

Article

On the Characterisations of the Impulse Breakdown in High Resistivity Soils by Field Testing [†]

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[†] This paper is an extended version of our paper published in International Conference on High Voltage Engineering and Application 2020, Beijing, China, 6–10 September 2020.

Abstract: This paper presents experimental results of high-current impulse tests on six ground electrode configurations. A high impulse current generator is employed to inject different magnitudes of current into these rod electrodes, under both positive and negative impulse polarities. The effect of increasing the number of rod electrodes, hence the resistance at DC or steady-state (R_{DC}), on the impulse response of ground electrodes is analysed. From the analysis of the results, it was found that the larger the size of rod electrodes, the less current-dependent $Z_{impulse}$ becomes. The percentage of reduction of impulse impedance, $Z_{impulse}$ from its steady state, and R_{DC} values are found to be independent of impulse polarity. However, as the voltage magnitudes were increased, an occurrence of breakdown was seen, with higher breakdown voltage seen in negative impulse polarity in comparison to positive impulse polarity. Relatively, the higher the breakdown voltage is, seen in the ground electrodes subjected to negative polarity, the faster the time to breakdown is.

Keywords: ground electrodes; impulse impedance; breakdown in soil



Citation: Abdul Ali, A.W.; Nor, N.M. On the Characterisations of the Impulse Breakdown in High Resistivity Soils by Field Testing. *Energies* **2021**, *14*, 2401. <https://doi.org/10.3390/en14092401>

Academic Editor: Salvatore Celozzi

Received: 18 March 2021

Accepted: 20 April 2021

Published: 23 April 2021

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1. Introduction

Effective grounding systems are needed to ensure current is dissipated to the ground effectively, ensuring safety for persons and equipment in the vicinity of electrical installations. Many published standards [1–4] on grounding systems have given emphasis to low ground resistance values, to provide an effective path for currents to ground at power frequency and transient fault conditions. There are two main parameters that should be considered in order to achieve low ground resistance values: electrode and soil properties. Larger electrode and low resistivity values are preferred in order to obtain the required low resistance values at the power frequency. However, it was found in several studies [5–9] that the inductive effect can be significant in large grounding systems. Harid et al. [5] observed the presence of inductive effects when impulse tests were performed on vertical rods from 1.2 m to 4.8 m. Predominantly inductive behaviour was also seen for horizontal electrodes, particularly in long horizontal electrodes, when impulse tests were conducted on horizontal electrodes from 14 m to 88 m. Longer rise time in current waveform in larger horizontal electrodes was also seen in [8], when horizontal earth electrodes of 10 m to 60 m were subjected to fast impulses.

In some studies [6,7,9], the inductive effect was also thought to be present, which can be observed as a relatively higher impulse impedance ($Z_{impulse}$) than the steady state resistance (R_{DC}). This is normally seen in low R_{DC} values, where extended electrodes are normally used to obtain a low resistance value. Hence, with the steep fronted transients, higher frequencies are produced, making inductive effects become more significant. As generally accepted, there have been many published works showing impulse impedance values ($Z_{impulse}$) obtained under high impulse conditions are lower than those of R_{DC} [8,10–16]. Lower $Z_{impulse}$ values than R_{DC} values have been well understood to be associated with the ionization process in soil. During this process, the ionization zone causes an effective

increase in the dimension of the ground electrode, reducing impulse impedance values. Furthermore, several studies [17–19] have shown that soil conductivity increases, and relative permittivity decreases at higher frequencies, thus expectedly producing lower impedance values than those measured at the low frequency range. However, many studies [10–13] have shown that the reduction of Z_{impulse} from its R_{DC} value is more pronounced in the grounding systems with high R_{DC} (smaller electrode's geometry and lower soil resistivity). Thus, with the addition of earth electrodes, the R_{DC} will be improved, but it may not be as effective when these electrodes are subjected to high impulse conditions, due to a higher inductive effect, and to a lower percentage of reduction of Z_{impulse} from its R_{DC} , in comparison to smaller ground electrodes.

Due to a much-preferred low R_{DC} in the design of ground electrodes, it may be possible that ground electrodes are not as effective when subjected to impulse conditions, where it may be possible that the inductive component become more significant, hence increasing the Z_{impulse} . At the same time, however, it is difficult to confirm that the performance of the ground electrodes with high R_{DC} can be more effective than low R_{DC} when subjected to various magnitudes of impulse current, as it is conceptually understood that the lower the R_{DC} , the better the soil conduction is. Further, a limited study can be found in the observation of breakdown in practical ground electrodes, showing that good conduction can still be achieved in ground electrodes with high R_{DC} , which can be due to a large soil mass, and low R_{DC} values, hence lowering the electric field value of the soil, preventing the breakdown occurring in the soil. A remarkable, and the most recent, work on the occurrence of breakdown in soil in relation to electric field computation, using field testing, can be found in [20], where the ionisation and breakdown occurs at the high electric field region, which is at the interfaces of electrode and soil. In this current paper, the characterizations of impulse breakdown are carried out in high-resistivity soil, of more than 1000 Ωm , and under both impulse polarities.

Ionization is typically indicated by a clear trend of current traces following the voltage trace, while some initial oscillations are seen in some publications [11], and some delays in current traces are noted [5]. As highlighted in some publications [8,11,21], the ionization process in soil is thought to be caused by dielectric difference between the air voids and the soil, which produces the ionization zone and reduces the ground impedance values. The rate of growth of the ionization zone is dependent on several factors, such as current magnitudes, soil resistivity, grain sizes, impulse polarity, and current rise times. As for the testing at field sites, due to large soil mass, having the majority of the air gaps filled with water, and small air gaps that may appear in natural soil, more current/energy is needed to create dielectric difference between wet soil and air gaps. Due to these factors, slower ionisation growth and shorter current paths may occur, which are shown as the current traces follow the voltage traces, as seen in several other publications [5–13]. However, in this paper, all the ground electrodes are installed in high-resistivity soil, more than 1000 Ωm for the upper layer, which may be drier and have more air voids than the other test sites presented in much research work [6–10,12,13]; hence, at certain voltage levels, it resulted in larger ionization zones, indicated as the occurrence of breakdown in soil.

This paper is aimed at investigating the performance of fast impulses of ground electrodes installed in high-resistivity soil, hence high R_{DC} , which leads to the occurrence of breakdown in soil. In this work, experimental results of six ground electrodes installed in high-resistivity soil are presented. Since little emphasis on the time to peak current, current discharged time, and impulse impedance during the breakdown in soil has been presented in literature, this paper is directed towards this measurement.

2. Experimental Arrangement

A 1-rod electrode consists of a vertical copper rod of 16 mm diameter and 1.5 m length. This 1-rod electrode was joined by a clamp to another vertical rod with a copper tape with a width of 2.5 cm, and with length of 3 m from one electrode to another, and buried 30 cm below the ground's surface. The grounding device with spike rods (GDSR) and the

remote ground electrode were similar to those presented in [13]. Six similar practically tested electrodes are adopted in the present work, as in [13], where ground electrode (GE) 1 consists of a single rod electrode; GE 2 consists of a GDSR; GE 3 consists of two rod electrodes in parallel; GE 4 consists of a single rod, in parallel to GDSR; GE 5 consists of three rod electrodes in parallel; and GE 6 consists of two rod electrodes in parallel to GDSR. In order to provide easy references to the readers, the diagrams of all six electrodes are presented in Table 1. With the Wenner method, the soil resistivity data of the site was obtained, and CDEGS was used, interpreting the soil data into two layers of soil, with the upper layer found to be 1464.4 Ωm , with a height of 8.14 m, and the lower layer 443.4 Ωm with an infinite height. Resistance values (R_{DC}) for all electrodes were measured with a fall-of-potential method, and expectedly, due to high soil resistivity, high R_{DC} values were seen, which were 833.78 Ω , 704.18 Ω , 372.38 Ω , 364.18 Ω , 267.58 Ω , and 253.38 Ω , respectively, for GE1, GE2, GE3, GE4, GE5, and GE6. Return earth for the current during the testing is needed to dissipate high current into the ground during testing, or during the switching on and off of the impulse generator. Though the measured R_{DC} value for the return earth is high, 32 Ωm , the value is considerably accepted, since it is lower than all the six tested electrodes, which are in a range of 253 Ωm to 834 Ωm . Figure 1 shows the test arrangement, which is similar to that used in previous studies [10], where an impulse generator of 300 kV, a resistive divider, a current transformer, and digital storage oscilloscopes (DSO) were used. A divider with a ratio of 3890:1, a Pearson current transformer with a sensitivity of 0.01 V/A, and Lecroy HDO4054 high-definition oscilloscopes of 500 MHz, with 2.5 GS/s and 12.5 Mpts/Ch, were used in the measurements. Distances from one piece of equipment to another are also indicated in the figure; however, the diagram and distances shown are not drawn to scale. With the same test set up, impulse tests were carried out on a linear resistive load, to conform that its voltage and current traces were of a standard impulse and acceptably reliable [22]. In the work [22], it was observed that the current trace follows the voltage trace, and the resistance value under impulse is linear, independent of current magnitudes, and 14% lower than that specified by the manufacturer. A similar result is also seen in [23], where a linear resistor under high impulse conditions was found to be lower than its R_{DC} in a laboratory setting. Here, despite longer meshed copper wires being used, and with other challenges at the field site, it can be concluded that the test set-up used in the study is acceptably accurate and reliable enough to be used for field testing.

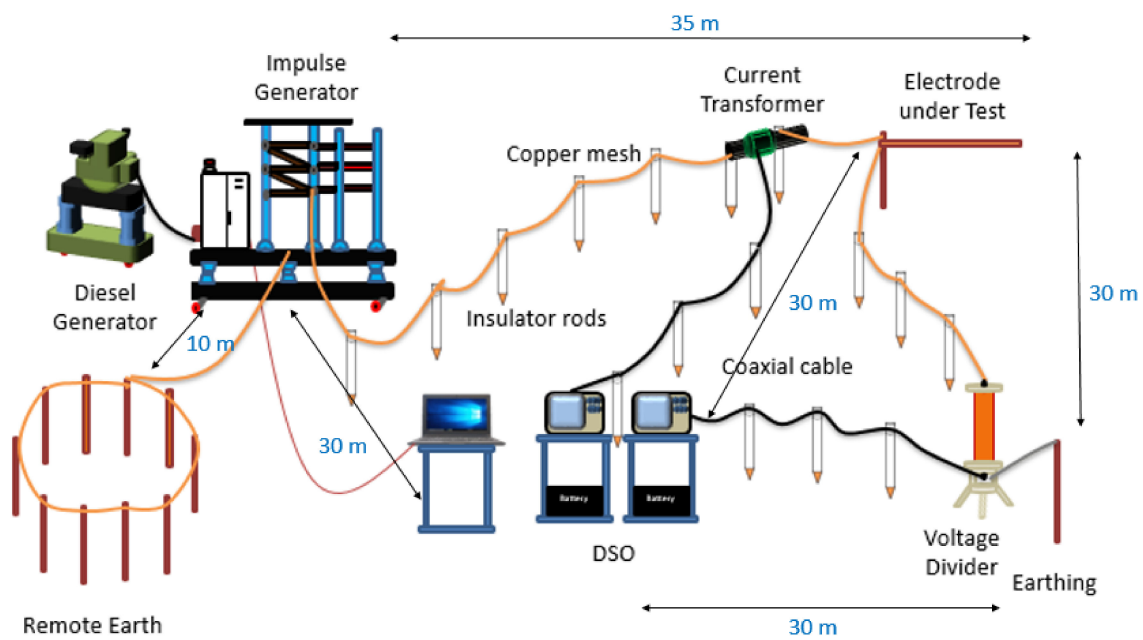


Figure 1. Impulse test arrangement on practical ground electrodes.

Table 1. Various ground electrodes and measured R_{DC} values.

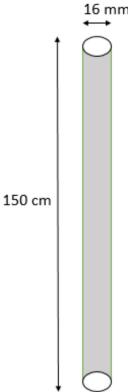
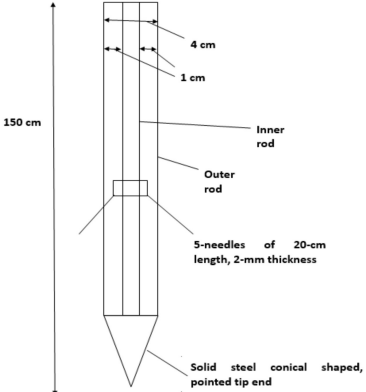
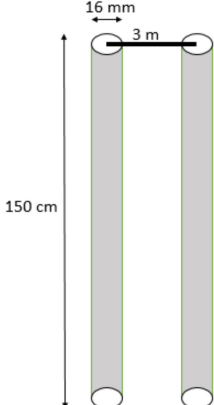
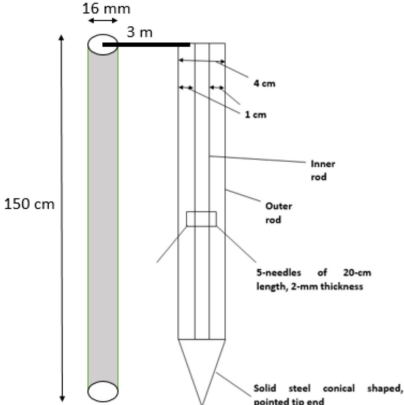
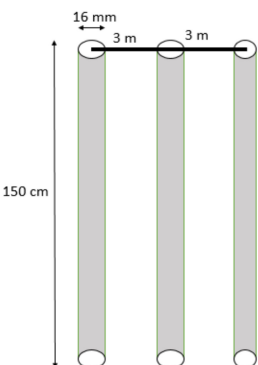
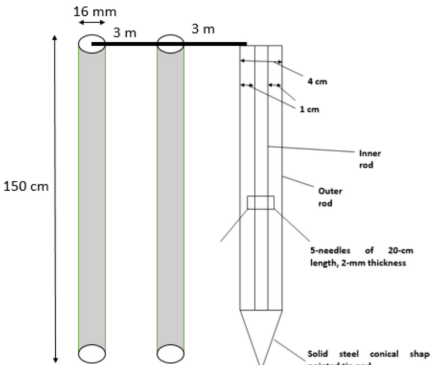
Ground Electrodes	
 GE 1, R_{DC} is 833.78 Ω	 GE 2, R_{DC} is 704.18 Ω
 GE 3, R_{DC} is 372.38 Ω	 GE 4, R_{DC} is 364.18 Ω

Table 1. Cont.

Ground Electrodes	
 GE 5, R_{DC} is 267.58 Ω	 GE 6, R_{DC} is 253.38 Ω

3. Test Results

3.1. Before the Occurrence of Breakdown

Figure 2 shows the voltage and current waveforms obtained for GE5 at 100 kV. Similar voltage and current impulse shapes were seen for all six GEs, at different voltage/current levels. From these voltage and current traces, Z_{imp} values are measured, taken as the ratio of peak voltage to the peak current (indicated in the figure); these values are plotted later on for all GEs. Figure 3a,b show the current waveforms obtained for GE5 when subjected to various charging voltages, at short and long time scales, respectively. As can be seen from Figure 3a, there are clear differences in the current rise times, despite the presence of oscillations on the initial current trace. These current rise times are plotted in Figure 4 and ??s-1168943-f005, for positive and negative impulse polarity, respectively. These initial oscillations are thought to be caused by the capacitive component that may be present due to air voids within the soil, and between the electrode and the soil, as mentioned in [11]. It can be also seen in Figure 3b that the current discharged times are dependent on the current magnitudes: the higher the current magnitudes, the faster the current discharge times are. From the voltage and current waveforms for all test ground electrodes, the current rise and discharged times, and impulse impedance vs. peak current magnitudes are plotted for both impulse polarities. Figures 4 and 5 show the current rises times, for positive and negative impulse polarities, respectively. It can be seen in both figures that the larger the ground electrode configurations (low R_{DC}), the faster the current rise times become, indicating a better conduction in ground electrodes. A better conduction is also seen at higher current magnitudes: the current rise times decrease with increasing current magnitudes. There are, however, some inconsistencies in the current rise times, which can be due to several factors, such as uneven air voids, water movement in soil, soil heterogeneity, and grain size distribution in soil, as well as the initial oscillations that are present in the current traces. GE 6 (with the lowest R_{DC}) has the fastest current rise times for both impulse polarities, indicating good conduction of ground electrodes, due to a relatively low R_{DC} value.

A similar trend can also be seen in the current discharged times, where the fastest discharged times can be seen in the GE6 (with the lowest R_{DC}), while for other electrodes, they are not affected by the R_{DC} values, for both impulse polarities (see Figures 6 and 7, respectively, for positive and negative impulse polarity). This could be due to the presence of the five needles of the GDSR, and its low RDC in GE 6, providing a better conduction level in comparison to other electrodes. In this work, current discharged time is defined as the time taken for the current trace to discharge to zero. It can also be seen from the figures that these current discharged times are high, more than 1000 μ s, which are two times higher than those in previously published work [10,13] for practical ground electrodes.

This is due to the ground electrodes used in this paper being installed in much higher soil resistivity in comparison to those earlier publications [10,13]. It was, however, highlighted in [21] that it is important to have the ionisation occur in a shorter time, so that the impulse impedance can decrease quickly, hence reducing the potential at the top of the tower. Further, the flashover time of the insulator is stated in [21] as occurring within 3 s to 4 s; thus, the ionisation would be expected to occur in a faster time in order to reduce the tripping out rate of the systems. In relation to this study, though the soil resistivity and, relatively, the values of R_{DC} are high, the current discharged times are found to occur below 0.002 s, faster than the flashover time of the insulator.

In this paper, the impulse impedance parameter is defined as the ratio of voltage at peak current to the peak current value. Figure 8 shows the impulse impedance (Z_{impulse} values) at different peak current magnitudes for positive and negative impulse polarities, respectively. As can be seen, the Z_{impulse} decreases with increasing current magnitudes, in both impulse polarities, indicating non-linearity behaviour in soil. Impulse impedance values are plotted with increasing current for all GEs, and it is found that the higher the R_{DC} values, the higher the impulse impedance values are, and the steeper the curves are. It can be seen from the dashed lines that the impulse impedance values of the same GEs are in the same range, for both impulse polarities, indicating that no observable impulse polarity effect is seen for all GEs. The percentage differences are calculated from $(R_{DC} - Z_{\text{imp}})/R_{DC} \times 100\%$, where the Z_{imp} values are considered for their maximum and the minimum. It was noted that percentage differences are found to be in a range of 73% to 89% for these GEs, and these percentages are not affected by impulse polarity. Table 2 summarises the percentage differences for all GEs under both impulse polarities.

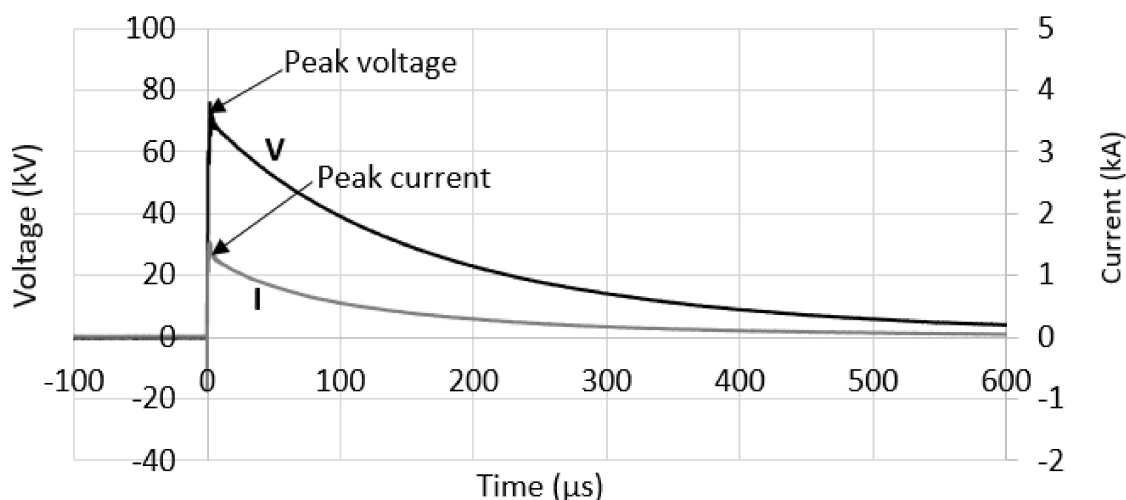
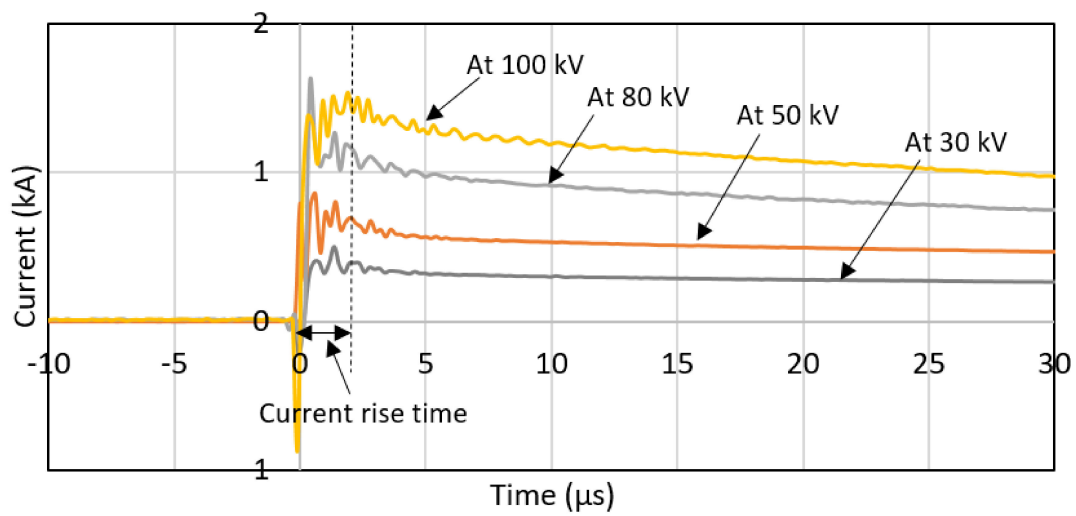
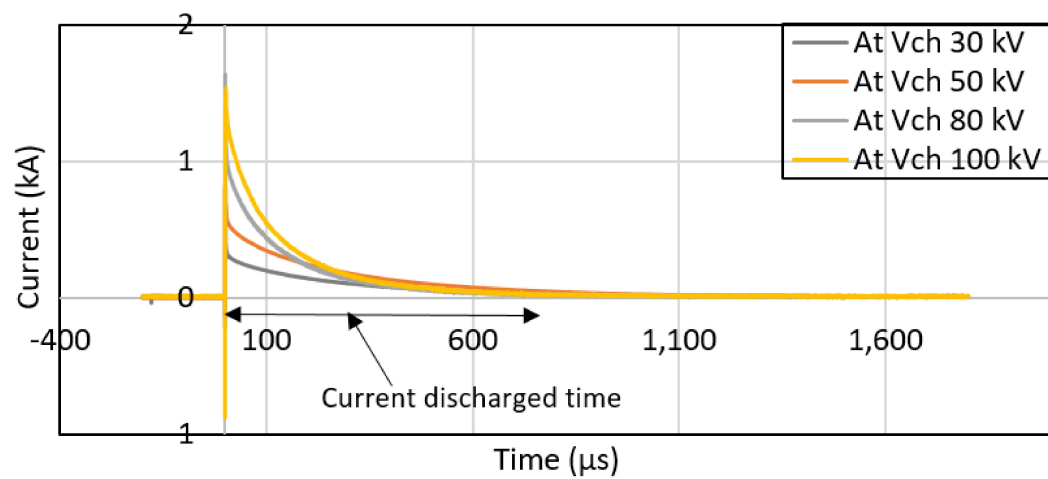


Figure 2. Voltage and current traces of GE 5, at charging voltage of positive impulse polarity at 100 kV.



(a)



(b)

Figure 3. Current traces of GE 5, at various charging voltages of positive impulse polarity: (a) short time scale, (b) long time scale.

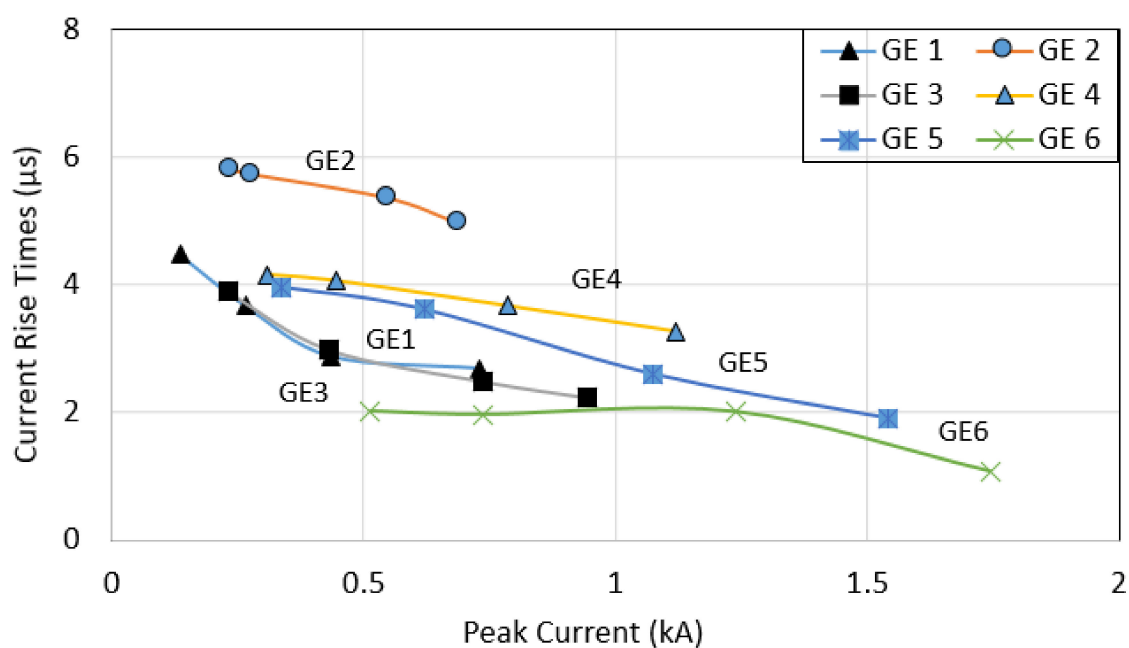


Figure 4. Current rise times for GEs at various peak current magnitudes under positive impulse polarity.

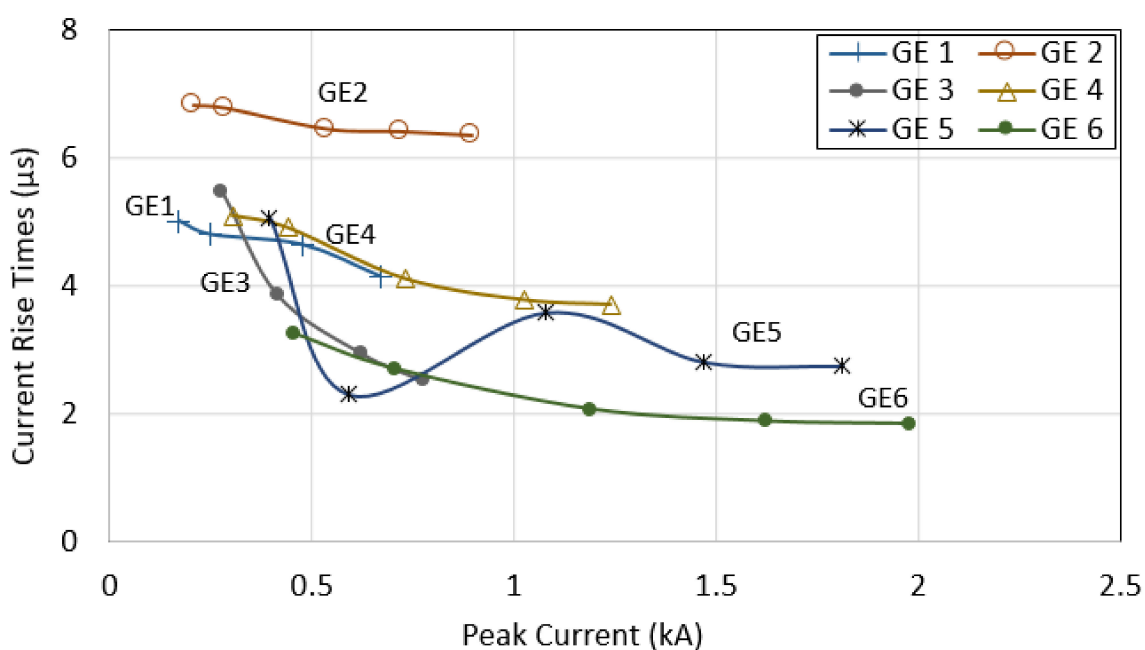


Figure 5. Current rise times for GEs at various peak current magnitudes under negative impulse polarity.

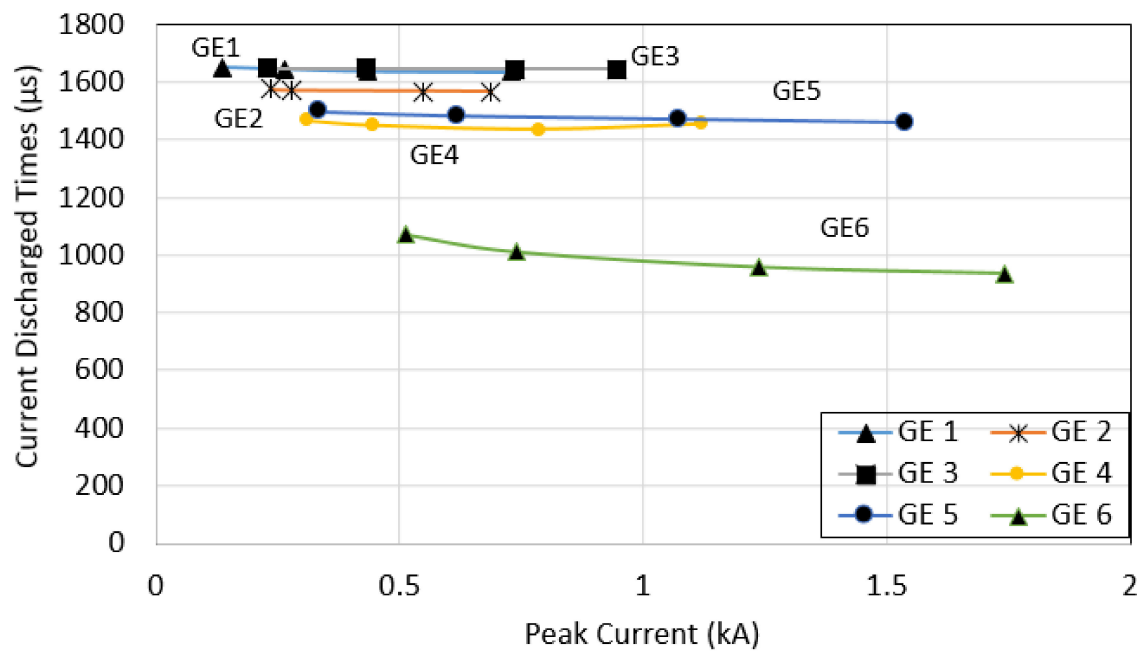


Figure 6. Current discharged times for GEs at various peak current magnitudes under positive impulse polarity.

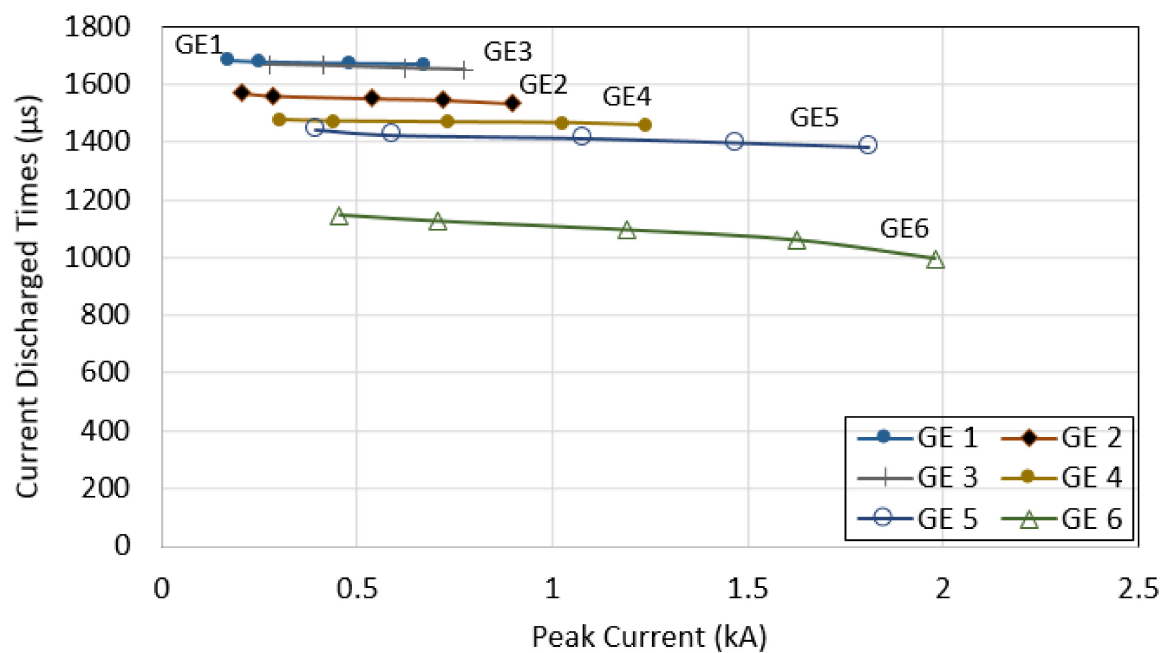


Figure 7. Current discharged times for GEs at various peak current magnitudes under negative impulse polarity.

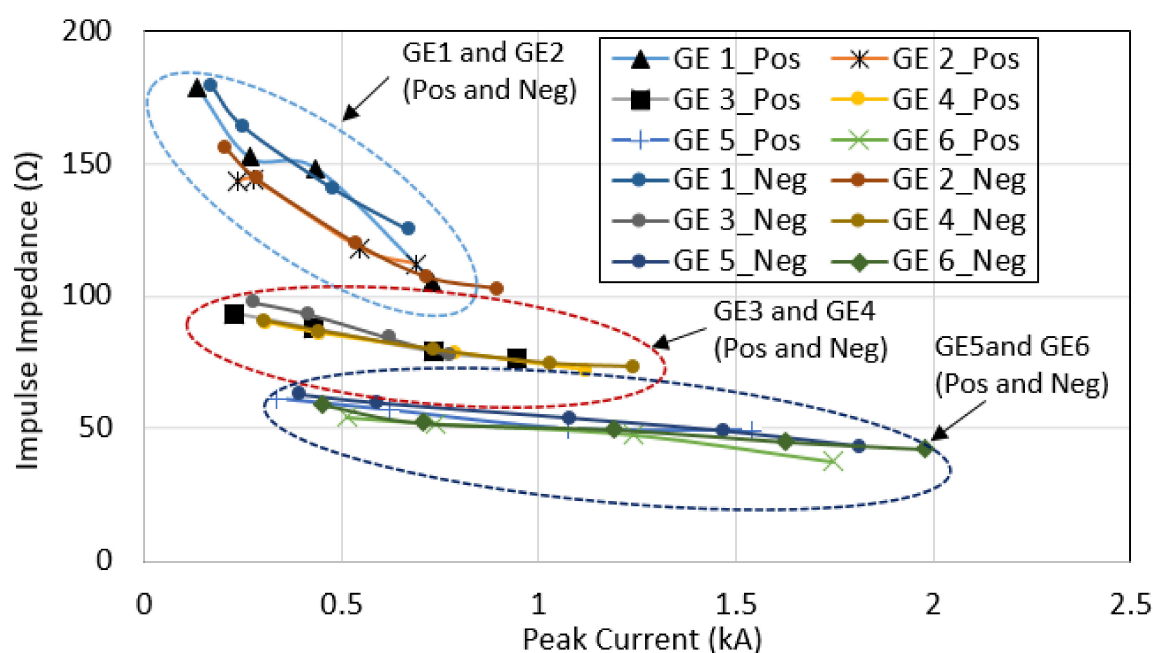


Figure 8. Impulse impedance for GEs at various peak current magnitudes.

Table 2. Percentage drop of Z_{imp} values from its R_{DC} .

Ground Electrodes		Percentage Drop (%) for Positive Polarity	Percentage Drop (%) for Negative Polarity
GE 1	The highest Z_{imp}	78.6	78.5
	The lowest Z_{imp}	87.3	85
GE 2	The highest Z_{imp}	79.7	77.9
	The lowest Z_{imp}	84.1	85.4
GE 3	The highest Z_{imp}	75	73.7
	The lowest Z_{imp}	79.5	79.2
GE 4	The highest Z_{imp}	75.3	75.1
	The lowest Z_{imp}	80.2	80
GE 5	The highest Z_{imp}	77.1	76.5
	The lowest Z_{imp}	81.6	83.8
GE 6	The highest Z_{imp}	78.6	76.7
	The lowest Z_{imp}	85.2	83.3

3.2. During Occurrence of Breakdown

As the voltage magnitudes are increased, breakdown in the soil was observed, as shown in Figure 9. It was noticed from the figure that there was a small rise in current magnitude, during a slow rate of decrease in voltage magnitudes. Upon measuring the impedance values in this pre-breakdown region, it was found that the impedance values were 125 Ω , 90 Ω , 70 Ω , 90 Ω , 44.4 Ω , and 60 Ω , respectively, for GE 1, GE 2, GE 3, GE 4, GE 5, and GE 6 for positive impulse polarity. These values are within the dashed lines, shown in Figure 8. Close values, within the dashed lines indicated in Figure 8, are seen for the case of negative impulse polarity: 100 Ω , 69 Ω , 83 Ω , 69 Ω , 50 Ω , and 52 Ω , respectively, for GE 1, GE 2, GE 3, GE 4, GE 5, and GE 6. These impedance values, which are within the obtained values presented in Section 3.1, indicate that the small current rise in the pre-breakdown region could possibly be due to the growth of conduction, with a smaller ionisation zone, exhibited the during ionisation process, as seen in Section 3.1. After a short time, further conduction in soil had occurred, which resulted in a sudden fall in voltage, and a sharp increase in

current, indicating a bigger ionisation zone was produced. The current magnitudes were found to reach more than 9 kA in several GEs, hence reducing the impulse impedance significantly. Taking the impulse impedance as a ratio of breakdown voltage to peak current, the impulse impedance values are found to be below $20\ \Omega$, pronouncedly reduced from R_{DC} values. The percentage difference between the impulse impedance and the R_{DC} is calculated as $(R_{DC} - Z_{imp})/R_{DC} \times 100\%$ (i.e., for GE 1, R_{DC} is $833.78\ \Omega$, and Z_{imp} during breakdown, taken as peak voltage divide by peak current, is $100\text{ kV}/5.7\text{ kA}$, which gives Z_{imp} of $17.5\ \Omega$; thus, $(833.78 - 17.5)/833.78 \times 100\%$ yields 98%). It was noticed that during breakdown, the Z_{imp} of all GEs dropped more than 95% from R_{DC} values.

It was also observed that the discharged time for current is reduced sharply in comparison to the case without breakdown, presented earlier in Section 3.1, indicating a more effective performance of ground electrodes in discharging high current into the ground. These times to breakdown are also lower than the discharged times for the same tested electrodes that were installed in very low-resistivity soil, and under higher magnitudes of currents, presented in [13]. It was also noted in [21] that with an increase of the peak voltage, a decrease in breakdown time delay is seen for the ground electrodes of rod-to-plate electrodes. Figure 10 shows the typical voltage and current traces during breakdown in soil for all GEs under positive impulse polarity. From these traces, the applied voltage and the time to breakdown are measured for all GEs, as presented in Figure 11. As can be seen in Figure 11, the breakdown voltage of negative impulse was found to occur at higher voltage, and the times to breakdown occurred at shorter times than for positive impulse polarity. It was also noticed that the time to breakdown decreases with increasing breakdown voltage in soil for negative impulse polarity, which was also seen in [11]. On the other hand, the breakdown voltage was found to be constant for positive impulse polarity. The breakdown voltages are found to be independent of the R_{DC} values for both impulse polarities.

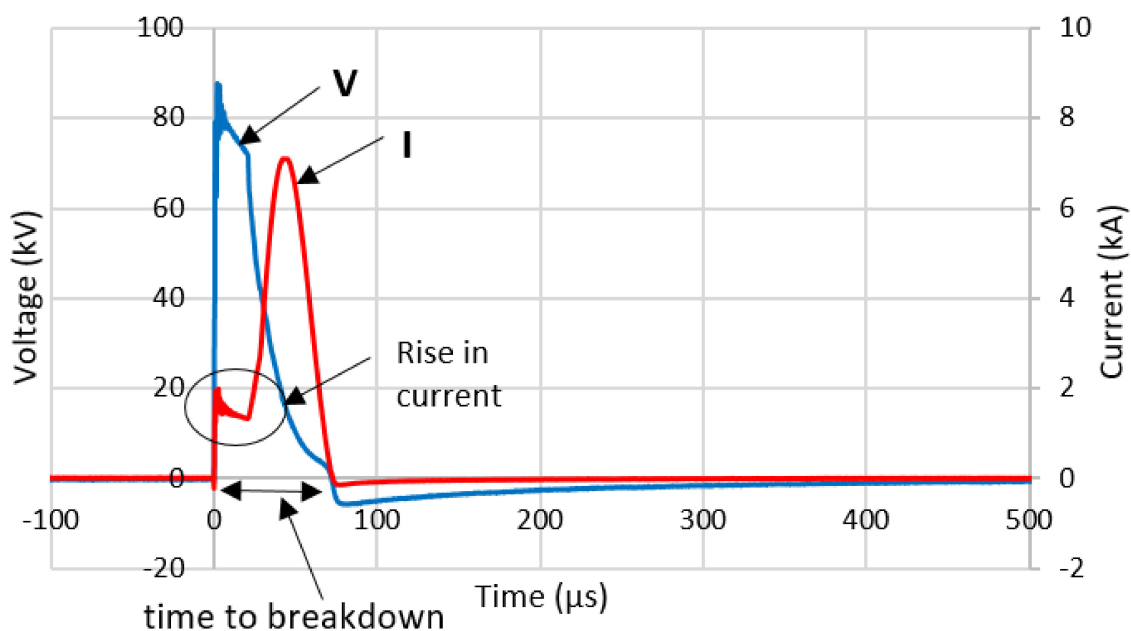


Figure 9. Voltage and current traces during breakdown in GE 5, at charging voltage of 120 kV.

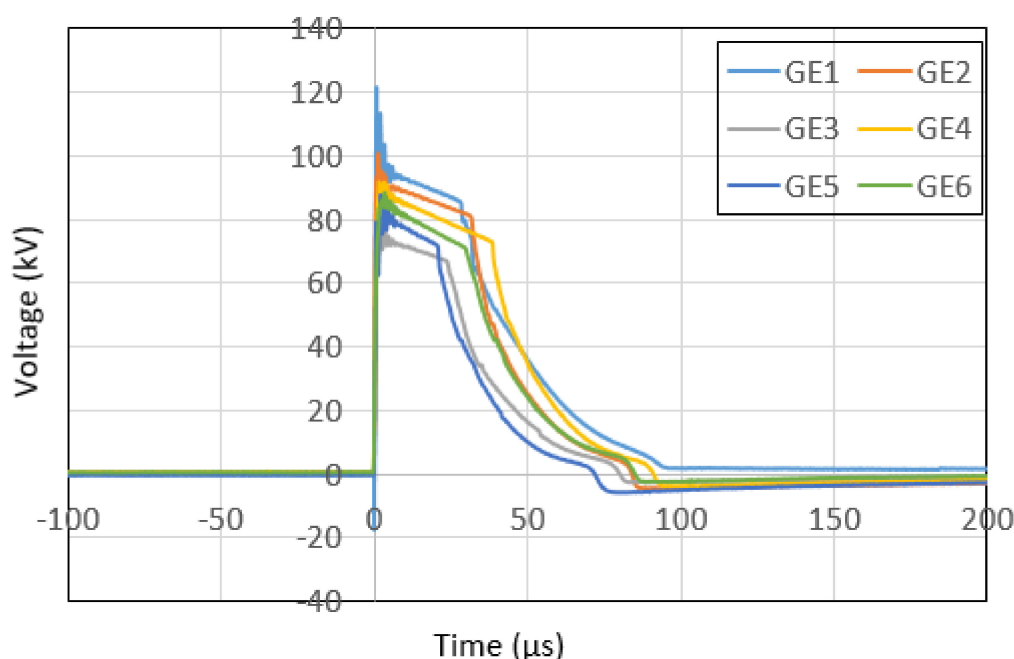


Figure 10. Voltage traces during breakdown at various applied voltages for all GEs at their breakdown voltages.

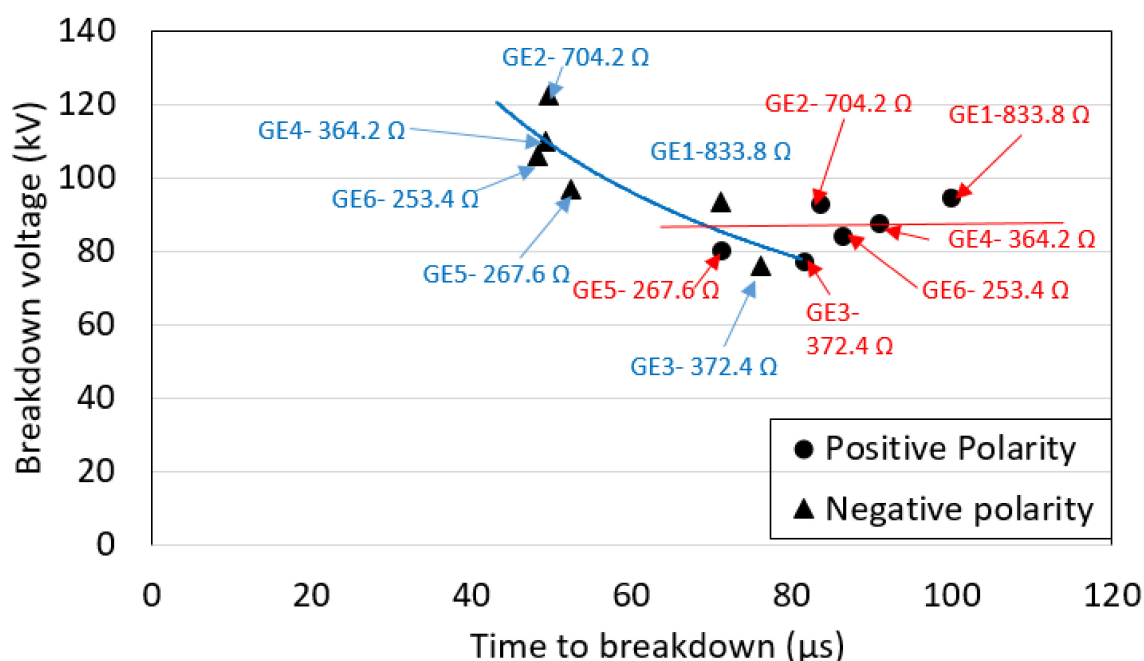


Figure 11. Breakdown voltages vs. time to breakdown for all GEs, with their corresponding R_{DC} s.

4. Conclusions

Experimental tests on six practical ground electrodes under impulse currents by field measurements are presented. From close examination of the current waveforms, it can be seen that current rise times are the lowest in electrodes with low R_{DC} values, while other electrodes have slower current rise times, indicating the inductive effect can be significant in high R_{DC} values. The fastest current discharged times are also noted for GE 6 (with the lowest R_{DC}), whilst the current discharged time are not affected by the R_{DC} for other electrodes. Adding the rod electrodes relatively reduces the R_{DC} . Under impulse conditions, it was found that the percentage drops of $Z_{impulse}$ from the resistance of steady

state (R_{DC}) are in a range of 73% to 89%, and these percentages are independent of the R_{DC} values and impulse polarities. It was, however, observed that $Z_{impulse}$ becomes less dependent on current magnitudes for the GEs with low R_{DC} (GEs 5 and 6). As the voltage magnitudes were increased, breakdown in soil was observed, with a sudden increase of current reaching up to 9 kA in several electrodes, giving a drop of impulse impedance values from their R_{DC} of more than 95%. It was observed that the breakdown voltage of negative impulse polarity is higher than that of positive impulse polarity, giving a corresponding faster breakdown time in negative impulse polarity. The study also found that the impulse impedance is remarkably reduced to below $20\ \Omega$, indicating an effective grounding system during the occurrence of breakdown in soil for these tested electrodes installed in high-resistivity soil. It can be recommended that for hard and high-resistivity soil, where it is difficult to reduce the R_{DC} , impulse tests should be conducted, which can provide some reasonable justification, to some extent, for allowing certain R_{DC} values as adequate, especially for the tower footing, which are normally located in hilly sites, with high soil resistivity, in which it is more challenging to obtain the required R_{DC} .

Author Contributions: A.W.A.A. and N.M.N. were involved in setting up the experiment; A.W.A.A. and N.M.N. sorted out the data; A.W.A.A. prepared the draft; N.M.N. helped with validation of analysis. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by TELEKOM MALAYSIA RESEARCH AND DEVELOPMENT (TMR&D) under grant number MMUE190085.

Conflicts of Interest: The authors declare no conflict of interest.

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