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Comparison of the antenna model and experimental analysis of an impulse impedance of the horizontal grounding electrode

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A B S T R A C T

The paper deals with the comparison of two methods for the calculation of the impulse impedance of the horizontal grounding electrode defined as a ratio of maximum values of induced voltage and current at the injection point on the electrode. The current distribution along the electrode is calculated using the antenna theory based model featuring the thin-wire approximation and corresponding Pocklington integro–differential equation in the frequency domain. The equation is solved using analytical technique. The scattered voltage is subsequently calculated from the Generalized Telegrapher's equation. On the other hand, experimental technique based on three-pole/potential drop method is implemented at the actual measurement site, and the data obtained are used for the assessment of impulse impedance of the grounding system. The results obtained via different methods agree satisfactorily, thus validating antenna model of the grounding electrode.

1. Introduction

The response of the grounding electrode to the lightning current pulse can be represented using impulse impedance, which is defined as a ratio of peak voltage induced at the feeding point on the electrode and a maximum value of the lightning current [1,2]. To calculate the maximum voltage induced at one end of the electrode, transient voltage along the grounding electrode has to be determined from the current distribution. Alternatively, impulse impedance can be obtained from in-situ measurements [3].

One of the most commonly used approaches for the calculation of transient currents and voltages along grounding electrodes are the Transmission Line Model (TLM) [4–6]. TLM offers simplicity and low computational cost with somewhat lower degree of accuracy. However, the full wave approach, based on related integral relationships arising from the antenna theory, reported in [7–11], ensures the higher accuracy of the results related with higher computational costs.

For canonical geometries, analytical solution of corresponding integro-differential equation can be obtained as discussed in [5,12,13] and more recently in papers by the authors [10,11,14]. The solution for the current distribution along the electrode can be obtained in either frequency or time domain. In the case of frequency domain analysis, the use of inverse fast Fourier transform (IFFT) is necessary to obtain transient response.

In this paper, an extension of the model presented in [10,11] is given. Impulse impedance of a horizontal grounding electrode is calculated using frequency domain analytical solutions for the current and the scattered voltage along the horizontal electrode, respectively. Exact solution of the integral over Green's function is used in the derivation of the analytical solution, as opposed to previously reported simplified solution. The results are subsequently transformed into time domain via IFFT. Once the maximum of the current and the voltage in the time domain is determined, the impulse impedance is readily computed.

To compare adequately this model with the actual in-situ conditions and the consecutive constraints, the field measurements have to be carried out. The main experimental challenge arises from the lack of a well-defined procedure for lightning impedance measurements. Several techniques have been reported and have been frequently used by researchers and engineers. The most commonly used method is a low frequency earth resistance method based on 3 or 4-point stake-probe measurements [15]. However, this method is designed for the estimation of the grounding system protection behavior in conditions of single or multiple line-to-ground short-circuits [16]. Consequently, considering the frequency con-

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tent of the lightning pulse, this approach may result in a non-reliable data, i.e. measurement of the earth resistance instead of the grounding impedance [3]. These parameters can significantly differ in the case of fast front and high amplitude lightning current pulses [15].

To account for the lightning pulse frequency content, several research laboratories and manufacturers apply frequency sweep based measurements [17–19]. Most of these measuring systems are limited by the upper cut-off frequency (several tens of kHz) consequently limiting accuracy of the IFFT-reconstructed impedance. Additionally, sophisticated instrumentation, enabling measurements up to few MHz, requires extensive probe grids, limiting the field applications particularly in the rocky terrain [19]. Furthermore, frequency sweep implies the series of sinusoidal waveforms characterized by discrete frequency step, where pulses are injected in the grounding system consecutively [17]. The problem of the frequency sweep based measuring systems can be circumvented by pulse injection measurement. Pulse based grounding impedance measuring systems generate pulse identical to the lighting waveform, except for the peak current value [18].

The complexity of pulse impedance measurements, particularly in terms of setup-induced parasitic inductivities, constraints the practical applications, motivating research orientated towards correlating earth resistance and earth impulse impedance [20]. In [21], the author modeled impulse efficiency of the horizontal/vertical electrode based grounding system, showing that, up to a certain frequency, earth resistance is equal to the impedance. For the frequencies above the limit, impedance-resistance ratio increases linearly.

On the other hand, Visacro et al. [16] showed that the model reported in [21] exhibits conservative approach failing to take into account capacitive influence of the ground, particularly for the high-resistivity soils. The effective length of the grounding electrode and ground resistivity are essential parameters [16]. For the electrodes shorter than their effective length, impedance-resistance ratio is lower than one, for both high- and low-resistance soils. The electrodes longer than effective length exhibit impedance-resistance ratio above one while resistance continues to decrease with the increase of electrode length. Taking [16] as initial point, this paper deals with the estimation of the earth lightning impedance based on the ground resistance measurements in the case of horizontal grounding electrode. Applying well-known measurement method, reliable and reproducible set of data is obtained and subsequently used for comparison with the analytical model. Once the earth resistance of the grounding system, soil resistivity and grounding electrode geometry are obtained, it is possible to estimate the impulse impedance for given pulse characteristics (rise and tail time). Results obtained by measurements and calculations according to [16] are compared to the developed analytical model ensuring the validity and providing simple method for obtaining grounding impedance using existing techniques. Comparison of the results obtained via different methods can be used in determining the limitations of the proposed models. To the best of authors' knowledge, this kind of validation of the analytical model with experimentally obtained results has not been previously reported in the literature.

In Section 2, Pocklington integro-differential formulation for the current distribution along the grounding electrode, buried into a lossy half-space and excited with a transient current source is posed in the frequency domain. The influence of the earth-air interface is taken into account via simplified reflection coefficient arising from the modified image theory (MIT). The Pocklington equation is then analytically solved using the approximation of the current distribution. In Section 3, measurement methodology is outlined along with site description and results of the post-processing procedures. Results for the transient and impulse impedance, respectively,

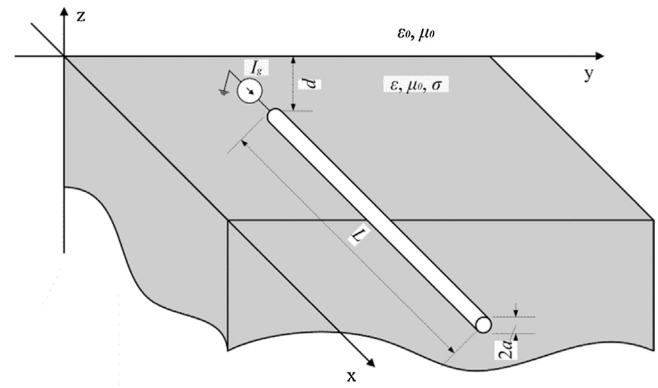

Fig. 1. Horizontal grounding electrode buried in a lossy medium.

as well as the results obtained via the measurement procedures are presented in Section 4. Concluding remarks are given in Section 5.

2. Antenna model of the horizontal grounding electrode

Fig. 1 shows a horizontal grounding electrode of length L and radius a, is buried in a lossy medium at depth d. Properties of the medium are given in terms of the electrical permittivity ε and conductivity σ. The electrode is excited at one end with an equivalent current source, representing lightning strike current.

Current distribution along the electrode is governed by the homogeneous Pocklington integro-differential equation [10]

$$j\omega\frac{\mu_0}{4\pi}\int_0^L I\left(x'\right)g\left(x,x'\right)\mathrm{d}x' - \frac{1}{j4\pi\omega\varepsilon_{\mathrm{eff}}}\frac{\partial}{\partial x}\int_0^L \frac{\partial I\left(x'\right)}{\partial x'}g\left(x,x'\right)\mathrm{d}x' = 0, \tag{1}$$

where $I(x')$ denotes the unknown current distribution along the electrode.

Complex permittivity of the medium is given as

$$\varepsilon_{\mathrm{eff}} = \varepsilon_r\varepsilon_0 - j\frac{\sigma}{\omega}, \tag{2}$$

where ε_r and σ represents relative electric permittivity and conductivity, respectively. These parameters, assumed here to be constant, are actually frequency dependent. However, the complex permittivity of the medium is used to account for the frequency dependence of the medium properties, providing the simplicity of the solution while maintaining acceptable level of accuracy [11].

Detailed definition of Green's function $g(x, x')$ can be found elsewhere, e.g. in [11,22]. Presence of the earth-air interface is taken into account via the reflection coefficient in Green's function arising from the modified image theory (MIT) and defined as follows [23,24]

$$\Gamma_{\mathrm{ref}}^{\mathrm{MIT}} = -\frac{\varepsilon_{\mathrm{eff}} - \varepsilon_0}{\varepsilon_{\mathrm{eff}} + \varepsilon_0} \tag{3}$$

The spatial distribution of the scattered voltage is defined as [25]

$$V^{\mathrm{sct}}(x) = -\frac{1}{j4\pi\omega\varepsilon_{\mathrm{eff}}}\int_0^L \frac{\partial I\left(x'\right)}{\partial x'}g\left(x,x'\right)\mathrm{d}x'. \tag{4}$$

To calculate the transient impedance of the grounding electrode, time domain counterpart of the scattered voltage (4) has to be determined by applying the IFFT algorithm. Once the scattered