=10$, 2 and 1 mS/m, along the frequency range of interest. As may be observed, at LF range, the ratio is near to the unity. As frequency rise, the ratio become smaller than unity, that is, the attenuation in Soil 1 is more pronounced than in Soil 2. This behavior is due to the high values of soil permittivity observed in experimental data of typical soils and obtained by application of the formulation described in Section 3. Above certain frequency, which depends of $\sigma_0$ value, the influence of the conductivity increase with frequency becomes more relevant and the ratio is larger than unity. Such frequency increase with the soil conductivity at low frequency ($\sigma_0$).

Fig. 6 shows the simulation results of the low frequency ground resistance $R$ and the impulse impedance $Z_p$ of horizontal ground electrodes in a range from 5 to 80 m, for both Soil 1 and 2, with $\sigma_0=10$, 2 and 1 mS/m.
According to Fig. 6, the value of the ground resistance is larger for less conductive soils and decrease with the increase of the electrode length. Similarly, the impulse impedance, for both soil models, presents larger values for less conductive soils and decrease with the increase of the electrode length; nevertheless at a certain length it becomes constant, while the LF resistance continues to decrease. Therefore, only a certain electrode length is effective in controlling the impulse impedance, which is referred as effective length \( \ell_{ef} \). The effective length decreases with soil conductivity \( \sigma_0 \) and frequency rise. This can be understood as both parameters are responsible for increasing ground losses, leading to an increase in the attenuation of the current wave that propagates along the electrode [3].

Fig. 6 also shows two very important differences between simulated results for Soil 1 and 2. First, it may be observed that the effective length is larger for soil with frequency variation of its parameters (Soil 2). This effect is more appreciable in less conductive soils and probably is due to the reduction of the attenuation constant of soil in the intermediate frequency range, when its parameters are assumed to be frequency dependent (Fig. 5). Second, the values of impulse impedance for soil with frequency variation of its parameters (Soil 2) are lower than that obtained for soil represented by only its LF parameters (Soil 1), especially for high-resistivity soils. Such difference between the obtained values becomes larger above the effective length for Soil 1, since the impulse impedance continues to decrease for Soil 2. As a conclusion, the reduction of the amplitude levels of the transient voltages, due to the soil parameters variation with frequency, is more significant for electrodes lengths larger than the effective one for Soil 1.

4.3 Impulse coefficient

The impulse coefficient \( A \) is a typical parameter in the analysis of transients in grounding, which allows a simple comparison between the grounding performance at low and high frequencies. It is defined as the ratio between the impulse impedance and the LF ground resistance. The results obtained in subsection 4.2, directly impact in computation of the impulse coefficient.

Fig. 7 illustrates the impulse coefficient for horizontal electrode, considering results of subsection 4.2, for both Soil 1 and 2. For Soil 1, the impulse impedance is equal to the ground resistance for electrode lengths below the effective one (Fig. 6). Hence, the impulse coefficient for such soil model is equal to one for lengths smaller than the effective and above unity for lengths larger than the effective. These results are in agreement with that obtained by Grecév [11]. Nevertheless, when the soil parameters dependence with frequency is taken into account (Soil 2) a completely different behaviour is obtained. As illustrated in Fig. 7, it is observed a significant reduction of the impulse coefficient and, the most important, it is noted values of \( A \) smaller than unity, mainly for high-resistivity soils. In the analysed cases, for Soil 2, the ratio \( Z_p/R \) is within the range 0.9-5.24, 0.76-1.7 and 0.66-0.95, respectively, for \( \sigma_0=10 \), 2 and 1 mS/m. These results are in conformity with a recent experimental work [12]. According to this work, and as it was shown in this paper, the capacitive effect in high-resistivity soils is more pronounced than usually assumed in some traditional studies and is at least partially responsible for the values of impulse coefficient below unity [12].
**5 CONCLUSION**

This paper presents a study of the influence of the soil parameters variation with frequency in grounding performance to lightning currents. From the obtained results and presented analyses, the following main conclusions can be drawn:

1. When the soil parameters dependence with frequency is taken into account, it is observed a significant capacitive effect, which is responsible for the reduction of the amplitude values of both transient voltages and impulse grounding impedance. These reductions are more pronounced for high-resistivity soils.

2. The effective length of the grounding electrode, obtained by simulations, is larger for soils with frequency variation of its parameters. As a consequence, larger reductions in both transient voltages and impulse impedance are expected for electrode lengths larger than the effective one obtained for soils represented by only its low-frequency parameters.

3. A significant reduction of the impulse coefficient and also values below unit are observed, when the soil parameters dependence with frequency is included. This behaviour is due to the capacitive effect and is in accordance with some experimental results.

4. The negligence of the soil parameters dependence with frequency leads to conservative, but unrealistic results. In some applications, for example, those associated with lightning performance of transmission lines, in order to optimize the tower footing design, more realistic and accurate results should be used.

**6 REFERENCES**