CIRCUIT–BASED TRANSIENT MODEL OF GROUNDING ELECTRODE WITH CONSIDERATION OF SOIL IONIZATION AND CURRENT RATE–OF–RISE FACTORS

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DEDICATION

To my wife Sepideh, to my daughter Bahar, and to my parents

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ABSTRACT

The behaviour of a grounding electrode can be predicted by using either the electrical circuit model or electromagnetic computation. Despite its advantages over the latter, the grounding circuit model fails to accurately predict the behaviour under transient conditions due to the absence of two key factors, namely the soil ionization, and the current rate–of–rise. A new equivalent circuit model of a grounding electrode with dynamic circuit elements (R_d, C_d, and L_d) was developed to consider both soil ionization and current rate–of–rise factors. A generalized formula was derived to calculate the dynamic inductance, L_d, for all standard current wave shapes such as *Conseil International des Grands Réseaux Électriques* (CIGRE), double–exponential, and IEC 62305–1 (International Electrotechnical Commission). The computed inductance, L_d, dynamically changes with the change in the lightning current parameters, thus improving its accuracy for all current rate–of–rise conditions. The consideration for the soil ionization effect on grounding electrode resistance, R_d, and soil capacitance, C_d, within the equivalent circuit model was achieved by modelling the soil with a network of two layer capacitors (TLC) in which soil particles and air voids are the TLC components. Differential equations were derived to incorporate the soil ionization phenomenon inside the TLC network. The voltage response of the new equivalent circuit model and the dynamic circuit elements were determined by using the above–suggested methods, is more accurate than that of the conventionally determined grounding circuit models. The overall differences between the equivalent circuit model and several experiments are 3.3% for the electrode resistance and 2.8% for the electrode peak voltage. The new equivalent circuit model helps to optimize the overall grounding electrode design, and to provide a better fast transient protection and insulation coordination.

ABSTRAK

Tingkah laku elektrod pembumian boleh diramal dengan menggunakan sama ada model litar elektrik atau menggunakan pengiraan elektromagnetik. Walaupun mempunyai kelebihan dari yang kedua, model litar pembumian gagal untuk meramal dengan tepat kelakuan pada keadaan fana disebabkan ketiadaan dua faktor iaitu pengionan tanah dan juga kadar kenaikan arus. Satu model litar setara yang baru yang mempunyai unsur litar yang dinamik (R_d, C_d, dan L_d) telah dibangunkan untuk mengambil kira kedua–dua faktor iaitu pengionan tanah dan juga kadar kenaikan arus. Satu formula umum telah diterbitkan untuk mengira kearuhan dinamik, L_d, untuk kesemua bentuk gelombang arus piawai seperti *Conseil International des Grands Réseaux Électriques* (CIGRE), eksponen kembar dan IEC 62305–1 (International Electrotechnical Commission). Kearuhan L_d yang dikira secara dinamiknya berubah dengan perubahan parameter arus kilat, seterusnya ia meningkatan ketepatan pada kesemua keadaan kadar kenaikan arus. Kesan pengionan tanah pada perintang elektrod pembumian, R_d, dan kemuatan tanah, C_d, di dalam model litar setara telah dicapai dengan memodelkan tanah menggunakan kapasitor dua lapisan (TLC) di mana zarah tanah dan juga lompang udara adalah komponen TLC. Persamaan pembezaan diterbitkan untuk menggabungkan fenomena pengionan tanah di dalam rangkaian TLC ini. Sambutan voltan model litar setara baru di mana elemen litar dinamiknya ditentukan dengan menggunakan kaedah yang disyorkan di atas, adalah lebih tepat daripada model litar pembumian konvensional. Perbezaan keseluruhan di antara model litar setara dan beberapa uji kaji ialah 3.3% untuk rintangan elektrod dan 2.8% untuk voltan puncak elektrod. Model litar setara baru ini membantu untuk mengoptimumkan reka bentuk elektrod pembumian secara keseluruhan, dan untuk menghasilkan perlindungan dan koordinasi penebatan fana pantas yang lebih baik.

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LIST OF SYMBOLS

a – Physical electrode radius
a_{eq} – Equivalent electrode radius
L – Electrode inductance
n – Maximum number of consecutive TLCs along which soil ionization occurs
q – Electric charge
Q – Total electric charge
R – Low current and low frequency grounding electrode resistance
x – Soil ionization length
a_{eq} – Equivalent radius
A_{arc} – Area of the arc channel
C_d – Dynamic capacitance
C_g – Soil capacitance of non–ionized region
C_{1i} – Soil capacitance of ionized region
d_a – Length of air void
d_s – Length of soil particle
d_{TLC} – Length of TLC
E_a – Electric field in air void
E_{arc} – Electric field intensity in arc channel
E_s – Electric field in soil particle
J_a – Current density in air void
J_s – Current density in soil particle
k_μ – Electron mobility
L_d – Dynamic inductance

$P_a(t)$ – Instantaneous heat power absorbed by the soil

$P_b(t)$ – Instantaneous heat power balance in the arc channel

$P_p(t)$ – Instantaneous heat power produced in the arc channel

Q_b – Heat energy balance

R_d – Dynamic resistance

R_g – Soil resistance of non–ionized region

$R_G(t)$ – Dynamic grounding electrode resistance

$R_{1i\text{–}arc}$ – Arc resistance

$R_{1i\text{–}soil}$ – Soil resistance of ionized region

T_{br} – Time to breakdown

T_f – Current front time

T_h – Current half value

t_i – Required time for air breakdown

t_u – Sufficient voltage breakdown time

U_a – Voltage across the air void

U_s – Voltage across the soil particle

U_{sa} – Voltage across a TLC

$v(t)$ – Grounding electrode voltage at current injection point

x_{max} – Maximum soil ionization length

$Z_{1i}(t)$ – Equivalent impedance of the parallel elements $R_{1i\text{–}soil}(t)$, $R_{1i\text{–}arc}(t)$, and $C_{1i}(t)$

Z_g – Equivalent impedance of the parallel elements R_g and C_g

ε – Permittivity

σ – Conductivity

ρ – Soil resistivity

τ – Time constant

ε_s – Soil permittivity

ε_a – Air permittivity

σ_s – Soil particle conductivity

σ_a – Air conductivity

σ_{arc} – Arc conductivity

$\sigma_{arc}(t)$ – Time dependent arc conductance

v_d – Electron drift velocity

LIST OF ABBREVIATIONS

CDEGS	–	Current Distribution, Electromagnetic Fields, Grounding, and Soil Structure Analysis
CIGRE	–	The International Council on Large Electric Systems (in French: Conseil International des Grands Réseaux Électriques, abbreviated CIGRÉ)
DBN	–	Distance Between Nodes
DBP	–	Distance Between Points
DFS	–	Distance From Surface
EM	–	Electromagnetic Approach
EM–MoM	–	Electromagnetic Approach with Method of Moment
EMTP	–	Electromagnetic Transient Program
FFT	–	Fast Fourier Transform
IEC	–	The International Electrotechnical Commission
IEEE	–	The Institute of Electrical and Electronics Engineers
IFFT	–	Inverse Fast Fourier Transform
MATLAB	–	Matrix Laboratory
MoM	–	Method of Moment
PSCAD	–	Power System Computer Aided Design
TLC	–	Two–Layer Capacitor

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CHAPTER 1

INTRODUCTION

1.1 Research Background

Grounding electrodes are used to efficiently disperse the high amplitude currents in the event of power system faults or lightning strikes. In addition, they are also important to ensure low and safe ground voltage levels are maintained. A typical configuration of a single grounding electrode is a buried horizontal electrode (counterpoises) or a driven vertical electrode (rod). The current that flows through these electrodes, especially due to lightning strikes, has a fast rate–of–rise and together with the effect of soil resistivity, it dictates the characteristic of the grounding electrode as either inductive or capacitive. This characterization is a significant factor in determining the overall grounding electrode impedance. The grounding electrode impedance can be modeled under transient conditions by using circuit models [1–5]. In the circuit models, the grounding electrode is represented either as a distributed or as a lumped circuit [6] with R, C, and L elements. In the lumped circuit model, the circuit elements are combined together into one section to give only a single resistance, inductance, and capacitance to represent the whole electrode impedance. On the other hand, in the distributed model, the elements are uniformly (as per–unit–length parameters) or non–uniformly distributed along the electrode. The elements of the circuits are computed by using relevant formulae proposed by Sunde [7] and Dwight [8]. According to Sunde formula, the resistance and capacitance of the grounding electrode are related. In other words, R need to be first obtained before the value of C is determined. However, inductance, L, is determined independently. These circuit elements (R, C, and L) have static rather than dynamic values, that is they do not change during the impulse current duration. Hence, the effect of current amplitude and current rate–of–rise are not taken into account when computing the voltage response. Soil ionization is a phenomenon which occurs when impulse current is dispersed in the soil. This is especially true when the amplitude of the discharge current is high. The phenomenon substantially affects the values of R and C. In addition, the impulse current rate–of–rise also has a significant effect on the electrode inductance. Consequently, because of the soil ionization and current rate–of–rise are not taken into account [9] when computing R, C, and L, their static values are therefore overestimated. Hence, the computed voltage response of the grounding electrode using those static values is erroneous and sometimes this error can be significantly large and require further attention.

Various soil ionization models were proposed to improve the accuracy of computed R and C. These include work by Bellaschi *et al*. [10], Mohamad Nor, *et al*. [11], CIGRE [12], Geri [13], and Liew and Darveniza [14]. An attempt to include the soil ionization mechanism is described by Geri in [13]. In addition, the author also describes electric field enhancement in soil when subjected to high impulse current discharge, which in turn causes the breakdown of air voids that do exist among the mostly solid soil particles. The air breakdown is usually described in the form of arcs and arc growth. The arc growth is also usually further described as either in continuous form or discrete (or stepped) form. A discrete type of arc or ionization growth occurs because of the fact arcs cease to grow when the electric field intensity becomes less than the critical value, E_c. It is to be noted that previous soil ionization models assume a continuous or diffused ionization growth. Furthermore, the models incorporate the soil ionization effect by modifying either the soil resistivity or the grounding electrode radius. However, this modification is not a valid technique when considering the above–mentioned soil ionization mechanism.

It is also to be noted that, the majority of the soil ionization models proposed in [10–13] assume that the grounding electrode resistance is only a function of discharge current. Therefore, these models fail to determine the transient grounding electrode resistance during the current decay (tail) period. This is because in current decay period, the value of the grounding electrode resistance is mainly dependent on the energy balance between the produced heat energy in the arc within the voids and the absorbed heat energy by the soil particles. The so–called energy balance concept is defined as a concept where the computation of the air void arc resistance (and hence the grounding electrode resistance) is obtained by computing the actual balanced heat energy transferred between the air voids and the soil solid particles. A detailed explanation of this concept is given in the methodology section of this thesis.

In the grounding models developed by Bellaschi *et al*. [10], Mohamad Nor, *et al*. [11], CIGRE [12], and Geri [13], the arc resistance is assumed to be equal to zero. Therefore, previous soil ionization models fail to characterize the relationship between grounding electrode resistance and impulse current, in particular the hysteresis characteristic. It is known that neglecting the hysteresis characteristic causes a large error in the computation of the grounding electrode resistance especially when the impulse current reduces during the decaying period. According to [103], compared to the experimental value, the grounding electrode resistances obtained by models proposed by CIGRE [12], Bellaschi *et al.* [10], and Mohamad Nor *et al.* [11] at the current half time (T_h) give errors of 20%, 17%, and 25%, respectively.

It is also known that the computation of resistance, R, and capacitance, C, are related. Hence, the computation of C becomes erroneous when R is not accurate. Among the previous soil ionization models, only the soil ionization model proposed by Liew and Darveniza [14] gives an adequate accuracy when computing the transient grounding resistance. This is because the energy balance between the arc and the bulk of soil is considered. Nevertheless, the Liew–Darveniza’s model still has several shortcomings. For example, the model assumes a diffused rather than a discrete ionization growth. Hence, the discrete–breakdown path, which exists because of an air breakdown in voids enclosed among the soil particles, cannot be modeled [14, 15]. Furthermore, the solution for the general expressions of the soil resistivity (with soil ionization effect) often results in numerical divergence [16]. Another deficiency of the Liew–Darveniza’s model is that the effect of soil capacitance is not considered. It is known that neglecting the soil capacitance leads to inaccurate grounding electrode voltage [9, 17].

In addition, to overcome the deficiency caused by inductance value, L, on electrode voltage, two methods were previously proposed, namely, the constant and the length–dependent distribution of parameters along the electrode. According to these methods the simultaneous effect of inductance value and current rate–of–rise factor on electrode voltage ($v = L\, di(t) / dt$) is reduced by distributing the inductance along the electrode. However, the results obtained from the above–mentioned methods are only valid under slow–fronted current waves (that is, the front time, $T_f > 1$μs). Incorrect voltage responses are still obtained when the circuits are under fast–fronted current waves ($T_f < 1$ μs).

Overall, the accuracy of the previously proposed models is dependent on several key parameters of the grounding electrode and the impulse current. The key parameters are defined as the electrode length, the current amplitude, the current front time, and the soil resistivity.

It is concluded that the soil ionization and current rate–of–rise factors have significant effects on both the circuit element values and the voltage response of the grounding electrode. However, these two factors are not properly considered in many grounding circuit models.

1.2 Research Problem Statement

A major drawback of both lumped and distributed grounding circuit models is that they fail to produce the correct transient voltage at the injection point of the lightning current. The root–cause of this error is due to the static nature and inaccurate estimation of R, C, and L, which are computed without considering two important influencing factors, namely, the soil ionization and current rate–of–rise.

Although several soil ionization models were previously proposed to enhance the value of R, but they still have several shortcomings. Firstly, in the previous models, the effect of soil ionization is only indirectly considered on the soil resistivity and on the electrode radius rather than the preferred direct effect on the grounding electrode resistance itself. Secondly, the previous soil ionization models can only be used for continuous type of ionization growth rather than the preferred discrete type of ionization growth, which frequently occurs when the grounding electrode is subjected to high amplitude impulse currents. Thirdly, apart from the soil ionization model proposed by Liew and Darveniza, all previous soil ionization models are inaccurate in determining the grounding electrode resistance because they neglect the effects of two important aspects, namely, the arc resistance and the so–called energy balance concept. Even though the soil ionization model proposed by Liew and Darveniza can be considered as accurate, the proposed model is complicated and the general expressions given to compute the variation of the soil resistivity often result in numerical divergence.

The effect of current rate–of–rise plays a direct role in determining the inductance, L. Two previous methods, namely, the constant, and the length–dependent distribution of parameters along the electrode, have been proposed to compute L. Both methods do not provide a correct electrode voltage response under fast front current waves (that is, the front time, $T_f < 1$ μs). Under such current waveforms, correct electrode voltage response can only be obtained using a dynamically variable inductance depending on the front time of the waveform. It is obvious that the effect of current rate–of–rise must be directly considered when computing the inductance L.

It is important to consider the soil ionization and current rate–of–rise factors in designing and implementing the power system protection and safety. This is because these factors directly affect the resultant grounding electrode voltage when discharging high current impulses. For example, the electrode peak voltage significantly reduces when the soil ionization is considered. Consequently, a direct improvement in the grounding electrode performance is achieved [9]. According to [13], for a typical horizontal grounding electrode, a 66.5% reduction in electrode voltage is observed when the soil ionization is considered in the computation of the grounding electrode resistance and voltage. Therefore, by considering the soil ionization effect on the behavior of the grounding electrode when discharging high current impulses, the margin of the protection level in power system can be increased. On the contrary, the high current rate–of–rise factor together with the electrode inductance cause the peak voltage of the grounding electrode to increase considerably. The peak voltage computed by the previously proposed grounding circuit model is considerably higher because of neglecting the current rate–of–rise factor. According to [9] a difference of 26% in the peak voltage of a typical grounding electrode was observed when computed using the electromagnetic computational model and the circuit model. Therefore, an overestimation may exist when designing the power system insulation coordination including the ratings of the protective devices. In short, by considering both the soil ionization and the current rate–of–rise factors, the cost of power system insulation coordination implementation can be reduced and hence the economic benefit of such considerations.

In this thesis, several new methods of computation are developed and proposed to enhance the accuracy of the above–mentioned static R, C, and L circuit elements. The key contribution to the success of the developed methods is the incorporation of two additional factors namely, 1) the effect of soil ionization (for improved R and C), and 2) the consideration of current rate–of–rise (for improved

L), in a new equivalent circuit model of a grounding electrode with dynamic elements for transient conditions.

1.3 Research Objectives

The objectives of the study are as follows:

(i) To develop a new equivalent circuit model of a grounding electrode with dynamic resistance, capacitance, and inductance elements, which are achieved by considering the soil ionization and current rate–of–rise factors.

(ii) To validate the accuracy of the equivalent circuit model of a grounding electrode by comparing the results obtained from the model with those obtained from other well–known experimental work and theoretical models.

(iii) To evaluate the performance of the equivalent circuit model of a grounding electrode by changing the key parameters of the grounding electrode and impulse current.

1.4 Research Scope

In this research, an equivalent circuit model of a grounding electrode is developed to model the grounding electrode with the consideration of soil ionization and current rate–of–rise factors. The effect of soil ionization is directly considered in the form of a dynamic electrode resistance. Similarly, a dynamic soil capacitance is also proposed using Sunde equation ($RC = \rho\varepsilon$). As for the dynamic inductance, L_d, a new generalized formula is also derived.

MATLAB codes and CDEGS software are used to compute the dynamic resistance, capacitance, and inductance of the equivalent circuit model. When CDEGS software is used as a part in the computational step, all assumptions made in the corresponding electromagnetic approach with the method of moments are accepted as correct. For example, the electrode is assumed as a thin wire to presume a zero current at the open ends of an electrode. In addition, the grounding electrode is assumed to be made of cylindrical metallic conductor at which the ratio of the length of the conductor segment to its radius is larger than one.

In the performance analysis of the model, the soil critical electric field value, E_c, is considered as 300 kV/m, as suggested by IEEE standard. In the validation process, the results obtained from the model are compared to those obtained from the widely known theoretical models and experimental works. In particular, the following ranges of parameters are used: 40 Ω.m $\leq \rho \leq$ 5000 Ω.m, 3 m $\leq l \leq$ 30 m, $I_m \leq$ 30 kA, $T_f >$ 0.15 µs, $d \geq$ 0.5 m, and $E_c \geq$ 70 kV/m, where ρ is the soil resistivity, I_m is the current amplitude, T_f is the current front time, l is the electrode length, d is the burial depth, and E_c is the soil critical electric field.

The application of the new equivalent circuit model is limited to single horizontal electrode (counterpoise) or single vertically driven rod. Furthermore, the new equivalent circuit model is only valid for homogeneous and uniformed soil. Finally, the voltage response of the grounding electrode model is computed at the current injection point, which is usually at one end of the said electrode.

1.5 Research Contributions

The significant contributions of the study are as follows.

i) Critical Review on Previous Models

Several lumped and distributed grounding circuit models were previously proposed to characterize the grounding electrode impedance behavior under transient conditions. However, the previous models fail to accurately determine the electrode voltage. In this study, previous models were critically reviewed to determine the root–causes of error in determining the electrode voltage response. A critical and comprehensive review is presented in Chapter 2. A review on the previously proposed circuit models of grounding electrodes revealed that neglecting two factors, namely, the soil ionization and current rate–of–rise factors, substantially affect the accuracy of the circuital models to determine the electrode voltage under slow– and fast–fronted currents. The review had enabled the development of a new and more accurate equivalent circuit model for a grounding electrode.

ii) A New Equivalent Circuit Model for Grounding Electrode with Improved Accuracy

Previous transient models for a grounding electrode are inaccurate and require further improvements. An innovative and accurate equivalent circuit model of a grounding electrode with consideration of the key factors of soil ionization and current rate–of–rise was developed. In the equivalent circuit model of the grounding electrode, dynamic resistance, R_d, capacitance, C_d, and inductance, L_d, were used to characterize the grounding electrode resistance, soil capacitance, and electrode inductance, respectively. New models and methods were developed to determine the above–mentioned dynamic circuit elements. A new soil ionization model was developed to determine the grounding electrode resistance and soil capacitance. The principle of two–layer capacitor (TLC) was taken into account to model the soil particle and air void. Differential equations were derived to incorporate the soil ionization phenomenon inside the TLC network. A new method based on dynamic and static characteristics of arc and so–called energy balance concept was developed to compute the arc resistance in soil. Finally, a set of formulae were derived to compute the dynamic grounding electrode resistance and dynamic soil capacitance with soil ionization effect.

The significance of the developed soil ionization model are: 1) the dynamic grounding electrode resistance and dynamic soil capacitance values were obtained by considering the soil ionization effect, and 2) the hysteresis characteristic of the grounding electrode resistance was achieved. A new generalized formula was derived to calculate the dynamic inductance value of the grounding electrode with the consideration of the current rate–of–rise factor. The significance of the derived formula is that the dynamic inductance is accurately determined for all standard current wave shapes, such as CIGRE, double–exponential, and IEC 62305–1.

iii) Validation and Comparative Data for the Model

Several well–known experimental works and theoretical models were used to validate the accuracy of the new equivalent circuit model for a grounding electrode. The results from the experimental work are more accurate. The specifications and characteristics of the grounding electrode and impulse current defined in the several experimental works and theoretical models were used to set up the equivalent circuit model of the grounding electrode. The voltage responses and grounding electrode resistance values obtained from the equivalent circuit model were compared to those obtained by the experimental works and theoretical models. The comparison of the results with other theoretical models shows that the equivalent circuit model gives a better performance and accuracy in terms of voltage waveform, peak voltage, and grounding electrode resistance value. In addition, the grounding electrode resistance shows a comparable hysteresis characteristic compared to experimental ones.

iv) Evaluation and Performance Data of the Model

The performance of the equivalent circuit model was evaluated by changing key parameters values of the grounding electrode and impulse current (electrode length, current amplitude, current front time, and soil resistivity). It is noted that the range of values are stated in the scope of this thesis. The simultaneous effect of soil ionization and current rate–of–rise were taken into account. The time variation of the grounding electrode resistance, arc resistance, hysteresis characteristic, grounding electrode impedance as well as the voltage of the electrodes were obtained. The small differences between the values obtained from the equivalent circuit model and those from theoretical models show the excellent performance of the equivalent circuit model in the above–mentioned challenging conditions. The proposed equivalent circuit model can be used as to provide reliable and more accurate results when computing grounding electrode response to various injected currents.

v) Optimized Grounding Electrode Design

The main significance of the study is the improved accuracy of the new equivalent circuit model of a grounding electrode with dynamic elements of R_d, C_d, and L_d. The elements can be obtained by simultaneous consideration of soil ionization and current rate–of–rise factors. This research shows that the voltage response of the improved model is very accurate and comparable to the other theoretical and experimental results. The new equivalent circuit model can be used to obtain the voltage response of a grounding electrode in typical installations and hence helps to optimize the overall grounding electrode design due to the improved accuracy. This new model also indirectly addresses any safety concern arising from such grounding electrode design especially when subjected to fast transients.

vi) Improved Insulation Coordination

The obtained results can be used as a reliable source for validation of any grounding electrode model. Another important significance of the model is that the equivalent circuit model can be directly applied or connected to power system equipment in standard simulation platforms. In this way, an accurate grounding electrode effect on the transient performance of key power equipment such as surge arresters can be obtained. Using this integrated approach, a better protection and insulation coordination characteristics can be designed.

1.6 Thesis Outline

Chapter 1 gives mainly emphasis to the objectives of the study and the methodology used to solve the stated problems. Chapter 2 presents a critical review on related works conducted to model the grounding electrodes and highlights the existing problems of the models. Chapter 3 presents a methodology used to develop a new grounding electrode model. Chapter 4 is assigned to validate and evaluate the accuracy and the performance of the equivalent circuit model by comparing the results obtained from the equivalent circuit model with those obtained from the well–known experimental works and theoretical models. Finally, Chapter 5 presents the conclusions and future recommendations.

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