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Effect of high resistivity soil under high impulse currents

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ABSTRACT

In this paper, experimental test results of several ground electrodes surrounded with gravelly soil medium subjected to high impulse currents were studied, to investigate the effect of confined soil surround electrodes. Ground resistance measurements were performed at low magnitude of voltage and current, where the results are compared to the impulse characteristics of ground electrodes. This paper shows a significant difference in the R_{DC} values and impulse characteristics of ground electrodes when gravelly soil medium surrounded the ground electrode in comparison to the electrodes installed in natural soil. This indicates that the confined soil around the electrode has a major effect on the performance of ground electrodes, whether at steady state or under high impulse conditions. Equivalent circuit for each tested electrode was developed with personal simulation program with integrated circuit emphasis (PSPICE), where the effect of inductance was seen in the electrodes surrounded with gravelly soil.

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1. INTRODUCTION

Over the last century, grounding systems' characteristics under high impulse conditions have been known to be different than that at steady-state conditions. The reasons for the difference are caused by thermal and ionization processes in soil [1]-[25]. Among the numerous significant observations when these conduction processes are thought to occur are from experimental results, where a reduction of impulse impedance, $Z_{impulse}$ from the resistance values at power frequency, R_{DC}, and the reduction of $Z_{impulse}$ with increasing currents are observed. Other exceptional observations are gained from photographic observations and X-ray imaging on the soil characteristics published in several research work [10]-[12]. Factors affecting the percentage of the reduction of $Z_{impulse}$ from its R_{DC}, and reduction of $Z_{impulse}$ with increasing currents have also been an interest to many authors, most of the test results showed higher percentage of reduction of $Z_{impulse}$ from its steady state in high resistivity soil [1], [8] or R_{DC} values. Higher $Z_{impulse}$ is also seen under negative impulse polarity, than that positive. A study in [1] has seen the higher current dependent of impulse impedance in high R_{DC} and under negative polarity, which suggested that it is important to encourage soil ionisation to occur, in order to obtain a further reduction in impulse impedance from its steady state values. Among the reasons of the ionization or, and thermal processes occurrence are caused by the heating process in the soil, large dielectric difference between the soil grain size and non-uniform electric field. X-ray film buried inside the soil, placed near to an active electrode, that ionization channels are denser in wet fine sand soil, while less ionization paths, with arc and sparks were observed in the same sand soil, but in dry condition [11], [12]. This was reasoned out as the sizes of clay particles are rather non-uniform in wet clay, with many air voids of various sizes, which makes ionizations in wet clay become more significant.

It was noted in most studies [1], [8] that non-linearity in soil is mostly marked in high resistivity soil. Reffin *et al.* [1] performed impulse tests on the same test configurations, each installed at four different sites, hence variation in soil resistivity values. Reffin *et al.* [1] found that a high percentage of impulse impedance reduction of grounding systems installed in high resistivity soil, in comparison to that grounding systems installed in low resistivity soil. It was also evident by Elzowawi *et al.* [13] that, when the dry soil or low water content of sand soil was used as the upper layer, whereby the lower layer was filled with high percentage of water content, there was an initiation of ionization around the electrode at the upper layer, followed by further propagation to the lower layer, an indication that a larger degree of soil ionisation process in high resistivity soil.

Due to differences and non-conclusive findings, it was found in some publications [11], [12], that ionization is stronger in wet soil, although in work [1], [8] the higher reduction rate in impulse impedance, which indicates the degree of ionisation, was in dry soil, this paper is called for to obtain a better understanding on the variation of localized soil around the electrode and subjected under high impulse conditions. Experimental results are presented, and found that gravelly sand, with high soil resistivity has significant delay in terms of its current rise time, and current discharged time. Experimental test results will be applied into personal simulation program with integrated circuit emphasis (PSPICE), where equivalent circuit for various ground electrodes will be simulated. It was found that ground electrodes installed in gravelly sand are found to have the most significant inductive values, in comparison to other ground electrodes at low voltage magnitudes.

2. EXPERIMENTAL ARRANGEMENT

2.1. Ground electrodes

Figures 1(a)-(e) show five arrangements of soil layer and ground electrode, to provide analysis on the behavior of grounding electrodes with different soil layers under high impulse conditions. The five grounding electrode's arrangements are as follows:

a. Figure 1(a) is configuration 1, consisting of a vertical rod (first rod electrode) connected with a copper strip, where the soil was of original soil. A vertical rod of 1. 5 m of 16 mm diameter was installed below 300 mm under the ground's surface. A copper strip with the width of 2.5 cm, and length of 2.6 m, was also installed 30 mm below the ground's surface and combined to the vertical rod by a clamp.
b. Figure 1(b) is configuration 2, similar to configuration 1, but with the second vertical rod of the same size as the first rod and was installed in parallel to the first rod.
c. Figure 1(c) is configuration 3, similar to configuration 2, however the top layer was replaced with the gravelly sand media. This gravelly sand media was tested at Material Testing Laboratory for soil grain size distribution test and found the sand grain's size was between 2 mm–10 mm. The trench was excavated, where the gravelly soil was poured into the trench to 200 mm thickness. Excavated soil heap was used to fill up the trench.
d. Figure 1(d) is configuration 4, similar to configuration 3, but with the second rod removed.
e. Figure 1(e) is configuration 5, similar to configuration 2, but with the parallel rod was placed again, surrounded with the gravelly sand soil. This was done by first auguring the earth to make the hole 1.5 m in depth and 5 cm in diameter. A funnel where its tube can be screwed to different lengths was placed within the 1.5 m depth. A rod electrode was placed inside the funnel, where gravelly sandy media was poured into the funnel, until it is filled to 1.5 m depth. Slowly the funnel was then removed, leaving the second rod surrounded by the gravelly sand media. These electrodes were placed 300 mm below the ground's surface.

Earth resistance measurement at steady-state, RDC, was performed on all test electrodes, using a fall-of-potential (FOP), and found to be 63.7 Ω, 49.32 Ω, 64.1 Ω, 95.5 Ω, and 94.2 Ω, respectively for configurations 1 to 5. As expected, configuration 2 has the lowest R_{DC}, due to its large configuration, and installed in original soil, which has lower soil resistivity than the gravelly sand media. Despite ground rod electrode are added for configuration 5, its R_{DC} was similar to configuration 4, which could be caused by the presence of gravelly sand test media in configuration 5 with high soil resistivity. Wenner method was applied to measure soil resistivity, where the soil resistivity data was interpreted into 2-layer soil model, using current distribution, electromagnetic interference, grounding and soil structure analysis (CDEGS), and obtained as follows: resistivity of an upper layer, ρ_1 was 111 Ωm with the soil thickness of the first layer of 5 m, and resistivity of a lower layer, ρ_2, of 454 Ωm with infinite thickness.

Using these soil resistivity values of 2-layer soil model, CDEGS was also utilized to calculate for the ground resistance values of all electrodes, where ground resistance value for configurations 1 and 4 was 38.8 Ω, while the resistance value of configurations 2, 3, and 5 was computed as 32 Ω. These give percentage differences between measured and calculated R_{DC} values of 39%, 35%, 50%, 59.4% and 66% respectively for configurations 1 to 5. Low percentage differences between measured and calculated are noticed for configurations 1 and 2 as the electrodes are installed in natural soil, while other configurations with the added gravelly soil media have percentage differences more than 50%. This indicates that confined soil can be one of the major contributors to the differences between the measured and calculated R_{DC} values. The remote ground electrodes used in this study comprises a grid, of 30 m x 20 m, with multiple rods. R_{DC} value of remote ground electrode was measured as 8 Ω, as was expectedly lower than that of the test electrodes, due to its relatively larger grounding grid than the test electrodes. A connection via copper mesh was made from the remote earth to the earth terminal of impulse generator to discharge high magnitudes of current during testing.

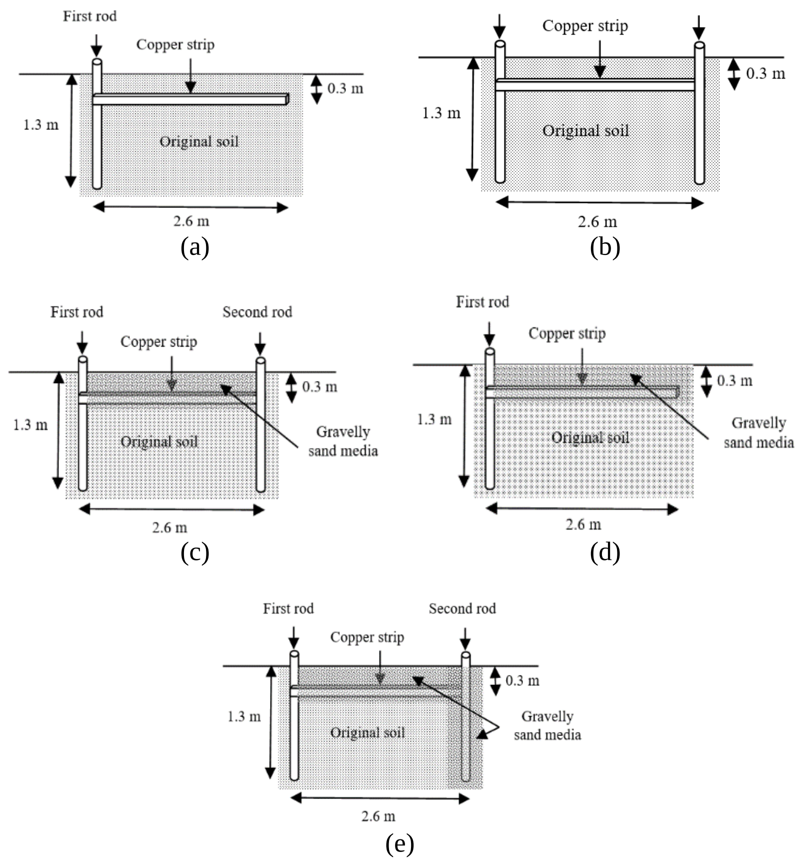

Figure 1. Ground electrodes used: (a) configuration 1, (b) configuration 2, (c) configuration 3, (d) configuration 4, and (e) configuration 5

2.2. Impulse testing facility

Impulse generator can generate up to 300 kV, which the current affected by the impedance or the characteristics of the electrode under tests (EUT), producing up to 10 kA, was used in this study. Impulse voltage measurement was made by means of a resistive divider, which was placed at a distance of 30 m away from the EUT, and the current measurements with a current transformer, with a sensitivity of 0.01 V/A. Remote earth was more than 40 m away from the test electrode. Voltage and current traces were captured with digital storage oscilloscopes (DSO), and the triggering of the circuit was controlled by a personal computer, where all of these devices were placed more than 40 m away from the impulse generator. Test arrangement is similar to that used in [1], [8], shown in Figure 2. Impulse voltages were injected into the EUT with increasing voltage magnitudes, where the results were discussed based on current rise time, current discharged time and impulse impedance values.

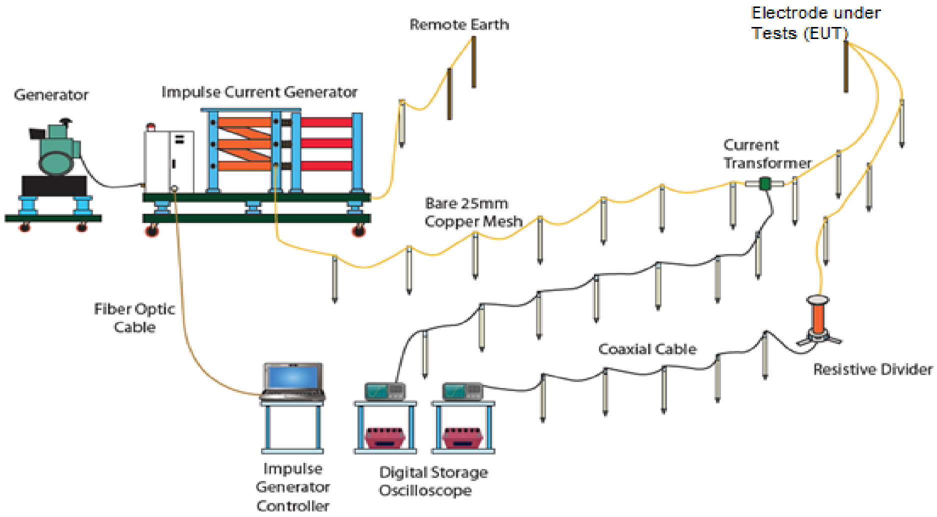

Figure 2. Impulse test arrangement used in the study (reproduced from [1])

3. EXPERIMENTAL RESULTS

3.1. Current rise and discharged times

Figure 3 shows the traces of the voltage and current for configuration 1, at charging voltage of 30 kV. The traces of voltage and current for other configurations, and at various charging voltages show quite similar traces. From the current traces obtained at different applied voltage, current rise time and current discharged time are plotted against the peak current for all configurations, as shown in Figures 4 and 5 respectively. Current rise time is found to decrease with current magnitudes, as shown in Figure 4, which means that better conduction and lower inductive effect as the magnitudes of current are increased. An obvious increase of current rise time for current magnitudes of below 1 kA is seen for configurations 3 and 5. These two configurations have been filled up with gravelly sand test media (high resistivity soil). Thus, the slower current rise times could be caused by the presence of inductive effect for larger size of ground electrodes, in high resistivity soil, which is also seen in simulated work later on, that at low voltage levels, inductive effect is significant in configurations 3 to 5, having gravelly medium soil added to the ground electrodes. Configuration 2 has the same electrode configuration as configurations 3 and 5, but the current rise time for configuration 2 is found to be occurring at faster times than configurations 3 and 5, for current magnitudes of below 1.5 kA. For configuration 2, original soil is used, which expectedly has lower confined soil resistivity around the ground electrode than the gravelly sand media used in configurations 3 and 5, hence faster current rise times are observed. It can therefore be inferred that the extended large ground electrodes in high resistivity could cause inductive effect and slower down the conduction of ground electrodes, especially at lower fault current magnitudes. At higher current magnitudes, no observable difference in current rise time is seen for all test electrodes. Similarly, an obvious observation on the presence of inductive effect in high resistivity soil, can be seen on the current rise times of configuration 4, which has gravelly soil, are found to be slower than the current rise times of configuration 1, of having the same configuration as configuration 4. This shows that, the high localised soil resistivity from the gravelly soil, can significantly cause delay in the current rise times.

Furthermore, the time taken for current trace to discharge to ground is found to have a slight decrease with increasing current magnitudes (see Figure 5), with slower discharged times for current traces are seen for configurations 3 to 5 (with gravelly soil), with the difference of approximately 300 μs, in comparison to the discharged times of configurations 1 and 2 (without the gravelly soil). All of these configurations 3 to 5 have been installed in gravelly sand media (high soil resistivity). Despite large grounding electrode used for configuration 3, with R_{DC} value, close to configuration 1, slow discharging time of current trace is seen in configuration 3, caused by the presence of gravelly sand media. This indicates that it is plausible for grounding electrode in high resistivity soil to experience slow current discharging time, though having large grounding electrode, with low R_{DC}, which points out that R_{DC} value may not always be the only basis used for the safety criteria of the grounding systems, which under high impulse conditions, the characteristics of grounding systems would change.

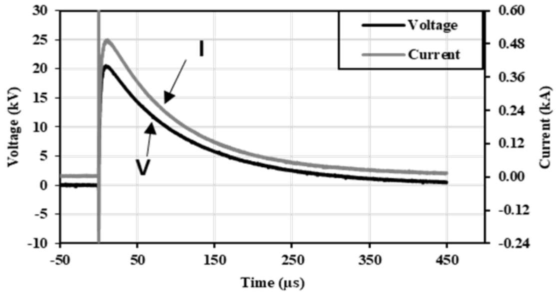

Figure 3. Voltage and current traces for configuration 1 at charging voltage at 30 kV

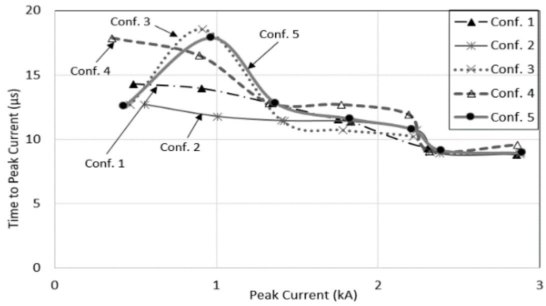

Figure 4. Current rise time versus peak current for all configurations

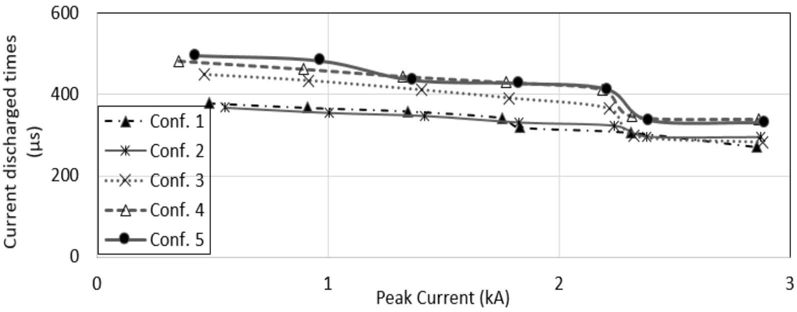

Figure 5. Current discharged time vs peak current for all configurations

3.2. Impulse impedance, Z_{imp}

It can be found that in several publications that a typical equivalent circuit of grounding systems under high impulse conditions, consists of resistive in series with inductive impedance [14], [15]. The studies have shown that if it is a low ionization, conduction or even breakdown in soil, it is likely that the grounding systems can be predominantly inductive, which can be influenced by the size of grounding electrodes. This is also demonstrated in [15], where inductive effect become significant in high R_{DC}, and high resistivity soil, of above 2 kΩm.

In this paper, $Z_{impulse}$ is measured as the ratio of voltage at peak current to the peak current, as used in [1]. Figure 6 shows the plot of impulse impedance versus peak current for all configurations. As can be seen, $Z_{impulse}$ has a strong marked non-linearity for the current magnitudes of below 1 kA, for all configurations, except for configuration 2, which is found to be less dependent on current magnitudes. Configuration 2 has the lowest R_{DC}, and as seen in many publications [1], [8], the lower the R_{DC}, the ground electrodes become less dependent on current magnitudes. Configuration 4, with the highest R_{DC}, and with the surrounding soils mostly filled with gravel, is found to have the highest marked of non-linearity for current magnitudes of below 1 kA, followed by configuration 5, with the second highest R_{DC} value. This high non-linearity in high R_{DC} and high resistivity soil is also seen in previous publications [1], [8], where the impulse impedance become highly dependent on current magnitudes for the ground electrodes with high R_{DC}.

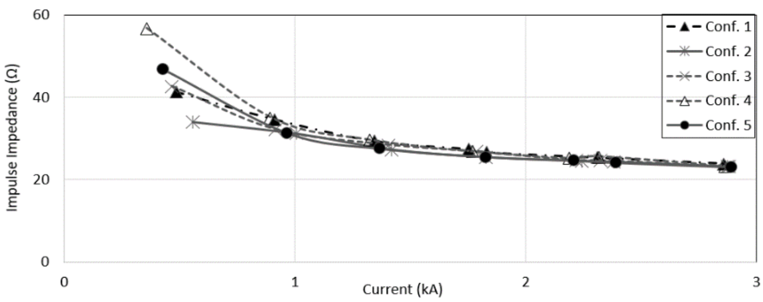

Figure 6. $Z_{impulse}$ vs peak current for all configurations

Despite having close R_{DC} values for both configurations 4 and 5, as presented in section 2. A, lower $Z_{impulse}$ is seen for configuration 5, which could be caused by the presence of gravelly sand test media, hence more ionization process may have expected to occur, causing lower $Z_{impulse}$. This indicates that gravelly test media has a probable condition in enhancing the ionisation process, and lowering the $Z_{impulse}$ when grounding electrodes are under high impulse conditions. On the other hand, for current magnitudes of above 1 kA, close $Z_{impulse}$ values are seen for all configurations and become less dependent on current magnitudes.

4. SIMULATED WORK

In this study, a PSPICE software package was used to obtain the equivalent circuit representations for the grounding electrodes in different soil conditions, subjected to high impulse conditions. Test circuit consists of impulse generating test circuit and the loads, where the load consists of resistive load, in series to the inductive component. This load is similar to the circuit proposed in literature [15], [16]. Figure 7 shows the simulated test circuit used in the study. For the non-linear resistive load, a similar non-linear equation of $V=kI^{\alpha}$ as used for grounding systems is used, where V is the voltage in V, I is the current in A, k is the constant and α is the non-linear component, where these expressions are obtained from the curve fitting method of $Z_{impulse}$ vs I_{peak} plots, presented earlier in Figure 6. Table 1 lists the empirical expressions for the $Z_{impulses}$ obtained for all five configurations.

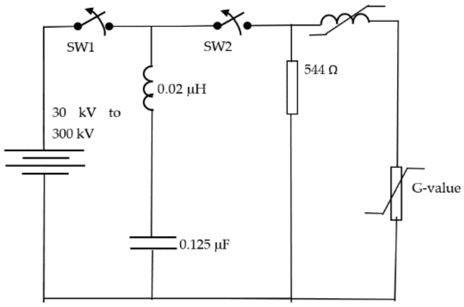

Figure 7. Simulated test circuit

Table 1. Empirical expressions of $Z_{impulse}$ for all configurations

Configuration	$Z_{impulse}$ expressions
1	$32.85\ I^{-0.315}$
2	$29.978\ I^{-0.247}$
3	$32.35\ I^{-0.332}$
4	$35.054\ I^{-0.422}$
5	$32.539\ I^{-0.365}$

Other than having the ‘G-value’ to represent for the $Z_{impulses}$ of all these configurations, inductive components are varied accordingly in the simulated test circuit, until the simulated voltage and current traces exhibit close current magnitudes, rise and discharged times to that obtained from experimental work. Switches were also added to represent for the spark gap switch and help in getting the current rise times closed to the experimental results, defined as SW1 and SW2, respectively. Inductance values adjusted in the test circuit for various voltage levels are listed in Table 2. Figure 8 shows the simulated and experimental traces, for configuration 1, which are found to be in satisfactory agreement.

Based on Table 2, Figure 9 is plotted for all configurations. It can be seen that the inductive effect reduces with increasing voltage, due to better conduction at higher voltage/current magnitudes, becoming predominantly resistive. For voltage magnitudes of below 80 kV (where from the experiments, the current magnitudes at this 80 kV ranged between 1.3 kA to 1.4 kA), inductive components are the highest for configurations 4 and 5 (with the highest R_{DC} values), and the lowest inductive component is seen for configuration 2 (with the lowest R_{DC}). Higher inductive component by 30% is seen in configuration 1 than configuration 3, despite having close R_{DC} values (0.62% difference) between both configurations, and configuration 1. As described in earlier paragraph, G-values with the derived equations for each configuration is used, and the inductive values are adjusted until a satisfactory agreement is seen between the experimental and simulated traces. Higher inductive values for configuration 1 could be due to higher impedance values used of G-value, having 32.85 Ω in comparison to 32.35 Ω for configuration 3, as seen in Table 1. The non-linear component, α is also found to be smaller in configuration 1, with the value of -0.32 in comparison to -0.33 for configuration 3, indicating that configuration 3 has a stronger non-linearity, hence giving better conduction than configuration 1 when subjected to high impulse currents. Stronger non-linearity in configuration 3 could be due to the presence of gravelly sand that was added, creating large dielectric difference between the soil and air voids, where under high enough stresses/fields, ionisation process in air voids would occur. This indicates that computation on the equivalent circuit integrating the experimental results can help to elucidate the soil behavior under high impulse conditions, which may not be fully achieved with the experimental work alone. It was clearly demonstrated from computational work that though the R_{DC} values of ground electrode are close, the performance of ground electrodes can be different when subjected under high impulse conditions, where the effective ground electrode can still be seen for configuration 3, though gravelly sand was added around the horizontal ground electrode.

Table 2. Inductive components for all configurations at different input voltages

Input voltage (kV)	Inductance (μH)				
	Conf. 1	Conf. 2	Conf. 3	Conf. 4	Conf. 5
30	130	100	100	150	165
50	180	125	180	185	180
80	120	100	100	100	83
100	90	90	100	98	98
120	120	90	98	88	80
150	65	65	68	68	69
180	80	60	65	69	69

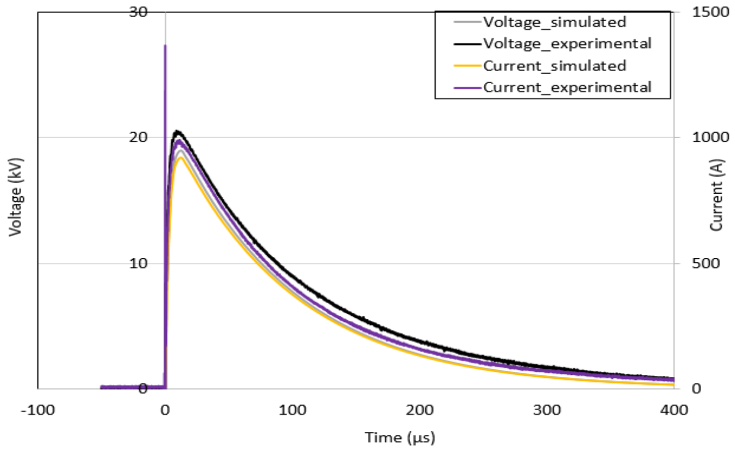

Figure 8. Measured and simulated voltage and current traces for configuration 1 at charging voltage of 30 kV

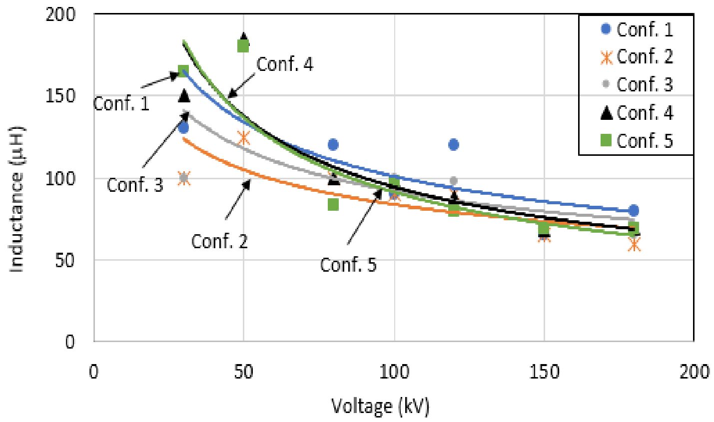

Figure 9. Changes in inductive components with increasing voltage magnitudes for all configurations

5. CONCLUSION

In this paper, impulse tests are performed at field sites, on five grounding systems, subjected to low and high voltage sources. When gravelly soil medium surrounded the ground electrode, R_{DC} values were found to be higher than that with natural soils. When R_{DC} values were computed, it was noticed that differences between the measured and computed R_{DC} are pronounced for ground electrodes surrounded by gravelly soil, which indicates that localised soil has major influence on the calculated R_{DC} values. It was found that with the addition of a gravelly test medium around the ground electrodes, the steady state ground resistance, R_{DC} values are approximately 50% higher than the ground electrodes installed in natural soil (without the gravelly test medium).

A more pronounced observation on the characteristics of ground electrodes under high impulse condition is seen in terms of its current rise and discharged times, which are found to be slower by approximately 24% for ground electrodes surrounded with gravelly soil, in comparison to electrodes installed in natural soil. On the other hand, the impulse impedance values were found to be less affected by the addition of gravelly test medium.

Based on the measured data, the simulation was carried out using PSPICE. Experimental results have shown that slow current rise time for configurations 3 to 5, where the grounding installations filled up with gravelly soil media (high resistivity soil) for the current magnitudes of below 1 kA. This indicates that an inductive effect can be pronounced for grounding systems in high resistivity soil, mainly for grounding systems with large cross-sectional area. Similarly, longer current discharged times the ground is also seen for configurations 3 to 5, where all of these grounding electrodes are filled with gravelly sand media. It was noticed from these experimental results that despite configurations 1 and 3 are having close R_{DC} value, delay in current rise and discharged times could occur for the electrodes installed in high soil resistivity. When Zimpulse values were plotted against the current magnitudes, it was noticed that for the current magnitudes of above 1 kA, close Zimpulse values are seen for all configurations, could be due to better conduction at higher current magnitudes, regardless the R_{DC} or ground electrode's configurations. A significant non-linear behavior of the grounding systems, which can be seen from the reduction of impulse impedance, Zimpulse is found to occur for configurations 4 and 5, where the non-linearity component, α for both configurations, are found to be high.

PSPICE was also utilized where the non-linear equations derived from the experimental work are represented as the non-linear resistance, in series to the inductive components. The inductive values were changed until close agreement between the experimental and simulated voltage and current traces were achieved. It was found that the highest inductive components are seen in configurations 4 and 5, and the lowest inductive component is seen in configuration 2, which are reflective of their R_{DC} values (for example, high R_{DC} values, give high inductive components, and vice versa). Configuration 1 is seen to have higher inductive component than that configuration 3 by 30%, despite close R_{DC} is seen between configurations 1 and 3. This is thought to be due to higher enhancement of ionisation process due to the presence of gravelly sand media in configuration 3, which is indicated as higher non-linear, α in configuration 3 in comparison to configuration 1.

As the voltage/current magnitudes were increased, these effects of impulse impedance, current rise and discharged times and inductive components do not seem to be observable. This could be due to high conduction through the large soil mass. This study shows that the confined soil used, which is gravelly sand media is known to have poor soil resistivity, where more precautions should be considered for the fault current of below 1 kA, since the delay in the current response times, and inductive components could occur more significantly in the grounding systems. In future, impulse characteristics for various soil conditions would need to be carried out, to understand whether the fall of impulse impedance due to ionisation process or the inductive effect in which would cause an increase in impulse impedance would occur in soil when grounding systems are subjected to impulse conditions.

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