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Influences of impulse generators on the impulse characteristics of grounding systems

Usman Muhammad[1], Fazlul Aman[1], Normiza Mohamad Nor[1], Nurul Nadia Ahmad[1], Miszaina Osman[2]
[1]Faculty of Engineering, Multimedia University, Cyberjaya, Malaysia
[2]College of Engineering, Universiti Tenaga Nasional, Kajang, Malaysia

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ABSTRACT

It is important to ensure the effectiveness of the experimental test set up and to accurately characterize grounding systems under high impulse conditions, the study on the effect of impulse generator is therefore needed. As with other experimental work, the test results may be influenced not only by the characteristics of the test load under study, but also the test arrangement, rating of the impulse generator and transducers. In this work, sources of this overshoot/spike observed in voltage and current traces of 1-rod, 3-rod, and 4-rod electrodes subjected to two impulse current generators of different rating: generating at maximum voltage and current of 100 kV, 1.5 kA, and 300 kV, 10 kA with the same response time of 1.2/50 μs are identified with the aid of simulation work.

Corresponding Author:

Normiza Mohamad Nor
Faculty of Engineering, Multimedia University
Persiaran Multimedia Road, 63100, Cyberjaya, Selangor, Malaysia
Email: normiza.nor@mmu.edu.my

1. INTRODUCTION

Ionization process in soil under high impulse currents, whose the changes in soil properties due to several factors; i.e., the current magnitudes, rise times, impulse polarity, ground resistance value at steady state, R_{DC}, soil resistivity and points of injections, causing different degree of non-linearity in soil, were quantitatively studied by previous authors [1]-[16]. Studies on the effect of increasing voltage/current magnitudes and current rise times were normally carried out using the same impulse generator, achieved by increasing the charging voltage and changing the front resistor's value [1]-[16]. There have also been studies presenting experimental results of different impulse generator and rating, producing different charging voltages [2], [5]-[7], however, these are found to be limited, hence will be studied here.

Ametani *et al.* [2] used pulse and impulse generator on horizontal ground conductor of various lengths and grounding mesh of various sizes. Pulse generator was used mainly of low voltage and current magnitudes to evaluate the velocity and attenuation of voltage and current for the horizontal ground conductor, and it was used to measure the steady-state ground resistance value, R_{DC} for the grounding mesh. On the other hand, testing with impulse generator on the grounding mesh produced current magnitudes of more than 10 kA, where the impulse impedance values were found to be 3 to 4 times lower than the corresponding R_{DC}. The work of Ametani *et al.* [2] is an extended work of Sonoda *et al.* [7], published in the year 2000, who have used both pulse and impulse generators. Similarly, Harid *et al.* [6] used a low voltage impulse generator and high current impulse generator producing 400 kV in their studies, and found that the results of low voltage impulse generator are close the R_{DC}, while the impulse impedance values decrease with increasing current magnitudes. On a contrary, Sekioka *et al.* [5] and Sekioka *et al.* [8] used two impulse generators, high impulse generator (HIG) and impulse generator, where both generators can generate tens of kilo amperes to study the performance of ground electrodes under impulse conditions. For the HIG, the current traces are affected by the impedance of the ground electrodes, while it is not the case for the IG. When a transient impedance (taken as transient voltage for a step response) was measured, it was noticed that the transient impedance values for both generators are close at lower crest current, and has slight differences at higher crest current [5], indicating that the performance of ground electrodes is current and energy dependent [5], [8].

In the study [8], impulse impedance values were found to be below 40 Ω, and these values were found to have a weak dependent on the impulse generator's rating for the front times, but have some differences at tail times. This shows that there is a need to study the effect of impulse generator's rating on the performance of ground electrodes, particularly in high steady-state resistance values.

In this current work, ground electrodes with higher range of impulse impedance values of between 50 Ω to 180 Ω are used. For higher steady state resistance values, R_{DC}, expectedly, the electric field is relatively higher, causing ionization to occur more easily than that of low steady state resistance value and soil characteristics can be more observable in ground electrodes of high R_{DC} subjected to different current magnitudes/times. However, the study of different voltage/current responses on ground electrodes of high R_{DC} has been found to be limited, and this paper is aimed to address this research gap. Other aspect that is thought to be lacking in this subject is the tail times. In literature work [2], tail times are associated with the de-ionization process. In this current work, tail times are found to be affected by the generator's rating, which is discussed in terms of the growth of electrons generated due to different size of the capacitors of different generators used.

In order to provide a better understanding on the influence of test circuit on the characteristics of grounding systems, simulation work was carried out to demonstrate the effect of different size of capacitors of impulse generator. From all of the experimental and simulated results, it clearly shows that there is still limited data on the comparison between two different rating of impulse generator, while this is an important topic to look at, as this study shows that the results were not only affected by the characteristics of the test load (grounding systems), but also appreciably affected by the impulse generator. This study provides the guidelines to the researchers that the results obtained should not be discussed strictly on the grounding systems, but also need to include the impulse generator test's circuit, particularly when comparing one study to another research work, and when changing the number of stages of the same impulse generator. Though a large number of studies have been conducted on the grounding systems subjected under high impulse currents generated from various types and rating of impulse generator, this paper is aimed to provide the reasons of some abnormal oscillations and wave shapes observed in voltage and current traces, particularly for the field tests and measurements.

2. TEST ARRANGEMENT

2.1. Impulse test

An experimental arrangement, as adopted in [4] was used in the study (see Figure 1). Each equipment was placed at least at 30 m away from one to another, for both impulse generators, where only the impulse generator and voltage dividers were changed where voltage measurement was achieved with a resistive divider with the ratio of 1000:1 and 3890:1, respectively for the small and big impulse generators. Current transformers with the sensitivity of 0.01 V/A was used for the current measurement for both impulse generators. Two separate digital storage oscilloscopes (DSOs) were used to capture for voltage and current measurements to avoid any residual voltage between the voltage divider and current transformer. In this test, the remote/return earth consists of a square grid having the length of 20 m by 30 m, subdivided into 8 quadrants sub-grid. All of these were interconnected with copper tapes, and installed at 0.5 m below the surface. The rod electrodes of 3 m length with the diameter of 16 mm are equally spaced along the perimeters of the square grid. With the fall-of-potential (FoP) method, as outlined in IEEE Std. 81 [17] ground resistance measurement was carried out, and the measured ground resistance was found to be 8 Ω, which is lower than the measured R_{DC} of the ground electrode under tests, presented in the next section.

2.2. Soil resistivity profiles

Wenner method, as outlined in IEEE Std. 81 [17] was used to measure the soil resistivity at field site. The measured soil resistivity data, was then keyed into current distribution, electromagnetic fields, grounding, and soil structure analysis (CDEGS) software, where the measured data is interpreted into 2-layer soil model. In this work, an upper and lower layer is 202 Ωm and 341 Ωm, respectively, while the depth is 2.7 m and infinity respectively for upper and lower layers. With large depth of the upper layer, all the ground electrodes are only affected by the upper layer, where the details of the ground electrodes are presented in the next section.

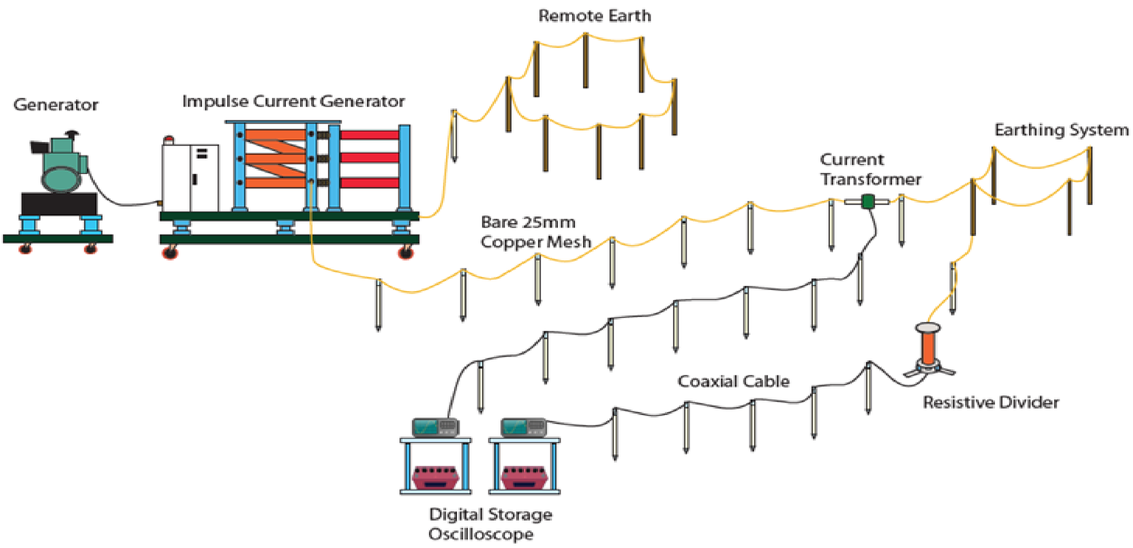

Figure 1. Test arrangement used in the study [4]

2.3. Ground electrodes under tests

Tested ground electrodes consists of a 1-rod, 3-rod, and 4-rod electrodes, which are shown respectively in Figures 2(a) to (c). Each rod electrode contains a 1.5 m, and 16 mm diameter, buried at a depth of 1.1 m from the surface, with 0.4 m above the ground's surface to allow for the connection, depicted in Figure 2(a). For the 3-rod and 4-rod electrodes, arranged in a triangular and in a 2 m×2 m square. With the FoP, ground resistance values were found to be 183 Ω, 62 Ω, and 53 Ω for a single, 3-rod, and 4-rod electrodes, respectively.

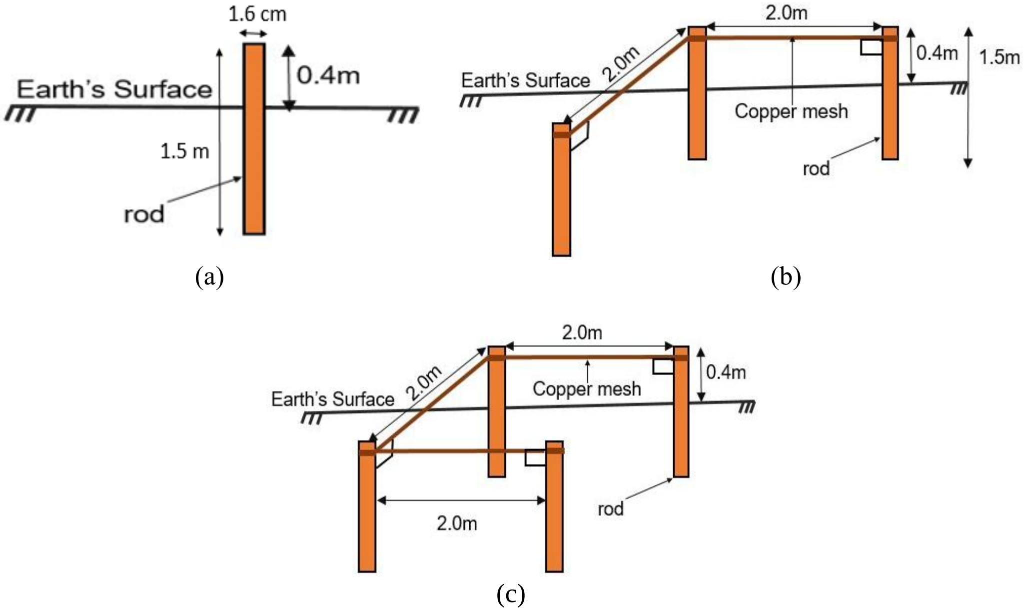

Figure 2. Ground electrodes used in the study; (a) 1-rod electrode, (b) 3-rod electrode, and (c) 4-rod electrodes

3. TEST RESULTS

3.1. Voltage and current traces

Impulse tests were conducted for increasing voltage magnitudes, where the small impulse generator is with the increment of 10 kV until 60 kV, while the big impulse generator is with no specific increment with the charging voltage levels of 20 kV, 30 kV, 50 kV, 50 kV, 80 kV, 100 kV, 120 kV, 150 kV, and

180 kV. Figure 3 shows typical voltage and current traces for a single rod when subjected to 20 kV from a small impulse generator. Similar voltage and current traces are seen when the voltage levels were increased for the single rod electrode. High initial oscillations on current traces are seen, which were thought to be associated with the capacitive effects due to the air voids within the soil and interfaces between the electrode and the soil, as discussed in [1], [11], suggesting that the equivalent circuit of the ground electrode under impulse conditions can be represented as a parallel R-C circuit. Typical voltage and current traces for ground electrodes, subjected to big impulse generator are shown in Figures 4 and 5, respectively at low and high charging voltages. Similar traces were observed for other ground electrodes when subjected to big impulse generator. Initial oscillations, as observed on current trace in ground electrodes subjected to small impulse generator were also observed in Figures 4 and 5.

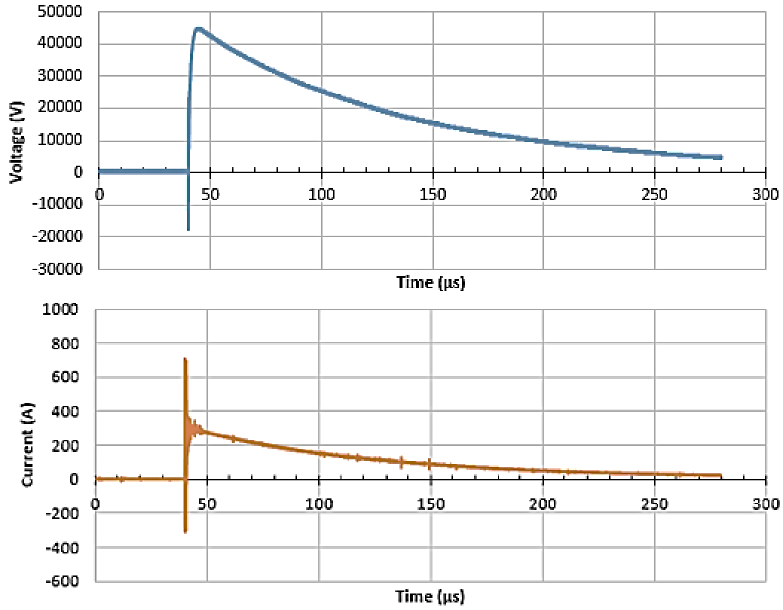

Figure 3. Voltage and current traces obtained with small impulse generator on a single rod electrode at charging voltage of 50 kV

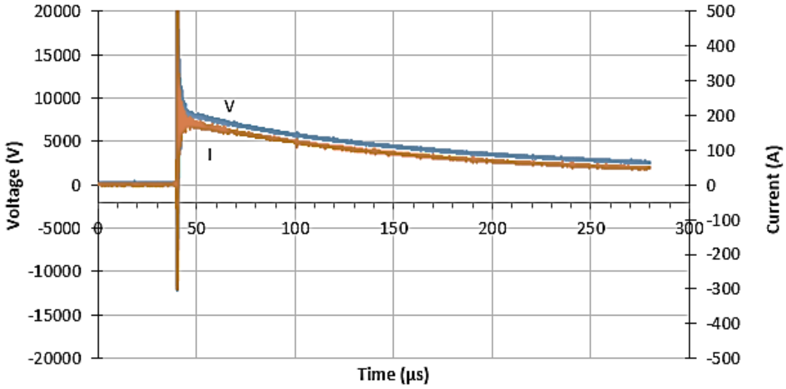

Figure 4. Voltage and current traces obtained with big impulse generator on 3-rod electrodes at charging voltage of 60 kV

3.1.1. Initial oscillations on the current traces due to the test load

In order to show that the initial oscillations are due to the capacitive component, simulated work based on personal simulation program with integrated circuit emphasis (PSPICE) was used. A generating circuit is constructed to produce a double exponential lightning response, where the switch U1 is to trigger the circuit (see Figure 6). An equivalent circuit consisting of an inductance in series with the parallel resistance and capacitive component was used to represent for the grounding systems under high impulse conditions. The capacitance value, C-load of 0.1 μF was used in parallel to a resistance value of 1 kΩ to simulate for high capacitive effect, in which later changed the capacitance value only to 0.0001 μF to simulate for low capacitive effect of the test load, while maintaining the other parameters fixed. Figure 7 shows the simulated current traces for small and large capacitive loads, where larger oscillations were seen in large capacitive load. In relating to the experimental work, initial oscillations on the current traces observed can then be considered as the large capacitive effect from the test load; presence of air voids within the soil and between the electrode and the soil. The effect of capacitance was also investigated for various resistance values in [18] for various ground resistance value, where it was found that the higher the resistance value of the test load, higher oscillations are seen indicating the capacitive component can be dominant, while for the linear test load with low resistance value, resistive component becomes dominant, hence showing no oscillation.

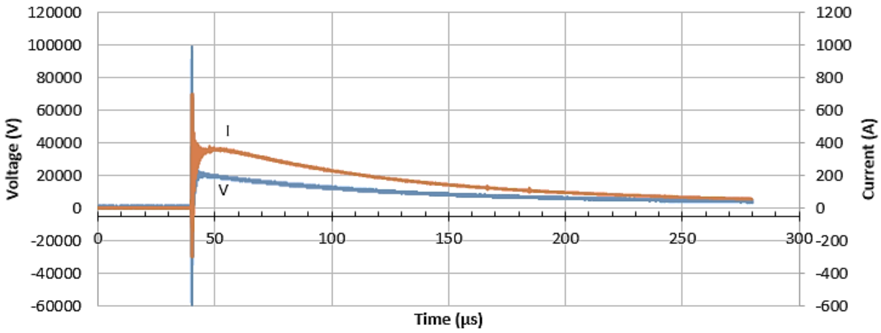

Figure 5. Voltage and current traces obtained with big impulse generator on 4-rod electrodes at charging voltage of 180 kV

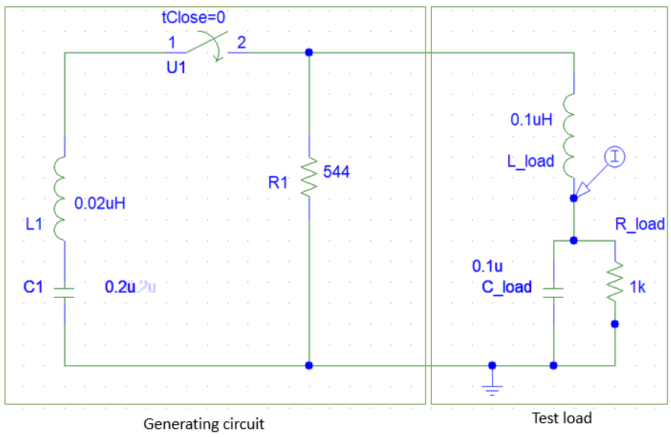

Figure 6. Simulated circuit

3.1.2. Initial oscillations on the current traces due to impulse generator

Careful examination on these initial oscillations on the current traces revealed that larger oscillations for the same ground electrodes subjected to large impulse generator. These oscillations were found to be dependent on the current magnitudes, where the oscillations were reduced at higher current magnitudes, which were thought to be due to relatively improved conduction in ground electrodes causing the system to discharge at faster times. In order to investigate the effect of capacitor of the impulse generator, the same simulated circuit as in Figure 6 was used, where all the parameters were kept the same (L1=0.02 uH, R1=544, L_load=0.1 uH, C_load=0.0001 uF, and R=1000), except for the value of the capacitance C1, which was changed to 0.001 μF and 1 uF, to represent for the small and large impulse generator, respectively. Figure 8 shows the presence of initial oscillations on the current trace of large capacitor (1 uF), which was similar to the results found in experimental work; higher initial oscillations on the current trace when ground electrodes were subjected to large impulse generator, having larger size of capacitor. This shows the initial oscillations on the current trace when subjected to large impulse generator is not solely due to the capacitive effect attributed to air voids within the soil but can also be affected by the large capacitor used in the generating circuit.

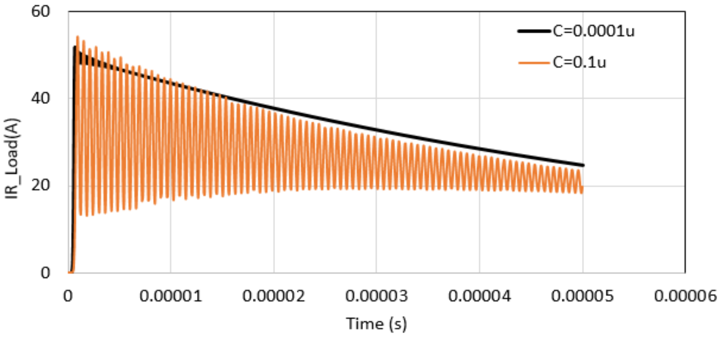

Figure 7. Computed current traces for a charging voltage of 50 kV for different capacitive load, C_load

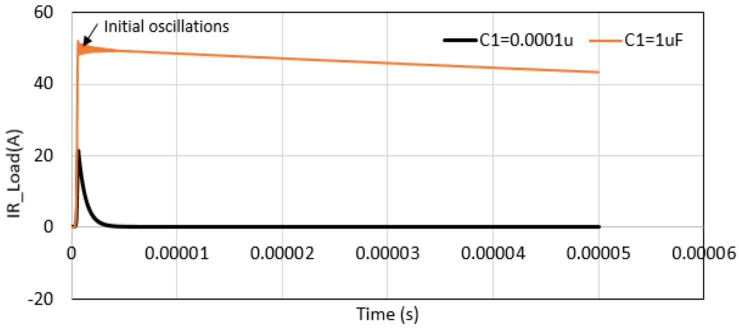

Figure 8. Computed current traces for a charging voltage of 50 kV for different capacitance of impulse generator, C1

3.1.3. Initial oscillations on the voltage traces due to impulse generator

All voltage traces of big impulse generator were found to have initial oscillations (Figures 4 and 5), where these oscillations were not noticed in small impulse generator (Figure 3). Initial oscillations on the voltage trace due to these inductive effects have been known to occur due to parallel arrangement of the voltage transducer to the test load, as highlighted in [18]-[21], causing the voltage measurements influenced by the characteristics of the test load. The effect of the size of the capacitor of the impulse generator on the degree of oscillations on the voltage traces was demonstrated in this work, using similar parameters as in section 3.1.3. Figure 9 shows the simulated voltage traces for large and small capacitance, C1, where the presence of oscillations were seen when C1 was set at 1 uF, while no observable oscillations on the voltage trace when simulated with smaller C1 (0.0001 uF). This proofs that the initial oscillations on the voltage trace observed in ground electrodes subjected to large impulse generator is due to the combination of inductive effects of the test circuit with the capacitive effect of the capacitor bank of large impulse generator, in which these oscillations on the voltage traces are suppressed in small impulse generator.

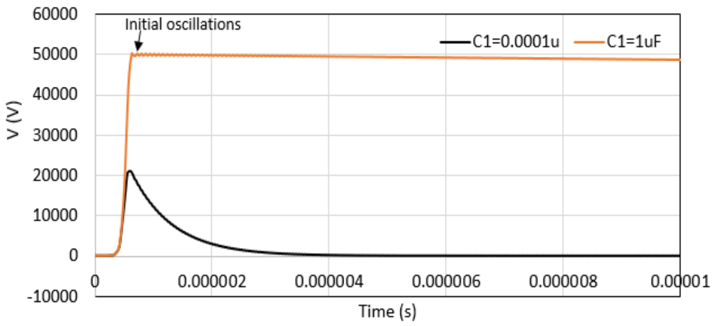

Figure 9. Computed voltage traces for a charging voltage of 50 kV for different capacitance of impulse generator, C1

3.1.4. Current discharged times

When the current discharged times of small and big impulse generators were compared, it was noticed that faster discharged times for both voltage and current traces for the ground electrodes subjected to small impulse generator, as seen in Figure 10, which could be due to a smaller capacitance (0.5 μF) used in small impulse generator than that the capacitance in big impulse generator (0.67 μF), hence faster discharged times. This is similar to the finding seen in [3] who observed that smaller capacitance gives faster times to current peak. Though there was no clear observation on the current discharged times for different capacitors used shown in [3], it would be expected that faster rise times in smaller capacitor would cause the current to discharge at faster time than that of big capacitor. Faster discharged times in smaller capacitor of impulse generator were can be observed from the earlier simulation work (see Figures 8 and 9). This can also be explained from the storage and discharge capability of the capacitors, where for the same voltage level, a smaller capacitor used in small impulse generator stores lesser charge than a big capacitor, hence takes faster time to discharge, in comparison to the big capacitors used in big impulse generator. From the fast discharged times of the capacitor in small impulse generator, electrons generated from the ground electrodes and air voids within the soil and interfaces with the ground electrodes occurred at faster times, hence would cause the conduction process to be shorter which discharged more effectively to the ground at faster time than that of the big impulse generator. All of these show that the results of ground electrode under high impulse conditions can be influenced not only by the rating of impulse generators, which have different size of capacitors but also by the number of stages used for the same impulse generator. This is because, the higher the number of stages, the larger capacitor of impulse generator is, leading to slower current discharged times. Typically, as the number of stages of impulse generator is increased, faster current discharged times are expected due to relatively better conduction at higher voltage/current. However, it can be the case that these current discharged times are not correctly reflected in the results due to slower current discharged times for higher stages of impulse generator due to larger capacitors used at higher stage.

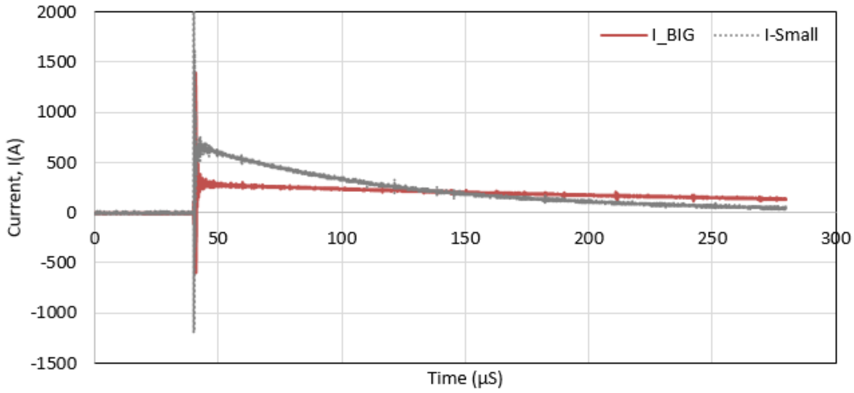

Figure 10. Current traces obtained with small and big impulse generator on 1-rod electrodes at charging voltage of 60 kV

3.1.5. Current rise times

This study did not observe significant difference in the current rise times, as the current traces have fast rise times and high initial oscillations, which make it difficult to see a relation between the current rise times and the impulse generator's rating. However, careful examination on all the traces showed that the current rise times have some delays (see Figure 5), where these delays were observed for 4-rod electrodes at 150 kV and 3-rod electrodes at 100 kV. Using a shorter time scale, it was revealed that longer duration of oscillations on these current traces that caused the delays in the current rise times, as shown in Figure 11. Several studies [1], [4], [10] associated these delays as due to soil ionization process, in which the rate of propagation in forming an ionization zone. At higher voltage magnitudes and in low steady state resistance values, faster current rise times are expected as the generation of electrons from the ground electrodes and the voids become easier, hence the time to ionization process is shorter. However, for the traces shown in Figure 11, it was noticed that the delay in the current rise time occurred at higher voltage magnitudes and the ground electrodes of low R_{DC} values (4-rod electrodes), where the current rise times are expectedly to have faster current rise times. These inconsistencies could be due to the known thermal process where drying and heating processes in soil and statistical nature of the ionization process in soil.

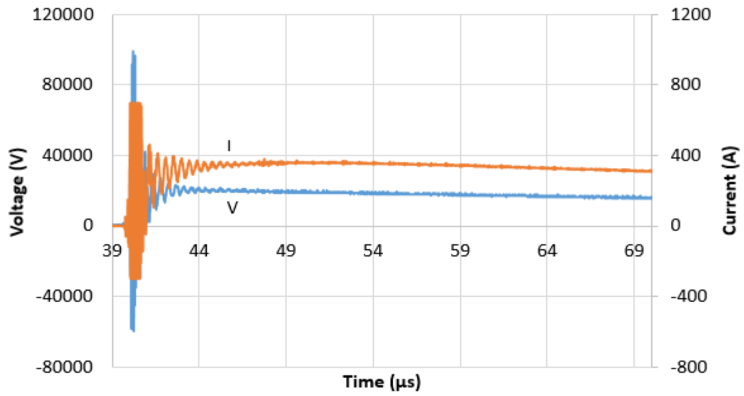

Figure 11. Voltage and current traces obtained with big impulse generator on 4-rod electrodes at charging voltage of 180 kV (short time scale)

Further, it is worth highlighting that several studies [22]-[25] observed from the X-ray imaging techniques that the stronger ionization zones were noticed at the surrounding areas, away from the ground electrodes, instead of near to the ground electrodes. Observations of high electric field at other localized areas and not at the electrodes could be due to electrons produced at high electric field of the air voids, which get multiplied and cause ionization process in soil. Due to different regions that initiated ionization process, it is plausible that different rate of propagation of ionization would occur, result in the current rise times to be statistical in nature, and not necessarily having shorter current rise times in higher voltage impulses and in ground electrodes of low R_{DC}.

3.2. Impulse impedance with current magnitudes

In order to compare the behavior of ground electrodes subjected to small and big impulse generator, the relationship between impulse impedance and the current magnitudes is presented, as shown in Figure 12 for all ground electrodes. Impulse impedance is measured as the ratio between the voltage at current peak to the current peak. As expected, 4-rod ground electrodes have the lowest impulse impedance, followed by 3-rod and 1-rod electrodes, due to the lowest R_{DC} in 4-rod electrodes and the lowest is in the 1-rod electrode.

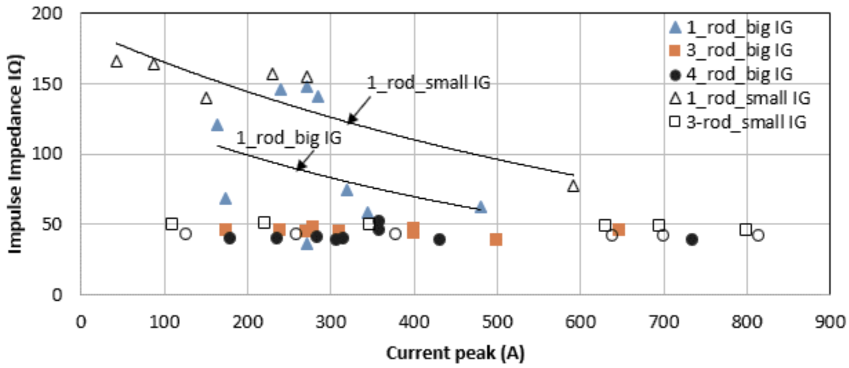

Figure 12. Variation in impulse impedance as a function of current peak for all ground electrodes

It can be seen that the impulse impedance values are independent of the current magnitudes and rating of the impulse generator for 3-rod and 4-rod electrodes. On the other hand, a non-linear behavior of ground electrode is seen for single rod electrode when subjected to both impulse generators. This is rather expected, as observed in [1], [2], [5]–[8], that the degree of non-linearity is dependent on the R_{DC}, where the lower the R_{DC}, the lower the current-dependent characteristics of ground resistance during the passage of high currents. Other significant observation for the impulse tests on the single rod electrode is that for the same current magnitudes, higher impulse impedance values were noticed when the single rod electrode is subjected to small impulse generator, than the big impulse generator. This could be related to a smaller capacitance (0.5 µF) used in small impulse generator than that the capacitance in big impulse generator

(0.67 μF), which is a similar observation seen in [3]. Liew and Darveniza [3] observed that smaller capacitance produces faster times to peak current, causing less time for the ionization process to take place in soil fully, hence higher impulse impedance, as observed in this study.

It was also noticed that the impulse impedance for the single rod are closer to the RDC values for the small than the big impulse generator. This again could be related to small capacitor in the small impulse generator, causing less times to cause ionization process to take place, hence smaller reduction in impulse impedance values than the RDC. This finding was also observed in other published work [6] when impulse tests of low magnitudes of currents were performed on the ground electrodes, where impulse impedance was found to be close to the R_{DC} values.

4. CONCLUSION

Impulse tests using a small and big impulse generator were carried out on 1-rod, 3-rod, and 4-rod electrodes, where the voltage and current traces were captured at various voltage levels. Small and big impulse generators were found to have some differences in their voltage and current traces, where the origins and causes of these differences were investigated with PSPICE software. The test results show that high initial oscillations on the current traces are due to the capacitive effects of the grounding systems. These initial oscillations on the current traces were found to be influenced by the impulse generator; the larger the impulse generator, the larger the degree of initial oscillations were.

The large impulse generator was also found to significantly contribute to the initial oscillations on the voltage trace for all tested electrodes. Slower current discharged times were seen in big impulse generator, which again it was confirmed with PSPICE simulation that the slower current discharged times are attributed to large capacitor of big impulse generator. Inconsistencies in test results were seen in terms of current rise times, which were thought to be due to thermal conduction process, as well as high electric field that may rise at other parts of the ground electrodes. Impulse impedance values for 3-rod and 4-rod ground electrodes were found to be independent of current magnitudes and the rating of impulse generator. However, for the impulse impedance values for 1-rod electrode, a strong decrease with increasing current magnitudes was seen.

Finally, it can be concluded that the work provides a better comprehension on the characteristics of grounding systems under high impulse currents, which show that the size of capacitor of impulse generator, whether when using different rating of impulse generator, or changing the number of stage of the same impulse generator, may affect the results.

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AUTHOR CONTRIBUTIONS STATEMENT

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Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Usman Muhammad	✓	✓	✓	✓	✓	✓		✓	✓					
Fazlul Aman		✓				✓		✓		✓				
Normiza Mohamad Nor	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓
Nurul Nadia Ahmad	✓			✓			✓			✓	✓	✓	✓	✓
Miszaina Osman						✓				✓	✓			

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

INFORMED CONSENT

Not applicable

ETHICAL APPROVAL

Not applicable

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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BIOGRAPHIES OF AUTHORS

Usman Muhammad received his bachelor of electrical engineering degree from Bayaro University Kano (BUK), Nigeria, in 2009. He later completed a one-year intensive power training program at the National Power Training Institute of Nigeria (NAPTIN) from 2014 to 2015. He started working as an energy meter engineer with the Kaduna Electricity Distribution Company in Nigeria in 2020. Currently, he is pursuing a master degree in the areas of earthing systems, lightning strike, and high voltage at Multimedia University in Cyberjaya, Malaysia. His studies are being funded by the Telekom Malaysia Research and Development Agency (TMRnD grant; MMUE/190085). He can be contacted at email: 1191402742@student.mmu.edu.my.

Fazlul Aman completed his bachelor of engineering (Honours) in electrical from Multimedia University (MMU) in Cyberjaya, Malaysia in 2021. He is currently enrolled in a master's degree program in engineering science at Multimedia University (MMU) in Cyberjaya, Malaysia, where he is conducting research in the areas of earthing systems, lightning, and high voltage. He is being supported by a research scholarship under Fundamental Research Grant Scheme (MMUE/210053) by Ministy of Higher Education (MOHE) of Malaysia. He can be contacted at email: 1161302721@student.mmu.edu.my.

Normiza Mohamad Nor received her degree in electrical and electronic engineering from University of Wales, College of Cardiff, UK in 1996. She obtained the Ph.D. degree in electrical engineering from the same university, in 2001. She has actively involved in the consultancy work and research projects in the areas of earthing systems, high voltage and lightning protection systems. She has also delivered a number of seminars on the earthing and protection systems in Malaysia. She is now a professor of electrical engineering at the Multimedia University, Malaysia. She can be contacted at email: normiza.nor@mmu.edu.my.

Nurul Nadia Ahmad received B.Eng. degree in electronic and communications from University of Bristol, UK in 1999, and the Ph.D. degree in electronics and electrical engineering (wireless communications) from University of Southampton, UK in 2005. Her main field of research is in signal and image processing. Her involvement in research has resulted in medals in MTE, ITEX, and PECIPTA. She can be contacted at email: nurulnadia.ahmad@mmu.edu.my.

Miszaina Osman received her bachelor of electrical engineering degree in 1999 and Ph.D. degree in electrical engineering in 2004, both from the University of Southampton, United Kingdom. She is an Associate Professor and currently a Deputy Dean (Research and Innovation) in College of Engineering, Universiti Tenaga Nasional (UNITEN). Her research interests include power system grounding, lightning protection, and high voltage engineering. Currently, she is a member in the National Mirror Committee of IEC TC81 (lightning protection) and CIGRE working group C4.50 on evaluation of transient performance of grounding system in substation. She can be contacted at email: miszaina@uniten.edu.my.