IMPROVED CIRCUIT-BASED GROUNDING ELECTRODE MODEL CONSIDERING FREQUENCY DEPENDENCY OF SOIL PARAMETERS

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DEDICATION

This thesis is dedicated to my father, who taught me that the best kind of knowledge to have is that which is learned for its own sake. It is also dedicated to my mother, who taught me that even the largest task can be accomplished if it is done one step at a time.

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ABSTRACT

A lightning protection system (LPS) provides protection against possible losses in human lives, services to the public, cultural heritages, and economic values. Good performance of a grounding system, which is a crucial part in the LPS, is vital for the overall performance of the LPS. Various attempts have previously been made to improve the grounding performance by means of experimental and simulation work, including the continuous improvement made to achieve a better grounding electrode model. The circuit-based grounding electrode model is known for its simplicity, computational efficiency, and compatibility with many leading software. However, previous circuit-based models neglect the frequency dependence effect due to difficulties in computation and overall formulation. This work aimed to improve the circuit-based model of grounding electrodes by taking frequency dependent soil into consideration. Two main equations, as proposed by Dwight and Sunde and by Scott, were used to model a horizontally laid grounding electrode. The frequency domain approach was chosen for the simulation of the transient performance of the grounding electrode using Current Distribution, Electromagnetic Fields, Grounding and Soil Structure Analysis (CDEGS), while Matrix Laboratory (MATLAB) was used to solve the frequency dependent equations. The performance of the developed frequency dependent soil model was compared to that of the frequency independent model. For the case of high soil resistivity (2000 Ωm), the frequency dependent model gave a 75.2% lower ground potential rise (GPR) than that of the frequency independent model. Analyses were also carried out to determine the effects of the current front time on the grounding electrode voltage response using both models. Again, for a soil resistivity of 2000 Ωm and current front time of 1 μs, a 75.2% difference was recorded between the two models. The differences were lower for the case of 10 μs and 20 μs current front times. The consideration of soil frequency dependence on the effects of other parameters such as electrode length, burial depth, and soil profile, was also studied. It was found that the GPR at the grounding electrode experienced a reduction in value as the frequency was considered compared to that of when the frequency was not considered. In short, this work has successfully developed an improved and reliable circuit-based grounding electrode model with the effect of frequency taken into consideration and hence it is more suitable for accurate transient analysis.

ABSTRAK

Sistem perlindungan kilat (LPS) memberikan perlindungan terhadap kemungkinan kehilangan nyawa manusia, perkhidmatan kepada masyarakat, warisan budaya, dan nilai ekonomi. Prestasi sistem pembumian yang baik, yang merupakan bahagian utama dalam LPS, sangat penting untuk prestasi keseluruhan LPS. Pelbagai usaha sebelum ini telah dilakukan untuk meningkatkan prestasi pembumian dengan cara kerja eksperiment dan simulasi, termasuk penambahbaikan yang terus dilakukan untuk mencapai model elektrod pembumian yang lebih baik. Model elektrod pembumian berasaskan litar terkenal dengan kesederhanaan, kecekapan komputasi, dan keserasian dengan banyak perisian terkemuka. Walau bagaimanapun, model berasaskan litar sebelum ini mengabaikan kesan kebergantungan frekuensi kerana kesukaran dalam pengiraan dan perumusan keseluruhan. Kerja ini bertujuan untuk memperbaiki model elektrod pembumian berasaskan litar dengan mempertimbangkan ciri tanah yang bergantung pada frekuensi. Dua persamaan utama, seperti yang diusulkan oleh Dwight dan Sunde dan oleh Scott, digunakan untuk memodelkan elektrod pembumian secara mendatar. Pendekatan domain frekuensi dipilih untuk menjalankan simulasi prestasi fana elektrod pembumian melalui perisian CDEGS, sementara perisian MATLAB digunakan untuk menyelesaikan persamaan yang bergantung pada frekuensi. Prestasi model tanah bergantung frekuensi yang telah dibangunkan dibandingkan dengan model bebas frekuensi. Didapati bahawa kesan frekuensi pada kenaikan potensi (GPR) tanah elektrod memberikan nilai 75.2% lebih rendah bagi kes kerintangan tanah yang tinggi (2000 Ωm). Analisis juga dilakukan untuk mengetahui kesan masa hadapan arus pada tindak balas voltan elektrod pembumian menggunakan kedua-dua model. Sekali lagi, untuk kerintangan tanah 2000 Ωm dan masa hadapan arus 1 μs, perbezaan 75.2% dicatatkan antara kedua-dua model. Perbezaannya lebih rendah untuk kes masa hadapan arus 10 μs dan 20 μs. Pertimbangan kebergantungan frekuensi tanah pada kesan parameter lain seperti panjang elektrod, kedalaman pembumian, dan profil tanah, juga dikaji. Didapati bahawa GPR pada elektrod pembumian mengalami penurunan nilai apabila frekuensi diambil kira dibandingkan dengan ketika frekuensi tidak dipertimbangkan. Pendek kata, kerja ini berjaya membangunkan model elektrod pembumian berasaskan litar yang ditambah baik dan boleh dipercayai dengan kesan frekuensi dipertimbangkan dan oleh itu ia lebih sesuai untuk analisis fana yang tepat.

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LIST OF ABBREVIATIONS

LPS	-	Lightning Protection System
CDEGS	-	Current Distribution, Electromagnetic Fields, Grounding and Soil Structure Analysis
ATP/EMTP	-	Electromagnetic Transient Program
TLM	-	Transmission Line Model
EMF	-	Electromagnetic Field Model
MoM	-	Method of Moment
FFT	-	Fast Fourier Transform
HEM	-	Hybrid Electromagnetic Field Model
ECM	-	Electromagnetic Computation Methods
FEM	-	Finite Element Method
FDTD	-	Finite Difference Time Domain
PEEC	-	Partial Element Equivalent Circuit
MIM	-	Modified Image Method
GPR	-	Ground Potential Rise
IFFT	-	Inverse Fast Fourier Transform
AC	-	Alternating Current
DC	-	Direct Current
JOBID	-	Create new job ID to start new project on CDEGS (HIFREQ)

LIST OF SYMBOLS

R	-	Resistor
L	-	Inductor
C	-	Capacitor
g	-	Distributed Conductance
r	-	Distributed Metallic Wire Resistance
Ω	-	Ohm
a	-	Radius
l	-	Length
d	-	Depth
ρ	-	Soil Resistivity
μ	-	Soil Permeability
ε	-	Soil Permittivity
n	-	Number of Section
m	-	Number of Column
n	-	Number of Row
σ	-	Conductivity
f	-	Frequency
ε_∞	-	High Frequency Limit of Dielectric Constant
m	-	Meter
f_{eq}	-	Equivalent Frequency
T_f	-	Front Time
$i(t)$	-	Current
α, β	-	Coefficient
I_m	-	Current Amplitude
A	-	Ampere
s	-	Second
Vp	-	Peak Voltage
Hz	-	Hertz
ρ_0	-	Nominal Soil Resistivity

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Grounding systems in the form of horizontal, vertical or grid electrodes, is an important part in a Lightning Protection System (LPS) [1, 2] of a given structure. When lightning strikes the LPS, the high return stroke current disperses into the ground through the grounding system. The resultant ground potential rise (GPR) at the ground entry point as well as touch and step potentials are dependent on the ground resistance value of the grounding system. Thus, a good grounding system with low resistance value for a given LPS is crucial for human safety and protection of electrical equipment. Among the grounding system design challenges are for areas with high soil resistivity, such as in rocky areas, and limitation of reach in terms of width and depth of electrode burial.

Until now, many studies had been conducted to improve the overall grounding system performance. Several issues were pursued. One of the crucial studies is the transient response of a grounding system using mathematical and theoretical modelling of the buried grounding system. Three most popular approaches to grounding system models developed by the researchers are known as the circuit-based, the transmission line, and the electromagnetic field [3-5] techniques. In the circuit-based model, the parameters involved are the traditional R, L and C, and the solution is based on the nodal analysis utilising Kirchhoff's Laws. In contrast, the transmission line model consists of R, L, C, g (distributed conductance) and r (distributed metallic wire resistance), and its solution is based on the so-called Telegrapher's equation. On the other hand, the electromagnetic field model is based on the solution to a rather complex set of Maxwell equations and hence rather difficult to compute, or it requires a rather long computation time.

Over the years, various attempts had been made to achieve a better transient response from each grounding electrode model, nearing its actual behaviour in real life. These attempts include various improvements made to the respective models while addressing issues such as model complexity, accuracy and applicability for various electrode configurations and soil conditions. In spite of these research, further improvements on the proposed models can still be made, for example, by investigating and considering several key factors not previously considered.

1.2 Research Background

The first and foremost in designing a grounding system is to determine the configuration of the grounding electrodes to be used for that grounding system. The most commonly used grounding electrode configurations are in the form of horizontal or vertical rods, horizontal rings, and grids. More often than not, a combination of electrode configuration is also used, for example, a ring structure with connected vertical rods in order to fulfil the minimum grounding conductor length requirement. The electrodes are usually made of copper, copper-clad steel, steel, or aluminium. While the choice of electrode material is mainly dependent on the tolerable corrosion level, the choice of electrode configuration is dependent on the size of the available soil space, for instance, a vertical electrode is preferable to be installed in a smaller or limited space area [6].

As previously mentioned, the grounding electrode which makes the grounding system for a given structure, is commonly buried in the ground. The grounding system is connected to the equipment, or the air terminations for the case of a Lightning Protection System, with down leads or down conductors, and thereby creating a path for the transient and fault current to dissipate. The main function of the grounding system is to create a path or interface for the lightning and fault currents to dissipate into the ground, or earth, and hence making sure that the potential rise in the grounding system due to the current flow is within safe limit. To achieve safe voltage rise limit, a very low grounding resistance is needed in the grounding system design, where ideally, the resistance value needed is 0 Ω. However, the ideal value is impossible to practically get, therefore, the grounding system is usually designed with the lowest grounding resistance possible by considering other grounding parameters. It is noted that several factors affect the resultant grounding resistance value of a given grounding system. Therefore, it is crucial to study and analyse a given grounding system design in various extreme conditions so as to optimize the protection provided by the grounding system.

As previously stated, several factors affecting the grounding system performance need to be considered when designing a grounding system. These factors include the soil condition, moisture content, temperature, ionization effect, current waveform, and discharging current frequency. Many research and studies have been previously made to improve the performance of the grounding system by taking into consideration these factors and through various methods, and it is noted that computational modelling is one of the popular methods used.

It is noted that the effects of discharging current frequency on the grounding system performance are often neglected in many transient analyses. In other words, the dependency of the soil properties, namely, the soil resistivity and permittivity, on the discharging current frequency is neglected. The soil is more often than not modelled as having constant resistivity and permittivity regardless of the discharging current waveshape or frequency. One of the reasons for this is due to the difficulties to include the frequency dependency in the soil model for the grounding system. This in turn, becomes one of the contributing factors to the poor performance of the developed grounding system [7] if its design is based on an approximate grounding system model. In addition, grounding systems are usually designed for power frequency condition only. However, many studies have proven that the response of a grounding system becomes different when injected with an impulse or transient current.

It is known that discharging current frequency has an effect on the behaviour of the soil through which the current dissipates. An increase in the discharging current frequency results in a decrease in the conductivity and permittivity of the soil. A change in the soil properties will definitely affect the grounding resistance or impedance of the buried grounding system. A neglect of this effect can definitely cause the grounding system design to be incomplete, especially for the case of switching and transient currents, such as that from lightning discharge. Hence it can be said that the influence of frequency on a grounding system design cannot be neglected especially for high frequency applications such as in lightning current discharges [8].

1.3 Problem Statement

As mentioned before, grounding system, or the buried electrode under the soil is crucial and important to provide the health and safety for the staff occupied at high-voltage substations, power plants and industrial areas. A good grounding system can prevent unauthorized step voltage and touch voltage that faces human health at risk, and provide the same common reference potential for all electrical and electronic components, especially protective equipment connected to the power grid. Therefore, a good grounding system model is crucial for the real system to be fully functional, and hence provide protection to human and also electrical equipment as expected.

The circuit-based model is known to be the simplest grounding electrode model compared to other models, namely, the electromagnetic field, transmission line, and hybrid models. The circuit-based model is made up of simple equations for the circuit components and the model can be incorporated in many transient programs such as CDEGS, ATP/EMTP, and MATLAB. However, its major drawback is that its accuracy is less than those of other models. Attempts to improve the circuit-based model have been done by many researchers by considering key parameters which have not been previously taken into account, including the soil ionization effect, current rate of rise, and the frequency dependency of soil resistivity and permittivity. The significance of considering the frequency dependency of soil resistivity and permittivity, instead of using constant soil properties, that is at a frequency equal to the power frequency, has been highlighted in several studies. Nevertheless, the frequency dependency is often neglected in the transient performance analysis of grounding electrodes due to the complexity involved in the frequency dependence formulation and computation difficulties. In other words, when analysing the transient performance of grounding electrodes, the effects of frequency variation, especially when the frequencies are much higher than the power frequency, are often neglected. In fact, the soil conductivity and permittivity are often assumed to be constant and independent of frequency. Because of this, when using such a frequency independent model, some errors in the voltage response still exist. An attempt to improve such a circuit-based model was previously done by Mehrdad by considering the frequency dependency. However, this was obtained by using an equivalent and constant frequency to represent the improved model. There is still a need to come up with a fully frequency dependent soil model where the frequency is not fixed to a single equivalent frequency. Hence, there is a need to develop and validate a new circuit-based model for grounding electrodes that actually takes into account the effect of frequency variation when computing the grounding electrode voltage response.

Because of the absence of adequate studies, the relationship between the effects of frequency variation and the effects of grounding parameter variation is not clearly known. In other words, how sensitive is the frequency dependency on the voltage response due to changes in grounding parameters such as the soil resistivity and the electrode configuration. This deserves a further detailed study.

1.4 Research Objectives

The main aim of this work is to develop and validate a new circuit-based model for a grounding electrode with a consideration of frequency dependency of the soil conductivity and permittivity.

To achieve the above aim, the following objectives are listed:

1. To develop a new circuit-based model for a grounding electrode with frequency dependent features of the soil properties.

2. To determine the sensitivity of the developed model with further analyses on the effects of frequency on the voltage response when several grounding electrode parameters are also varied.

3. To validate the proposed model by comparing the performance in terms of voltage response of the improved model with other published work, where the electrode parameters and the injected current are the same.

1.5 Scope of Work

In the process of completing this work, there are few limitations that will be highlighted in this section. Firstly, this study is only limited to a single horizontal grounding electrode. Secondly, for the case of impulse waveshape, a 10kA, 1/35μs lightning impulse current will be used throughout which is the condition to be analysed in this study. Thirdly, the frequency dependency of the soil properties is the only non-linear properties considered in this work, while other phenomena, such as the soil ionization, are not considered. This is due to the limitation in the CDEGS software used, where the soil ionization could not be included in the software simulation. Fourthly, the type of soil used in the analyses is a homogeneous soil, hence this work does not cover non-homogeneous soil.

1.6 Research Contribution

The contributions of the research are as follow:

i. A new frequency dependent circuit-based model for grounding electrode

This work has successfully modelled the influence of frequency on the grounding electrode performance in terms of the electrode resultant impedance and its corresponding voltage response. The developed grounding electrode model consists of three components such as a resistor, inductor, and a capacitor as a circuit which represents the electrode model. It is shown in this study that the electrode grounding impedance and its voltage response are significantly affected as the frequency dependency of soil resistivity and permittivity are considered. This work has also successfully produced an improved circuit-based model taking into consideration the frequency dependency. As a result, the accuracy of the voltage response is improved. This is in contrast to the conventional model which neglects the effect of frequency.

ii. *Sensitivity of frequency dependency on grounding electrode parameter variation*

Other electrode parameters such as electrode length, burial depth, soil profile, and also different types of current are varied to further analyse the frequency dependency of soil parameters. For the electrode length and burial depth variation, the outcomes are as predicted where the longer the electrode or the deeper the burial depth, the better. But when considering frequency, more accurate results can be obtained and prevent overestimated results. By comparing with different types of current (impulse, AC and DC), it is found that the impulse current is the most affected or the most sensitive by frequency where it shows the largest difference when compared to the frequency independent model. For soil profile variation, it is noticed that the effect of frequency is seen only when the second layer of the soil is frequency dependent while the first layer is not. When the first layer is frequency dependent, while the second layer is not, the voltage responses are the same.

iii. *Validation and comparative performance of the proposed model*

This work has also successfully compared the performance of the improved model with its predictions thoroughly, and the comparison study with previous works has validated this work. By comparing with the frequency independent model, it is found that the improved model with the frequency included gives much lower voltage response, which indicates that neglecting frequency effects will give overestimated results. The improved model also compared to the previous work which used the equivalent frequency in the transient analysis. Based on this comparison, it is noticed that the voltage response given by the equivalent frequency model gives lower response, which might be an underestimated result as compared to the improved model.

1.7 Research Significance

The significance of the research carried out in this work can be stated as follows. The research has enabled the modelling of frequency-dependent soil in the computation of potential rise due to the lightning impulse current flowing in a grounding electrode. Results of this research show that the potential rise, and hence the step and touch potentials, are overestimated when the soil frequency-dependency is not taken into account. This means a grounding electrode actually performs better when the soil is modelled as frequency-dependent compared to when it is not. There is a potential of an optimised design and savings in cost if this new information is considered when designing a grounding system for a lightning protection system of a given structure or installation.

1.8 Thesis Organisation

The main idea of this work is to improve the circuit-based model in the transient performance analysis, and the outcome of this study will eventually help other researchers in their grounding system analysis. This dissertation consists of five chapters which are Introduction (Chapter 1), Literature Review (Chapter 2), Research Methodology (Chapter 3), Results and Discussion (Chapter 4), and lastly, Conclusion (Chapter 5). In the first chapter, a brief discussion on the background of the study is presented to give the reader a picture of the whole work. This chapter is the most important part where the problem statement, objectives of the work, and the contributions were stated and discussed.

In chapter 2, a background of the grounding system is presented with more detailed explanation including the grounding system models, frequency dependence of soil parameters as well as frequency dependent models, and modelling methods.

Grounding electrode models such as the circuit-based model, transmission line model, electromagnetic field model, and hybrid model, are discussed and compared in this chapter. A review on the frequency dependent models such as the Scott model, Smith-Longmire model, and Visacro-Alipio model are also discussed, and a comparison study is made to choose the best model for the analysis.

The following chapter is chapter 3 which is the research methodology, where it consists of detailed explanation on the step by step taken in developing the improved model. Equations and formulas used in the analysis for the circuit-based model and the frequency dependent model are presented in this chapter. The simulation work using CDEGS is briefly described with detailed explanation of every section and parameters involved including the FFT and IFFT processes.

Results obtained from the simulation are analysed and discussed in chapter 4. In the first section, results of the transient response of a horizontal grounding electrode with frequency dependency of soil resistivity and relative permittivity are presented and discussed. Further analysis on the effect of frequency dependency of soil parameters is given in the following section by considering the current front time, type of injected current, and other electrode characteristics such as electrode length, burial depth, and soil profile. Previous work by other researchers is compared with that of this study in order to validate the results obtained.

After the findings of the work have been presented and discussed, Chapter 5 concludes all the findings and analyses. This chapter also states the limitations of the study and provides recommendations for researchers to further improve the work on the transient performance of grounding electrodes.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Grounding electrodes are part of key components in a Lightning Protection System (LPS). The most common grounding electrodes used are the horizontal and vertical rods, as shown in Figure 2.1. Accurate design enhancing modelling of a grounding electrode is crucial to ensure the proper functioning of the LPS for the safety of people and properties, including electrical equipment. This chapter reviews and discusses the grounding electrode modelling, frequency dependency of soil parameters and their models, and relevant modelling techniques.

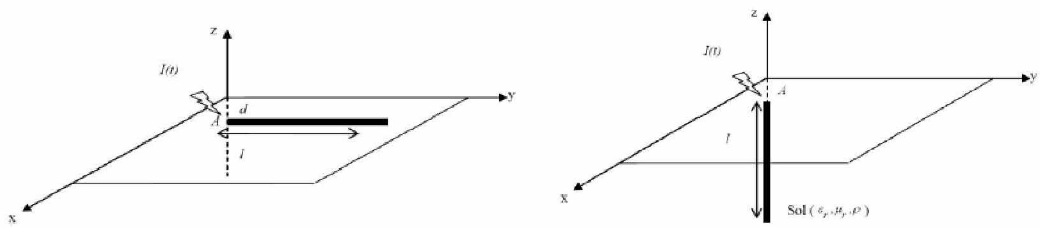

Figure 2.1 Horizontal and vertical grounding electrode configuration [2]

Specifically, various grounding electrode models, namely the circuit based-models, transmission line model, electromagnetic field model, and hybrid model, are critically reviewed. Main focuses are also given to the fundamentals of the models' advantages and disadvantages. The review of the modelling techniques includes the time domain and frequency domain methods.

2.2 Grounding System Modelling

Attempts to obtain more precise grounding systems have been made in the past few years with well-known modelling approaches such as circuit-based model, transmission line model (TLM), electromagnetic model (EMF), and hybrid model. This section will further discuss each of these model's pros and cons.

2.2.1 Circuit-based Model

The circuit-based model is simple and easy to develop and use for transient analysis of grounding electrodes. It consists of three components: resistance, *R*, inductance, *L*, and capacitance, *C*. The circuit-based model is represented by a lumped or distributed circuit. The lumped circuit was first introduced by Rudenberg [9] for transient performance analysis. Meliopoulos [10] in his study had proposed a circuit model for the transient response analysis of grounding systems consisting of ground mats and ground rods, by applying Laplace's equation to solve the parameters of the developed model. The circuit model was then extended in its application by considering the nonlinear ionization phenomenon, as described by Geri [11]. In a recent research, Mehrdad [1] proposed an improved circuit-based model for transient analysis of grounding electrodes by taking account of the soil ionization and current rate of rising, thus solving the previously known accuracy problem for the circuit model.

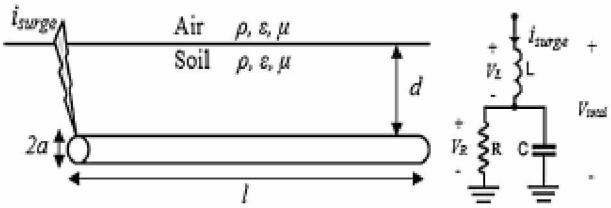

Figure 2.2 Equivalent lumped circuit representing grounding electrode [1]

Figure 2.2 shows the equivalent lumped circuit consisting of *R*, *L*, and *C*, representing the grounding electrode with radius, *a*, length, *l*, and depth, *d*, buried in

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Indexed Journal

1. Elgayar, A., Abdul-Malek, Z., Othman, R., Elshami, I. F., Elbreki, A. M., Ibrahim, V. M., ... & Wooi, C. L. (2019). Power transmission lines electromagnetic pollution with consideration of soil resistivity. Telkomnika, 17(4), 1985-1991.

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1. Othman, R., & Abdul-Malek, Z. (2018, October). An Improved Circuit-Based Grounding Electrode Considering Frequency Dependence of Soil Parameters. In 2018 International Conference on Electrical Engineering and Computer Science (ICECOS) (pp. 271-274). IEEE.

2. Othman, R., Abdul-Malek, Z., Jambak, M.I., Nawawi, Z. and Sidik, M.A.B. (2020). Circuit-Based Model Grounding Electrode Considering Frequency Dependent of Soil Resistivity and Relative Permittivity. In Advances in Electronics Engineering (pp. 87-92). Springer, Singapore.