

Circuit-based grounding electrode considering frequency dependence for different input current

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ABSTRACT

This paper presents a simulation work of circuit-based grounding electrode considering frequency dependence of soil parameters for three input currents which are impulse, AC 50 Hz, and DC. The circuit parameters were determined by using Dwight and Sunde equations where a single horizontal grounding electrode was considered. Scott model was used for the frequency dependent model, to determine the frequency dependent soil resistivity and relative permittivity. It is found that the voltage response of the impulse current was highly affected (75.2%) by the frequency compared to the voltage response of AC 50 Hz and DC. The impulse current response also gave the lowest peak in the analysis by the influence of frequency which make it better compared to the two other inputs. Therefore, it can be concluded that the frequency dependent of soil parameters is crucial and need to be considered in the transient analysis for any kind of input current to obtain accurate results.

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1. INTRODUCTION

Lightning Protection System (LPS) is one of the most important aspect to be considered in order to protect lives and electrical equipment from the high current of the lightning strikes, where grounding system need to be designed properly for the safety purposes [1-3]. The types of grounding system that are commonly used are horizontal electrode, vertical electrode, grounding grid, and ring electrode, where the purpose of these grounding electrode is to absorb the high current from the lightning strikes that dispersed into the ground[4-6]. Encouraged by the safety concerned, many researchers have come with the theoretical and mathematical approaches to improve the grounding system performance by using different modelling approaches. The most popular types of grounding system modelling are electromagnetic field model (EMF), transmission line model, hybrid model, and circuit-based model [7, 8]. Among these model, electromagnetic field model is known to be the most accurate model for the performance aspect, however the formulation and expression is complex since Maxwell equations is involved and is hard to compute [9-11]. In contrary, the circuit-based model is the easiest to compute and the expressions is simple, but it struggles from inaccuracy problem [12]. This work concerned is to improve the circuit-based model grounding electrode by considering the key parameters not previously considered.

Many studies have been done previously to improve the circuit-based model where some of the parameters have been considered, such as the integration of soil ionization effect, current rate of rise, mutual coupling, frequency influence, and others for all types of grounding electrode [13-23]. However, the study regarding the influence of frequency dependent of soil parameters is still not covered entirely since

there is only one study for each horizontal and vertical grounding electrode, and under lightning current only for the input signal, and the results is not sufficient since it used the equivalent frequency [16-19]. Due to the lack of information regarding the issue, further improvement needs to be done to tackle the inaccuracy problem for circuit-based model. One of the rising issues is on the transient response in impulse current condition, where previous work stating that the performance of the response when injected with impulse and transient current gives different behavior, for the earthing system previously designed for a low voltage and low power frequency only [2, 7].

This work aims to develop an improved circuit-based model for grounding electrodes considering the effects of frequency dependent of soil resistivity and relative permittivity on grounding electrode impedance and voltage response, under several types of input current (impulse, AC and DC), and it is limited to a single horizontal grounding electrode. The calculation and simulation work are done in MATLAB and CDEGS software.

2. RESEARCH METHOD

2.1. Circuit-based model parameters

A lump circuit-based model which consist of R, L, and C is used in the transient analysis to represent the horizontal grounding electrode as shown in Figure 1. Figure 2 shows a representation of the horizontal grounding electrode injected at a point with a download, with radius, a , length, l , and depth, d , buried in a uniform soil. As shown in (1) and (2) are given by Dwight and Sunde to determine the electrode resistance of the horizontal and vertical grounding electrode respectively.

$$R = \frac{\rho}{\pi l} \left[\log \left(\frac{2l}{\sqrt{2ad}} \right) - 1 \right] \quad (1)$$

$$R = \frac{\rho}{2\pi l} \left[\log \left(\frac{4l}{a} \right) - 1 \right] \quad (2)$$

where ρ is the soil resistivity (in ohm-meter), l is the electrode length (in meter), and a is the electrode radius (in meter). The inductance value is given by (3) which is,

$$L = \frac{\mu l}{\pi} \left[\log \left(\frac{2l}{\sqrt{2ad}} \right) - 1 \right] \quad (3)$$

where d is the depth (in meter) of the electrode buried in the soil, and μ is the relative permeability given by $4\pi \times 10^{-7}$. Conductance value can be found by using (4) which is,

$$C = \frac{\rho \epsilon}{R} \quad (4)$$

where ϵ is the soil relative permittivity (in Farad per meter).

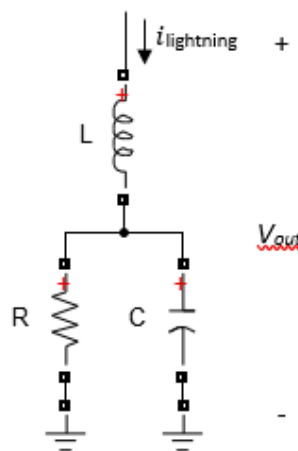


Figure 1. A lump circuit model of grounding electrode consisting resistor, inductor, and capacitor

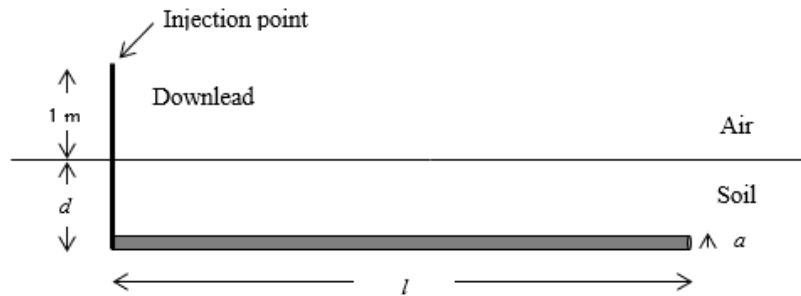


Figure 2. Representation of a single horizontal grounding electrode with radius a , length l , depth d , buried in uniform soil, injected at a point with a vertical downlead

2.2. Frequency dependence of soil parameters

Scott model is used in the analysis as the frequency dependence model due to its accuracy compared to other models based on the previous studies [16-20, 24, 25]. The expression of conductivity, $\sigma(f)$ and relative permittivity, $\epsilon_r(f)$ as a function of frequency proposed by Scott are given by (5) and (6) respectively.

$$\sigma(f) = 0.028 + 1.098\log_{10}(\sigma_0) - 0.068\log_{10}(f) + 0.036\log_{10}^2(\sigma_0) - 0.046\log_{10}(f)\log_{10}(\sigma_0) + 0.018\log_{10}^2(f) \tag{5}$$

$$\epsilon_r(f) = 5.491 + 0.946\log_{10}(\sigma_0) - 1.097\log_{10}(f) + 0.069\log_{10}^2(\sigma_0) - 0.114\log_{10}(f)\log_{10}(\sigma_0) + 0.018\log_{10}^2(f) \tag{6}$$

where σ_0 is the conductivity at 100 Hz in (mS/m), f is the frequency in Hertz (Hz) and ϵ_r is the soil permittivity (F/m). The overall computation process of the transient analysis is described in the flowchart in Figure 3. Firstly, the parameters of the circuit are determined by using (1), (3), and (4). Then, the frequency dependent circuit model is determined by using (5) and (6) as proposed by Scott. The frequency dependent circuit model is then computed by using CDEGS software (FFT-IFFT). The computation is repeated by changing the injected input current and the results obtained is compared.

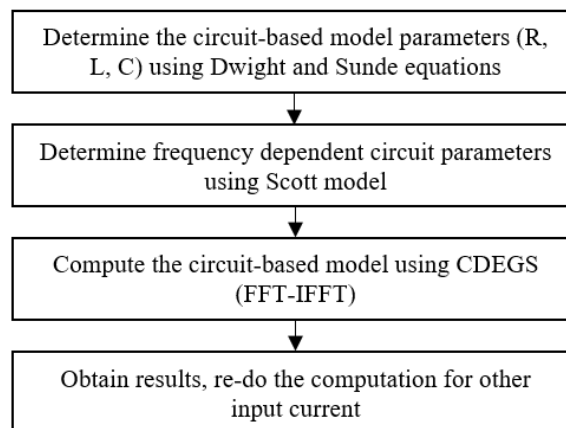


Figure 3. Flowchart of the computation process for the transient analysis

3. RESULTS AND ANALYSIS

A 15m long vertical grounding electrode, with 0.02m diameter, buried in 1m depth of uniform soil is considered in this study. The soil relative permittivity is assumed to be constant which is 1 for the frequency independent analysis, and the soil resistivity is set to several different values (100 Ω m, 500 Ω m, 1000 Ω m, and 2000 Ω m). The horizontal grounding electrode is injected at a point by a 10 kA-peak input current with various shape; 1/35 μ s impulse, 50 Hz AC, DC. The expression of the double exponential current is given by $i(t)=10.244(e^{-20000t}-e^{-550000t})$ kA.

Figure 4 and Figure 5 shows the peak voltages of frequency independent and frequency dependent model for three different input current which are impulse, AC and DC, and the results obtained is tabulated in Table 1. Voltage responses of the impulse current and AC 50 Hz for frequency independent model in Figure 4 seems to only have a slightly different (less than 4.7%), but DC voltage response gives much lower value compared to the other two (34% lower). DC does not affect by the frequency because it has no frequency element, so the response obtained is better than the impulse and AC 50 Hz.

In Figure 5, for the frequency dependent model, it can be seen that the peak voltage response for impulse current gives a better result with the influence of frequency where it gives the lowest response, 48.4% lower than peak voltage of AC 50 Hz and 62.5% lower than peak voltage of DC input at the highest soil resistivity of 2000 Ωm. As for the low resistivity (100 Ωm), the peak voltages of all the input current are not very much different. Based on the results obtained in Table 1, the peak voltage of the impulse current has the highest difference by comparing the frequency dependent and frequency independent model where the difference is 75.2%, while AC 50 Hz has 49.5% and DC has none because DC has no frequency. It reveals that the response obtained by the impulse current is the most affected by frequency. As for the shape of the voltage response, it is accordingly to the input current shape for every response.

Table 1. Peak voltage for both frequency dependent and independent model when impulse, AC 50 Hz, and DC injected at one end with varied soil resistivity

Nominal Soil Resistivity (Ωm)	V _p (kV) (1/35-μs)	V _{p(f)} kV (1/35-μs)	V _p (kV) (AC)	V _{p(f)} kV (AC)	V _p (kV) (DC)	V _{p(f)} kV (DC)
100	25.2	12.2	25.29	21.67	17.88	17.88
500	132	45	126.63	85.22	89.42	89.42
1000	264	77	254.21	149.89	178.82	178.82
2000	540	134	514.46	259.71	357.65	357.65

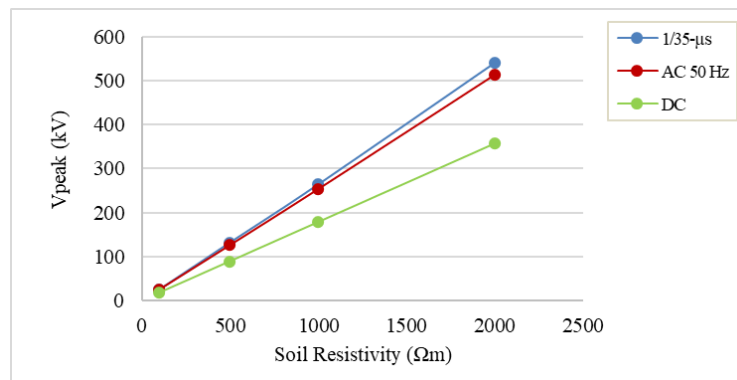


Figure 4. Effect of 10 kA-peak input current with various shape on the frequency independent electrode model peak voltage for varying soil resistivity; 1/35-μs impulse, AC 50 Hz, DC

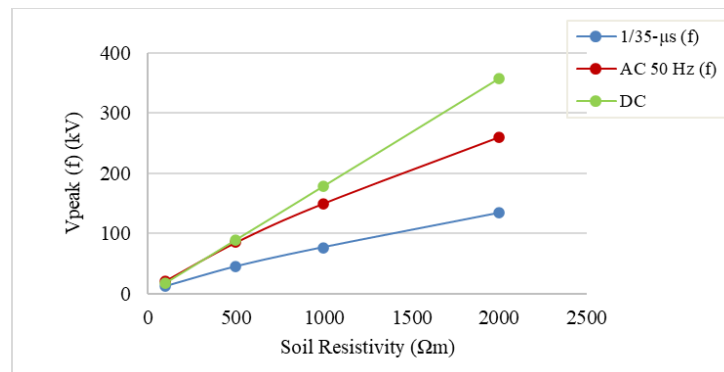


Figure 5. Effect of 10 kA-peak input current with various shape on the frequency dependent electrode model peak voltage for varying soil resistivity; 1/35-μs impulse, AC 50 Hz, DC

The results obtained somehow agrees with the previous work stating that the performance of the response when injected with impulse and transient current gives different behavior, for the earthing system previously designed for a low voltage and low power frequency only [2, 7]. Therefore, by considering the frequency in the transient analysis, more accurate results can be obtained especially for impulse current condition. The novelty of this work is by proofing that the impulse current experienced different behaviour in the transient response as stated in the previous work, where frequency need to be included in the analysis, which have been successfully achieved in this work by simulation and analysis.

4. CONCLUSION

The circuit-based model of grounding electrodes with frequency dependent of soil and three different input currents were successfully modelled. It is found that the voltage response of the impulse current is better with the influence of frequency and also the most affected by the frequency compared to the responses of AC 50 Hz and DC input. The study also concluded that considering the frequency dependence of soil parameters is crucial in the transient performance analysis to obtain accurate results.

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