An Improved Circuit-Based Grounding Electrode Considering Frequency Dependence of Soil Parameters

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***Abstract*— This paper presents the simulation of circuit-based vertically oriented grounding electrodes with the consideration of frequency dependence of soil resistivity and permittivity. The resistivity and permittivity were determined using equations proposed by Sundae and Dwight and the frequency dependence properties were modelled according to Scott's model. It was found that the voltage response was highly affected by the frequency, especially at high soil resistivity of 1000 Ωm and above (up to 4% decrease in voltage response). As for the low soil resistivity cases, the voltage response was less affected by the frequency, which is 1.4% and 1% lower for soil resistivity of 100 Ωm and 10 Ωm respectively. Obviously, the current circuit-based model (frequency independent model) tends to provide overestimated results. Therefore, the effect of frequency on the soil resistivity and relative permittivity should not be neglected when determining the transient performance of grounding electrode in order to obtain accurate results.**

Keywords—circuit-based, frequency dependence of soil, resistivity, relative permittivity, grounding

I. INTRODUCTION

Grounding system, which may be consisted of horizontal and vertical electrodes, is an important part in a Lightning Protection System (LPS). When lightning strikes, the high return stroke current disperses into the ground through the grounding electrode, thus a good grounding system is crucial for human safety and protection of electrical equipment. Many studies and research had been conducted to improve the overall grounding system performance, and mathematical or theoretical modelling of the grounding system is one of the crucial part that need to be looked into when trying to improve the transient performance of a grounding electrode. The most popular modelling approaches are known as the circuit-based, transmission line, and electromagnetic field techniques [1-3]. Among these models, circuit model is known to be a simple and easy to compute compared to others. However, circuit model is struggling from an inaccuracy problem.

Previously solved issues on electrode modelling using circuit-based concept are the integration of soil ionization effect, current rate of rise, and frequency dependent of soil under certain condition [4-7]. The soil ionization effect is covered for all type of grounding electrode, but for frequency dependent of soil resistivity and relative permittivity, there is only a study for horizontal grounding electrode under lightning current [8]. Due to that limitation, further improvement can still be made to overcome the accuracy problem of the circuit-based model by considering other key parameters not previously considered, such as the configuration of grounding electrode, and frequency variation.

This work aims to develop an improved circuit-based model for grounding electrodes considering the effects of frequency on grounding electrode impedance and voltage response, and it is limited to a single vertical grounding electrode. The calculation and simulation work are done in MATLAB software.

II. MODELING METHODS

A. Circuit-Based Model Parameters

A lump circuit-based model is used in the transient analysis where it is only limited to vertical grounding electrode. Fig. 1 shows the equivalent lumped circuit consisting R, L and C, that represents the grounding electrode in Fig. 2 with radius, a, length, *l*, and depth, *d*, buried in the soil. According to the equations given by Dwight and Sunde, the electrode resistance (ohm) of the circuit for horizontal and vertical grounding electrode are given by equation (1) and (2) respectively,

$$R = \rho/\pi l\ [\log (2l / \mathrm{sqrt}(2ad)) - 1] \qquad (1)$$

$$R = \rho/2\pi l\ [\log (4l / a) - 1] \qquad (2)$$

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 equation (3) which is,

$$L = \mu l/\pi\ [\log (2l / \mathrm{sqrt}(2ad)) - 1] \qquad (3)$$

where *d* is the depth (in meter) of the electrode buried in the soil and μ is the relative permeability given by 4π×10-7. Conductance value can be found by using equation (4) which is,

$$C = \rho\varepsilon/R \qquad (4)$$

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

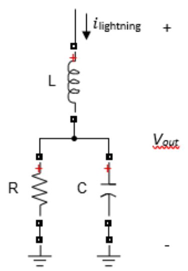

Fig 1. A lump circuit model of grounding electrode consisting resistor, inductor, and capacitor

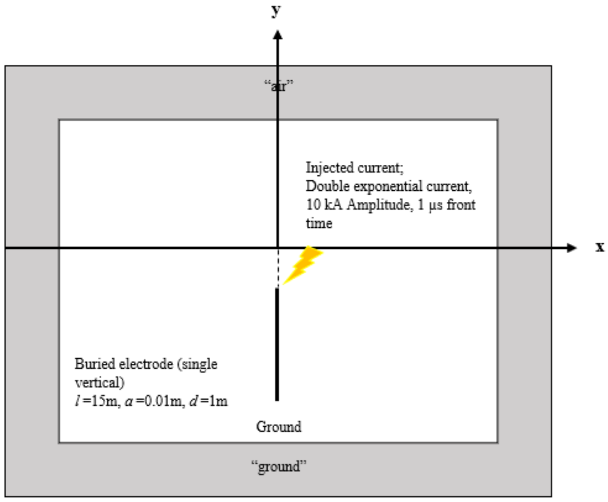

Fig 2. Representation of vertical grounding electrode buried in uniform soil, injected with double exponential current waveform

B. *Frequency Dependence of Soil Parameters*

The proposed frequency dependence of soil model discussed in this section is Scott model which is used in the analysis due to its accuracy by producing promising results based on the previous studies [8, 9]. The expression of conductivity, $\sigma(f)$ and relative permittivity, $\varepsilon_r(f)$ as a function of frequency proposed by Scott are given by (5) and (6) respectively.

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

$$\varepsilon_r(f) = 5.491 + 0.946 \log_{10}(\sigma_0) - 1.097 \log_{10}(f) + 0.069 \log_{10}^2(\sigma_0) - 0.114 \log_{10}(f) \log_{10}(\sigma_0) + 0.067 \log_{10}^2(f) \quad (6)$$

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).

Based on the graph in Fig.3, it shows that soil conductivity varies over the range of frequency of 100 Hz to 1MHz, where it increases with the frequency. It is highly affected by the frequency as it increases abruptly at higher frequency of 10 kHz to 1 MHz. The relative permittivity also is highly affected by the frequency, where it decreases when the frequency increases as shown in Fig. 4. The frequency dependent permittivity values are very different to the common assumed values of 10-20. The assumed values are only found at frequency of 100 kHz to

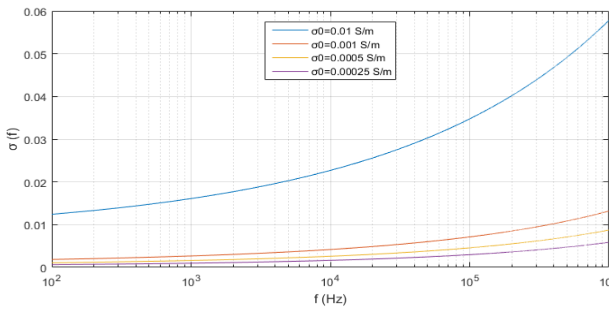

Fig 3. Variation of soil conductivity with frequency

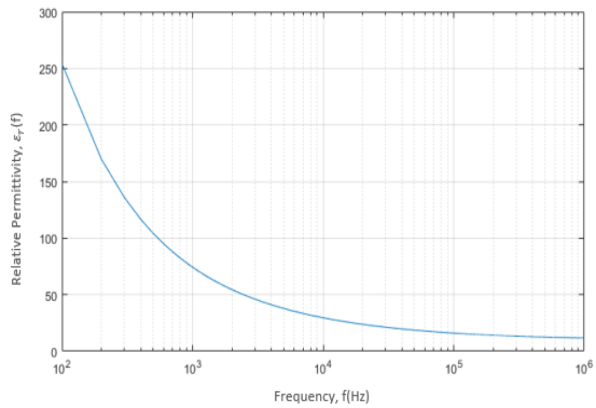

Fig 4. Soil relative permittivity of 15m long vertical grounding electrode with radius of 0.01m, buried in 1m depth, and soil conductivity of 0.01 S/m, with frequency variation

1 MHz where it is obviously higher for the frequency below 100 kHz.

Due to the difficulties in integrating the frequency in circuit-based model, an equivalent frequency is calculated and used for the analysis as proposed by [8]. The equivalent frequency is calculated by considering the front time of the current, which contribute to the different in the value of the peak voltage given by equation (7).

$$f_{eq} = \tfrac{1}{4}(T_f) \quad (7)$$

where f_{eq} is the equivalent frequency (in Hertz) and T_f is the front time of the current (in seconds).

The equivalent frequency is used in the Scott model to determine the frequency dependent soil conductivity and relative permittivity using equations (5) and (6) respectively. Then, a frequency dependent circuit is produced based on the equations (2), (3), and (4).

III. Results and Discussion

In this work, a 15 m long vertical grounding electrode, with 0.01 m radius, buried in 1 m depth is considered. The soil relative permittivity is assumed to be constant which is 10, and the soil resistivity is set to several different values (100 Ωm, 300 Ωm, and 1000 Ωm). The vertical grounding electrode is injected at a point by a double exponential lightning current waveform with 10 kA amplitude, and 1 µs front time. The expression of the double exponential current is given by $i(t)=10.244(e^{-20000t}-e^{-5500000t})$ kA.

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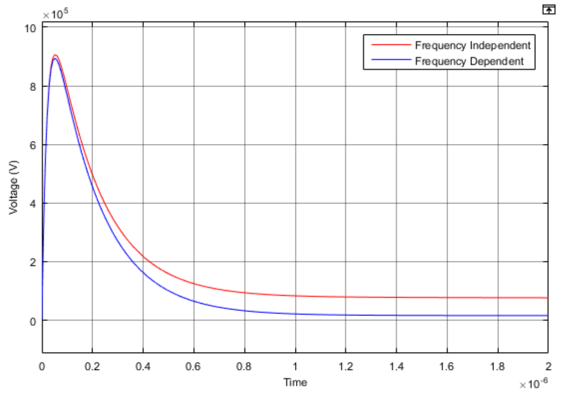
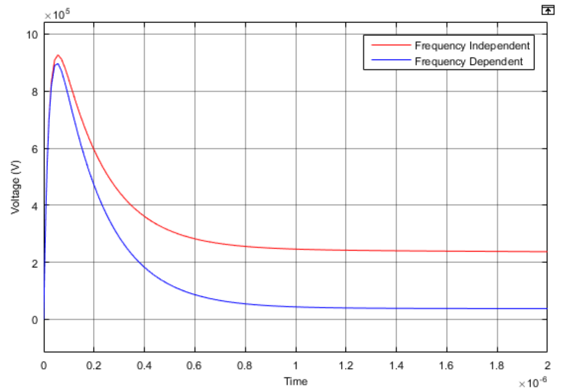
TABLE I. PEAK VOLTAGE OF FREQUENCY INDEPENDENT AND FREQUENCY DEPENDENT MODEL OF VERTICAL GROUNDING ELECTRODE

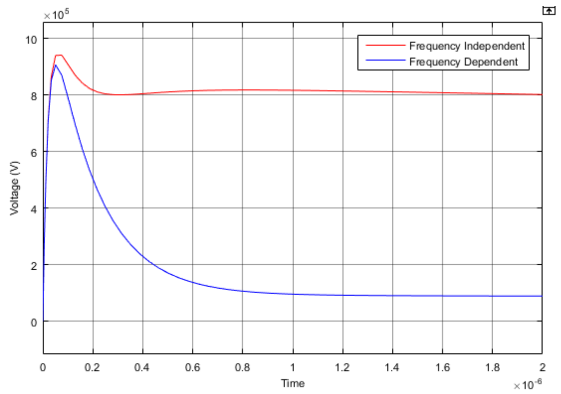
Parameters	**Frequency Independent**			**Frequency Dependent**		
Soil Resistivity, ρ (Ω.m)	100	300	1000	100	300	1000
Peak Voltage, Vp (kV)	906.8	926.8	940.8	894.0	896.8	906.5



(a) ρ = 100 Ωm



(b) ρ = 300 Ωm



(c) ρ = 1000 Ωm

Fig 5. Voltage response of 15 m long vertical grounding electrode with 0.01 m radius, buried in 1 m depth of uniform soil, injected with a double exponential current waveform of 10 kA amplitude and 1 µs front time for different soil resistivity (a) ρ=100Ωm, (b) ρ = 300 Ω.m, and (c) ρ = 1000 Ω.m

Based on the results in Fig. 5, the effect of soil resistivity variation (100 Ωm, 300 Ωm, 1000 Ωm) is to increase the difference in voltage response between frequency independent and frequency dependent circuit-based model of vertical grounding electrode at the point of injection. Table 1 shows the results obtained for the transient analysis between the frequency independent and frequency dependent model. The difference in peak between the response is 1.41% (Vpeak frequency independent = 906.8 kV compared to Vpeak frequency dependent = 894.0 kV) for soil resistivity of 100 Ωm. The difference in peak between the response increase to 3.23% (Vpeak frequency independent = 926.8 kV compared to Vpeak frequency dependent = 896.8 kV) for soil resistivity of 300 Ωm. It shows that the result has higher error when soil resistivity increase. At high soil resistivity case of 1000 Ωm, the difference in peak is 3.65% (Vpeak frequency independent = 940.8 kV compared to Vpeak frequency dependent = 906.5 kV) Overall, the error is more significant at higher soil resistivity.

IV. APPLICATION

To further validate the results, a 30 m long horizontal grounding electrode with 0.01 m radius buried in 1 m depth was considered. The vertical grounding electrode was injected at a point by a double exponential waveform with 12 kA amplitude and 0.8 µs front time. The current is given by given by $i(t)=39.9(e^{-759000t}-e^{-1761000t})$ kA. For frequency independent model, the soil relative permittivity is assumed to be constant of 15. The analysis was done by considering soil resistivity of 10 Ωm and 1000 Ωm. These values were chosen to observe on how significant the difference of voltage response between a very low soil resistivity and high soil resistivity value for both frequency independent and independent model.

Based on the results obtained, it shows a significant difference between the response at low soil resistivity and high soil resistivity. Table 2 reveals the results obtained from the analysis, where it is found that the difference between the response at ρ=10 Ωm in Fig. 6(a) is much smaller compared to response at ρ=1000 Ωm in Fig. 6(b). The difference in peak between the response is 0.07% (Vpeak frequency independent = 1387 kV compared to Vpeak frequency dependent = 1386 kV) for soil resistivity of 10 Ωm, while 3.32% (Vpeak frequency independent = 1447 kV compared to Vpeak frequency dependent = 1399 kV) for soil resistivity of 1000 Ωm. It shows that neglecting the frequency dependent effect leads to inaccurate results especially at higher soil resistivity.

TABLE II. PEAK VOLTAGE OF FREQUENCY INDEPENDENT AND FREQUENCY DEPENDENT MODEL OF VERTICAL GROUNDING ELECTRODE

Parameters	**Frequency independent**		**Frequency dependent**	
Soil Resistivity, ρ (Ω.m)	10	1000	10	1000
Peak Voltage, Vp (kV)	1387	1447	1386	1399

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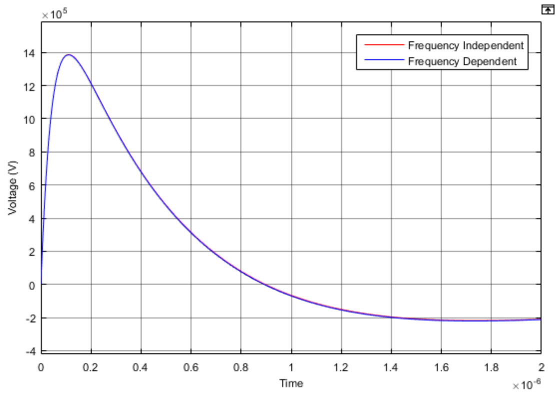
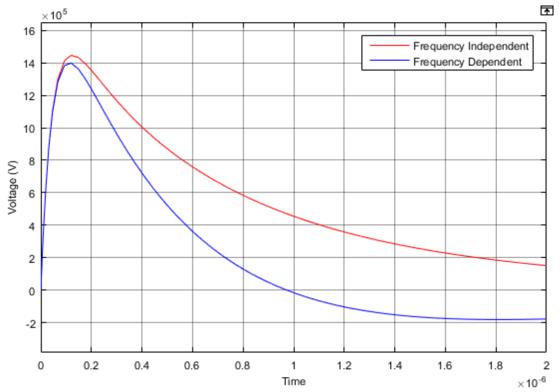


(a) ρ = 10 Ωm



(b) ρ = 1000 Ωm

Fig 6. Voltage response of frequency independent and frequency dependent model of 30 m long horizontal grounding electrode injected with double exponential current with soil resistivity of ρ = 10 Ω.m and ρ = 1000 Ω.m

It is noticed that the error for frequency dependent circuit at lower soil resistivity is still a very much smaller which is in good agreement compared to at higher soil resistivity value, where the frequency independent circuit at high resistivity provides overestimated results.

V. Conclusion

The circuit-based model of grounding electrodes with frequency dependent soil was successfully modelled. The values of soil resistivity and permittivity decrease with the applied frequency. Consequently, this has caused the grounding electrode voltage response to be significantly affected (up to 4% decrease in grounding electrode voltage), especially for soil with high resistivity (1 kΩ.m and above). Thus, it can be concluded that, instead of assuming constant values, the effects of frequency on the soil resistivity and permittivity need to be considered when determining the transient performance of a grounding electrode.

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