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Evaluation of Transient Response of Different Earthing Configurations due to Lightning Impulses

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Abstract: Earthing system is very important in order to protect the electrical equipment as well as the human's safety against over voltages. The main function of the earthling system is to remove unwanted excessive electrical currents caused by unusual conditions such as fault and lightning or switching over voltages by providing a low resistance path to the earth. Researchers had studied the behaviour of the earthling system to improve its performance for the past few years. There are few factors that influence the performance of the earthling system such as soil resistivity and soil ionization which need to be focused in order to improve the earthling. Thus, this paper evaluates on the factors that affect the behaviour of the earthling system based on simulation works using MATLAB and Safe Grid Software. Some analytical calculations are used to obtain the soil resistivity and resistance as well as the touch and step voltages. The simulation results were validated based on comparison with other studies on the factors that influence the earthling system performance. The results reveal that the variation of soil resistivity, the configuration of electrodes, current magnitude and frequency dependence can result in a change of transient response of the systems.

Keywords: Earthing, Lightning, Matlab and Soil resistivity

I. INTRODUCTION

Lightning is formed when the positive and negative charges are separated into two levels in the cloud, and negative charges are then being attracted by the earth surface positive charges. The positive charges from the ground connect with the negative charges from the clouds and form a spark of lightning strikes.

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According to the statistical analysis, Malaysia is the third in place of the country that has the highest number of lightning strikes. Almost 309 numbers of days lightning strike per year at KLIA, Sepang according to Malaysian Metrological Department. It is shown the effects of lightning strikes are very large and serious case in damaging the electrical equipment. Some serious cases of lightning strike cause the runway of Sultan Abdul Aziz Shah Airport in Subang being damaged and three Firefly flights to be disrupted [1]. Thus, earthling systems are very important in order to protect the electrical equipment as well as the human's safety.

The measurement of grounding resistance can be done using injected current to the earthling electrode or injection of high current with frequencies. It can be estimated for the earthling system behaviour under low frequency and yet, under lightning transient impulse condition, earthling systems are totally different. There are some factors that give impact to the earthling system, for instance, soil resistivity in where the earthling electrodes are installed, configuration and design of earthling electrodes, soil ionization, impulse current magnitude as well as the frequency of the impulse. All these factors comprise many challenges to meet the design requirement of the optimum level of an effective earthling system [2].

II. LITERATURE REVIEW

Basically, soil resistivity (SR) is affected by four factors which are the temperature, moisture content, presence of chemical salts and soil compaction. Each of the factors which affected the soil resistivity is further discussed in this section.

Effect of Moisture Content on Soil Resistivity

Moisture content plays a vital role in determining soil resistivity. That is, the dryness of soil proportional with the resistivity, wet soil will have lower soil resistivity. When the moisture content in soil increases, earth resistance will decrease until it reaches a certain point about 22% of moisture content, there will only a very little change in resistivity. According to the result shown in Figure 1, three soil with different water content level which are 10%, 15% and 20% were used for the test [3]. The soil test resistivity was obtained to make a comparison. Just as expected, a significant dependence effect of water content on soil resistivity was obtained. Almost up to 75% decrease in resistivity can be obtained when the water content increases from 10% to 20 %. The impact of this result to the earthling system is that the earth resistance will drop significantly in a rainy day due to the moisture of soil when the soil becomes dry, consideration of earth potential rise (EPR) and the safety implications become a vital issue. [3]

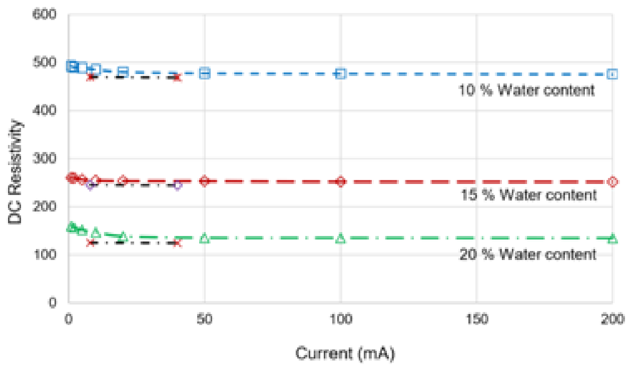


Fig. 1 Effect of water content on soil resistivity [3]

Effect of Temperature on Soil Resistivity

Thermal is one of the important effects on soil resistivity. It will cause the soil temperature to increase and affect the operation of the earthling system. Hence, we need to consider the resistive thermal effect when designing earthling systems. Wenxia Sima et al evaluated the temperature characteristics of soil parameters through the experimental measurement circuit. The equation of soil of transient heat conduction is expressed in the following equation according to heat transfer theory. [4]

$$\frac{\delta}{\delta x}\left(k_x\frac{\delta T}{\delta x}\right)+\frac{\delta}{\delta y}\left(k_y\frac{\delta T}{\delta y}\right)+\frac{\delta}{\delta z}\left(k_z\frac{\delta T}{\delta z}\right)+\rho J^2-C_v\frac{\delta T}{\delta t}=0, \quad (1)$$

Here;

k_x, k_y, k_z *are* thermal conductivity in X,Y,Z direction, C_v= volumetric heat capacity, ρ= resistivity, T = temperature and J= current density. Figure 2 shows the temperature increases with time. Before reaching 45°C, the consistency of the results can be seen in the terminal and middle of the electrode when low temperature. As temperature increases, the resistivity of soil performs large difference. We can see that the unstable resistivity of soil curve grows more rapidly than the constant resistivity of soil. The increase of resistivity of soil will enhance soil heating and induce temperature increase. [5]

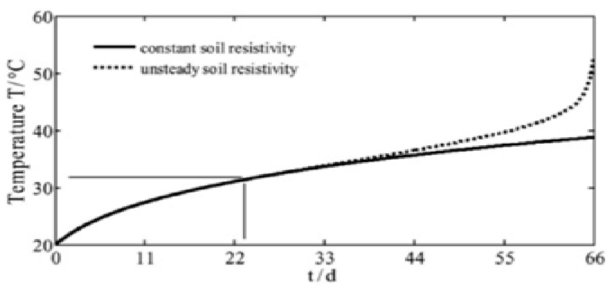


Fig. 2 Temperature change vs time in the middle of the earthling electrode [5]

Effect of Salt Content and Ionisation on Soil Resistivity

Ionisation process will happen between the reaction of salt content NaCl in soil and the copper earthling rod. When a high magnitude current passed through the salt solution, salt solution will breakdown into charged ions and move towards the opposite electrode charges. According to the electrolysis theory, sodium ions will move to the cathode while chlorine ions will move to the anode. The experiments were carried out with before adding the salt solution of NaCl, 24 hours after adding the salt solution of NaCl, and 15 days (360 hours) after adding the salt solution of NaCl. Figure 3 shows, the soil resistivity was reduced significantly almost up to 75 per cent after 24 hours of addition. However, it can be seen that the resistivity of soil increased again and even some segment went back to original values after 15 days of salt solution addition. Based on the results, salt water treatment particularly NaCl is an alternative way to decrease the value of soil resistivity. However, the disadvantage of this method is the effect of this only for a short period of time which is not applicable for some countries like Malaysia due to the large rainfall number in the whole year and also cause corrosion to earth electrodes.

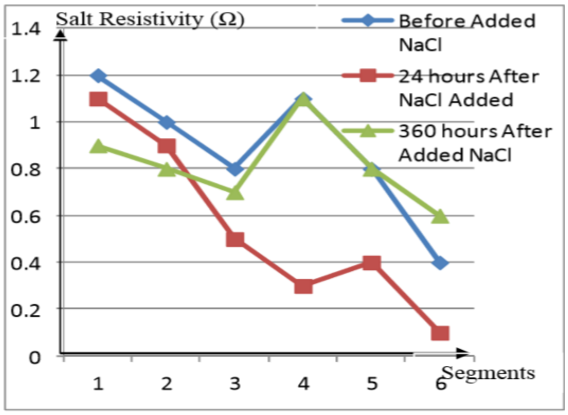


Fig. 3 Soil resistivity for each segment before and after adding salt solution [6]

Earth Electrode Configurations

In earthling system design, vertical earth electrode is a common type of electrode configuration and usually installed for overhead transmission lines. It was first published experiment work in 1928 by Towne et al [7] who carried out an experiment using a galvanized iron pipe with 6.1m length and a diameter of 21.3 mm buried in gravel soil to determine its behaviour when impulse currents were applied. It was energized with an injection current between 20 μs and 30 μs with peak currents up to 1500 A. The results shown the measured resistance was reduced from 24 Ω to 17 Ω with the frequency of 60Hz due to the non-linear behaviour of the conductor. This investigation gave better motivation to conduct more studies on this topic to obtain more understanding of earthling behaviour. Another investigation was carried out by Bellaschi in 1941 [8], an experimental tests on four steel rods of with diameter of 25.4 millimetres and up to length of 2.7 metres, which were installed, with the earth resistance between 30Ω and 40Ω at 60Hz of frequency in parallel with deep-driven earth rods to determine the behaviour earthling system and ways to improve earthling system performance under power frequency fault conditions. It was also found that the soil conducting medium and the arrangement of the electrode has a significant impact on impulse resistance. Its value, however, was independent of the current increase.

An analytical model was then developed by Liew and Darvenzia to describe the nonlinear behaviour of the earthling electrode. A 20kA of the current value with the rise times between 10 µs and 54 µs was injected into 0.61 m long, 12.7 mm of diameter vertical rods buried at 25.4 mm in the soil and 152.4 mm diameter electrodes buried under the soil surface with resistivity ranging from 5,000 Ωcm to 31,000 Ωcm [9]. The results were confirmed by Vainer, he applied a high impulse voltage of 1.5 and 0.8 MV to vertical rods between 10 m and 140 m [10]. Bewley had carried out an impulse test to test the behaviour of a horizontal earth electrodes in 1934 [11]. Long horizontal earth electrodes (counterpoises) with different lengths which were 281 metres and 465 metres were buried to up to a depth of 1 ft in the earth with soil resistivity of 100 Ωm. A 2 µs rise times with peak value of 900A impulse currents were then injected to the earth. The findings showed that when under 60Hz power frequency, the transient impedance of the counterpoises dropped rapidly. In his investigation, no ionisation effect occurred due to the low magnitude of the discharge current. It was reported in [12], the characteristics of earthling grids under transient conditions. In the experiments, an earthling grid with area 20 x 20 m^2 was buried to a depth of 0.8m into the earth with the resistivity value of 500 Ωm and permittivity of εr= 9 at the corner and centre with impulse current injection up to 10 kA with a 2.6/50 µs wave shape. The results showed that the impulse resistance gave a higher value for current injection at the corner of the grid compared with the injection at the grid centre [13-15].

III. METHODOLOGY

Simulated lightning impulse currents of 1.2/50 µs were produced using an impulse generator model based on an RC circuit. The impulse generator model consists of resistances (R) and capacitances (C) which are necessary to determine the front and tail time of the generated impulse currents. The RC parameters were used in the analytical calculation to obtain important values such as α and β using impulse response formulae. Hence, the variation of these parameters was simulated in order to produce different impulse current waveforms. Meanwhile, earthling system simulation models based on both vertical and grid configurations were constructed. Ultimately, the impulse generator was connected with the earthling system to ensure that the currents can be injected into the system. The models were simulated using MATLAB Simulink. Through calculations performed earlier in this experiment, the simulated result can be compared theoretically to determine the consistency of the model constructed. The full simulated model for vertical earthling and grid earthling systems are shown in Figure 4 and Figure 5 respectively.

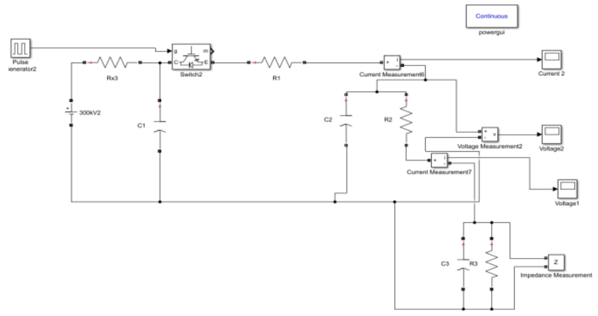


Fig. 4 Vertical equivalent circuit

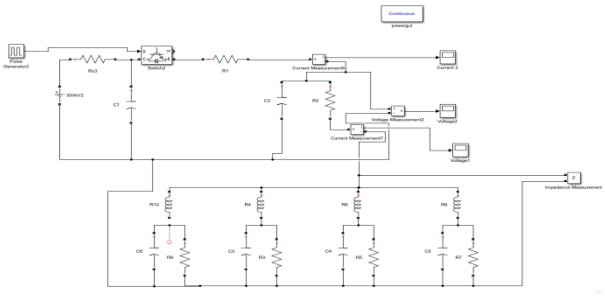


Fig. 5 Ground grid equivalent circuit.

An analytical method of Step and Touch Induced Voltage

Using the soil resistivity value is at 200 **Ω**m, which the grid resistance is 9.533**Ω**. X/R is the ratio at the fault is approximately 15 ms, the maximum duration of fault (T_S) is approximately 150 ms and the nominal frequency of the system is set at 50Hz. The maximum step and touch potential can be calculated using Equation (2) and Equation (3).

$$E_{touch,70} = (1000 + 1.5\, C_S \rho_S)\frac{0.157}{\sqrt{T_S}} = 1701.08\, V \qquad (2)$$

$$E_{step,70} = (1000 + 6\, C_S \rho_S)\frac{0.157}{\sqrt{T_S}} = 5588.22\, V \qquad (3)$$

Where,

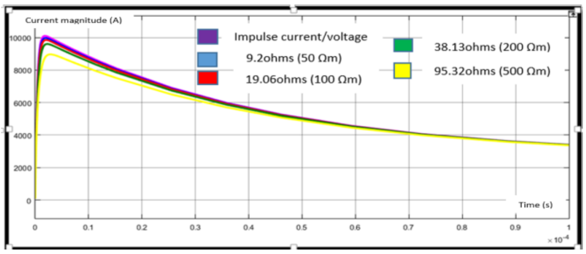
$$C_s = 1 - \frac{0.09\left(1 - \frac{\rho}{p_s}\right)}{2h_s + 0.09}, \qquad (4)$$

ρ = soil resistivity, Ωm, p_s= surface layer of soil resistivity, Ωm, h_s= thickness of the soil.

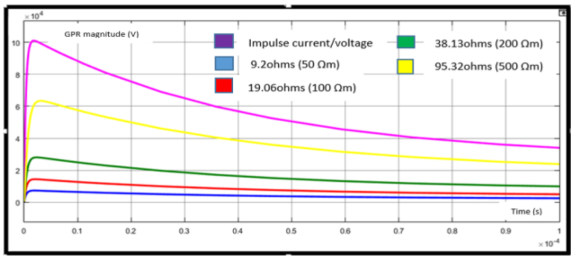
IV. RESULTS AND DISCUSSIONS

It is important to ensure that the system provides an adequately low impedance path but not simply low resistance path in order to ensure lower ground potential rise voltages over higher frequencies. In other words, the transient characteristic of lightning impulses will produce both low and high-frequency effects. The capacitances control the fast-rising front time of the impulse by allowing the high-frequency components to pass through it. Thus, the values of capacitances should be maximised in practical. The inductances control the rapid change of current with time when the current was injected into the earth.

According to the inductive current law, the voltage might become very large with the change of current with time. Therefore, inductances should be minimized to avoid large induced voltages. On the other hand, the resistance dominates the decaying tail time which ensures that the dissipation of current into the ground. This can be explained using Ohm's law. As the soil has low resistance, most part of the lightning current that initially injected below strike point, flown through the ground, letting a fixed amount of current entering the cable surge impedance which is in parallel with ground resistance. Figure 6a shows the results of impulse currents injected in different soil resistivity earthling system and Figure 6b shows the induced voltage produced by the respective currents. The results have shown that the soil with high resistivity allows a small initial current to enter the ground after a lightning strike. Other than the peak value changes due to the soil resistivity, the front time and tail time also being affected. The front time also increases from 1.2us to 2.0us due to the soil resistivity increases and the tail time increases from 50us to 62 us due to the soil resistivity increases. It is clearly showed that the resistance of the electrode is depending on the soil resistivity. Soil structures also affect a lot on the electrode design. This is because soil structures directly influence the induced voltage or ground potential rise (GPR) due to impulse injection in the grounding electrode. Thus, the GPR voltages influence the temperature rise and the life expectancy of the grounding electrode.



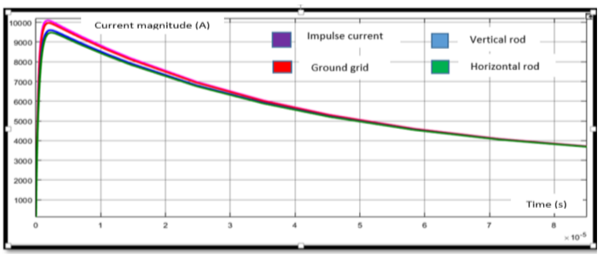
(a)



(b)

Fig. 6 Influence of soil resistivity and resistances. a) Impulse currents. b) Induced voltages.

The higher amplitude of impulse current produces a higher electric field gradient (E) in the soil around the earthling conductors. Hence, soil ionisation process will be increased. As a result of that, the earthling resistance and the maximum transient GPR decrease. The earthling resistance behaviours not only depending on earthling configuration and soil resistivity, but also on the front time and peak magnitude of the impulse currents. Figure 7a and 7b show the influence of electrode configurations on the impulse currents and induced voltages in the soil respectively.



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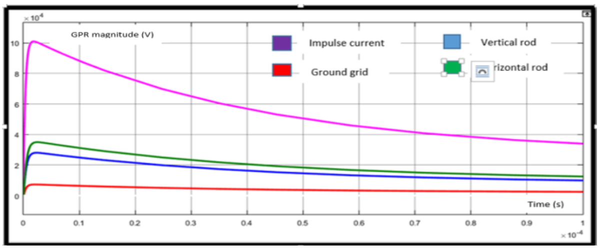
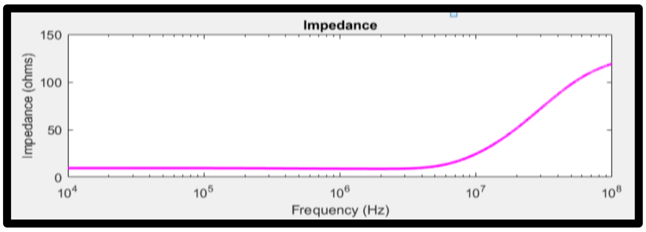


(b)

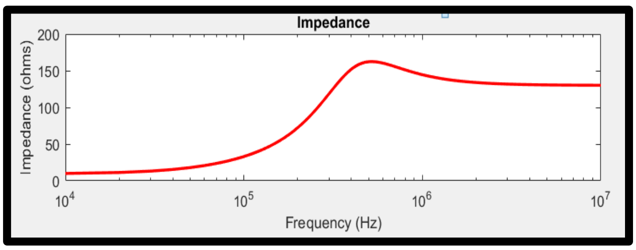
Fig. 7 Influence of electrode configurations. a) Impulse currents b) Induced voltages

Frequency Dependence of Earthing System

At low frequency, the capacitance and inductance effect is absent so that the earth resistance remains at a very low value of 9.53Ω. When low inductance, the resonance happens at very high-frequency value. After resonance happened, the earth impedance is being amplified according to the Q-factor. Resonance effect should be avoided to ensure that the ground impedance is low enough. Capacitance must be maximized to eliminate the high-frequency components whereas inductance should be minimized. Figure 8a and 8b show frequency dependent for earthling rod and grid configuration respectively. As shown in the figures, both configurations will produce higher earthling impedance at higher frequencies.



(a)



(b)

Fig. 8 Frequency dependence of the earthling system. a) Earthling rod b) Earthing grid

V. CONCLUSIONS

The earthling system is significantly affected by various factors such as soil resistivity, the configuration of electrodes, the magnitude of impulse current and the frequency dependence. Different analytical approaches, both experiments and computational models, were developed to achieve a better understanding and analysis. One of the most common numerical models used to simulate the earthling electrodes is based on the method of moments and is commercially available through software such as CDEGS. This numerical model has been used to characterise the behaviour of different earthling electrodes, specifically, vertical and horizontal electrodes. Other studies like frequency dependence of soil parameters and measurement of grounding system resistance based on ground high-frequency behaviour for different soil type are clearly used to characterise the behaviour of the earthling system. The measured soil parameters and their variation with frequency were compared with the published frequency dependent models. The results in the paper have shown reasonable agreement with some earthling models in high resistivity soil [3][7][8-9][13]. In practice for the design of the earthling system, the capacitance should be maximized to eliminate the high-frequency components and the inductance should be minimized in order to reduce the resonance in the earthling system.

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