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Influence of remote earth and impulse polarity on earthing systems by field measurement

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Abstract: There has been a vast vacuum in the literature on the importance of the location of remote earth carried out during impulse test on grounding systems using field measurements. Some published work show that the remote earth is installed surrounding the electrode under tests, whilst some have used separate remote earth, away from it. This work studies the impact of return electrode location on transient behaviour of the earthing electrode. The electrode under test is a single rod. Two types of remote earth configurations are used, a circular electrode with multiple rods surrounding the single rod, and one that is 80 m away from it. Impulse tests are conducted under both impulse polarities. Voltage and current traces are captured for a single rod, using two different types of remote earth configurations, with the impulse resistance measured as well. It has been established that the arrangement of the remote earth poses no influence on the test results. That said, higher oscillations of current traces and higher resistance values have been observed in negative impulse in comparison with positive impulse polarities.

1 Introduction

It is suggested by the standard [1] that, a proper remote earth must be constructed during high impulse test by field measurement in order to provide a path for return current from the electrode under test. However, this means that the influence achieved by the remote earth on the earthing system measurements under high impulse conditions by field measurements by having a separate earthing system or earthing systems around the electrode under test has not been specifically addressed in the standard [1]. Many studies [2–5] have used separate earthing systems as the return/remote/auxiliary earth when impulse tests are conducted on earthing systems by field measurements. Fig. 1 illustrates a layout of a test arrangement for field tests on earthing systems, where the remote earth is located more than 20 m away from the electrode under test. Having separate remote earth to discharge high currents during impulse tests on earthing systems by field measurements has been commonly adopted by many researchers [2–5].

Haddad *et al.* [6] have used a ring electrode around the electrode under test as the remote earth. An impulse test has been carried out on tower footings by a 20 kA impulse generator having a ring electrode connected to eight peripheral rods as the remote earth [6]. Based on the impulse resistance results, the authors of [6] found that the resistance value of the ring electrode is smaller than that of the tower base, therefore the measured results are mainly correspond to the tower base characteristic. This has led to another experimental study conducted to investigate the effect of remote earth on impulse characteristics of earth electrodes [7] with four types of remote earth configurations are presented where the tower footing is the electrode under test. A comprehensive study presented, comparing the effects of having four types of return/remote/auxiliary earth electrodes, namely, the commonly used separated single rod electrode placed at 30 m away from the electrode under tests (refer to Fig. 2*a*), eight rods in a circular ring configuration with multiple rods interconnected by an insulated copper conductor buried at 0.3 m surrounding the tower footings (refer to Fig. 2*b*), eight-rod electrode around the tower footings interconnected by bare ring electrodes buried at 0.3 m (Fig. 2*c*), and a circular ring electrode around the tower footings, disconnected from all the rods (refer to Fig. 2*c*). It has been observed by the authors [7] that different remote earth offers different rates of decrease of R_{impulse} with increasing currents.

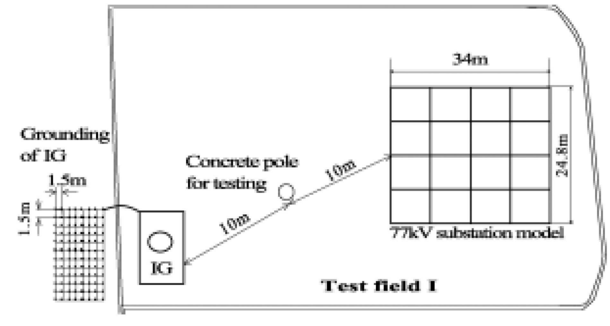


Fig. 1 *Separate remote earth configurations (reproduced from [2])*

On the other hand, Yunus *et al.* [8] carried out a detailed study on the effect of configuration/size of remote earth on the measurements of earthing systems using separated remote earth. Four configurations of the electrode under test are applied to four different types of remote earth configurations. The result achieved is that, when the resistance at power frequency, the R_{DC} of the remote earth is higher than the electrode under test, the impulse resistance of the main earthing systems becomes higher than that of their steady-state values, R_{DC}. This shows that the measurements of the electrode under tests are affected by the return/remote/auxiliary electrodes. The authors of [8] also highlighted that the R_{DC} values of remote earth must always be lower than the R_{DC} of the main electrode under test.

The construction of the circular electrode or ring configurations with multiple rods around the electrode under test as presented in [6, 7] is commonly perceived to be challenging when it comes to larger and more complex earthing systems such as the substation earthing systems. Therefore, this present study is essentially carried out to investigate how the results for both types of remote earth configurations can affect the measurements on earthing systems under high impulse conditions. Furthermore, there has been insufficient information found on the test set up, remote earth, the allowable distance for separate remote earth etc. This calls for a discussion on how two different places of remote earth can affect the measurements.

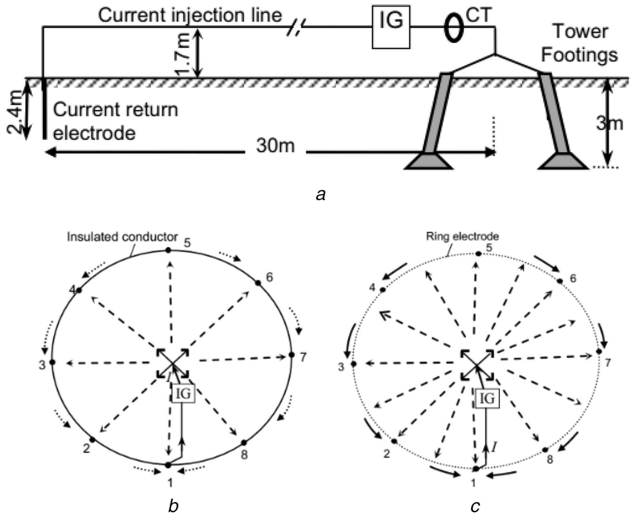


Fig. 2 *Remote earth configurations (reproduced from [7])*
(a) Single rod electrode, ***(b)*** Multiple rod electrodes, ***(c)*** Combined ring and rods electrode

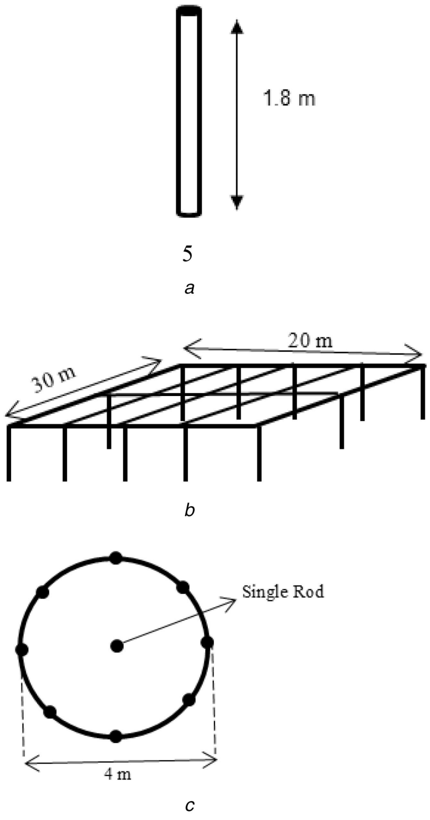


Fig. 3 *Earth electrode configurations*
(a) Main earthing system: a single rod, ***(b)*** Remote earth: grid with multiple rods located 80 m away from the earth electrode under tests, ***(c)*** Remote earth: circular ring electrode with multiple rods around the earth electrode under tests

In this work, impulse tests are conducted on a single rod electrode by using two types of remote earth configurations; separate grid with multiple rods and ring with multiple rods around the electrode under test, under both impulse polarities. Very limited information can be found in the literature on the effect of impulse polarities on earthing systems by field measurements. So far, to the authors' knowledge, one published work by Androvitsaneas *et al.* [9] has conducted field measurements with the effect of ground enhancing compounds (concrete and bentonite). They found that close percentage decrease of earth resistance for both impulse polarities.

So far, the authors of [10–15] have investigated impulse polarity on earthing systems in laboratory settings. Loboda and Scuka [10] and Cabrera *et al.* [11] find soil behaviour is independent of impulse polarity. On the other hand, Petropoulous [15] observes that soil behaviour is affected by impulse polarity, since he finds that for similar electrode dimensions and soil resistivity, higher E_c and breakdown voltage levels are observed in negative impulse in comparison with positive impulse. Similarly, Cabrera [12] observes that the discharge mechanism of soils depends on impulse polarity. With the aid of photographic studies, it has been observed that when an electrode is subjected to a positive impulse, the streamers are initiated from the central conductor and propagated outwards to the low-field regions. However, when a negative impulse is applied, the streamers are found to start far from the central conductor and propagated towards the central conductor.

These inconsistencies in the findings of the effect of impulse polarity on the characteristics of earthing systems call for further detailed studies. It is, therefore, necessary to investigate whether soil behaviour is affected by impulse polarity, which this study aims to address as well as the shortfall of the study on the effect of impulse polarity on earthing systems by field measurements. The results on the influence of remote earth and impulse polarities are presented and discussed.

In summary, this study is aimed to contribute towards the improvement on a field measurement and test set up on experimental work on earthing systems under high impulse conditions. This involves the study on the effect of having a different arrangement of the remote earth (whether a separate remote earth away from the electrode under test or the remote earth around the electrode under test), which has not been addressed before. This study is hoped to provide flexibility, confidence, and safety for future researchers in constructing the remote earth for field measurements on earthing systems under impulse conditions. Another contribution of the work is the study of soil characteristics undergoing these both polarity impulses, which allow the effect of polarity by field measurement being investigated and clarified. Impulse test results in this study have revealed that further work is needed in the earthing systems under high impulse conditions by field measurements due to limited availability of published data.

2 Experimental arrangement

2.1 Earth electrode configurations

In this study, three earthing systems are constructed, with one used as the main earthing system under test, whilst the other two as the remote earth configurations. The main earthing system under test consists of a single rod, with the dimension of 1.8 m in length and 8 mm in diameter. The rod is buried at a depth of 1.4 m in the soil with some parts of 0.4 m deep is left exposed to the external surface of the earth for connection and measurement purposes later on (refer to Fig. 3*a*). On the other hand, the other two earthing systems act as the remote earth; one is a separate grid with multiple rods away from the main earthing systems under test, while the other one is a circular ring electrode with multiple rods around the earth electrode under test as shown in Figs. 3*b* and *c*, respectively.

For a separate remote earth, it consists of a grid located 80 m away from the single rod under test, and a ring electrode that was constructed around the main earthing system (single rod). The remote earth that was placed 80 m away from the single rod is a rectangular grid of (20 m × 30 m) and equally spaced, which makes up of eight meshes. The grid consists of a copper plate of 2 cm in width and buried at a depth of 0.5 m inside the earth. These copper plates are clamped together to form a grid. There are 12 vertical rods connected to the grid, each of which is 1.8 m in length and 8 mm in diameter and is connected to the grid by copper clips refer to Fig. 3*b*. On the other hand, another remote earth is constructed using eight vertical rods in a shape of a ring wrapped around the single rod electrode. Each rod used in this ring configuration is of 1 m in length and 8 mm in diameter buried 30 cm under the ground. A steel wire of 5 mm diameter is laid and connected to the multiple rods by clamps as presented in Fig. 3*c*. The radius of the ring electrode with multiple rods is 1.5 m from the rod under tests. Since the rod under test is 8 mm in diameter, 2 m radius of the ring electrode with multiple rods makes up to more than 2000 times

Table 1 Measured direct current resistance of remote earth

Earth electrode configurations	R_{DC}, Ω
single rod (main electrode under tests)	67.8
ring (remote earth around the single rod)	21.2
grid (remote earth 80 m away from the single rod)	2.58

bigger than that the electrode under tests. By having an 'adequate' distance between the rod under test and the ring with multiple rods surrounded around it, it can reduce the mutual inductance and resistive coupling effect that may be present and included in the measurement results. At this stage, it is out of the scope of this paper to study in detail on the effect of distance of remote earth between the rod and the remote earth surrounding it. However, the authors wish to address this issue in a separate publication which will be worthy of study in near future. Other factors that can affect the remote earth are the soil resistivity and moisture contents of remote earth built surrounded the rod under test. It has also been seen in many studies that soil resistivity and moisture contents have a strong influence on the grounding systems [13, 14, 16–19], and these effects cannot be ignored. It would be expected that if the distance of the remote earth from the rod is changed to a different location, the results would be expectedly different too. However, in this study, these soil resistivity and moisture contents are not being considered. Further study in future in a separate publication will help to clarify and quantify these effects.

2.2 R_{DC} measurements

Using the fall-of-potential method, as outlined in IEEE standard [1], the earth resistance, R_{DC} for each remote earth and single rod are measured and presented in Table 1. Expectedly, the grid has the lowest value of earth resistance due to its large size configurations. The earth resistance values of the two electrode geometries presented in Table 1; single and ring earth electrodes are the resistance of each configuration depending upon different dimension parameters of each configuration and non-reliant to the distance which separated them.

2.3 Impulse test set-up

Figs. 4*a* and *b* show the test set up for the impulse current tests. The impulse current generator is a custom-made impulse generator that can generate lightning impulse current with the ability to be mobilised to the test sites. The three-stage impulse generator is capable of producing charging voltage from the lowest 30 kV to the maximum of 300 kV. The voltage divider and current transformer are used in this test to measure both voltage and current signals, respectively. The voltage divider ratio is 3890:1 with a response time of 8 ns and the current divider has a sensitivity of 0.1 V/A with a response time of 20 ns. Impulse tests are conducted at different voltage levels, under both positive and negative impulses for a single rod, with different remote earth. Meanwhile, two digital storage oscilloscopes (DSOs) of 350 MHz are used to capture the voltage and current signals separately, to avoid any residual voltage that may develop during the tests. These DSOs are powered by two separate power banks (1000 Ah) and converters (24–240 V) for isolation purposes. The voltage divider is earthed to an isolated earthing system.

3 Influence of remote earth

In this section, the influence of remote earth on a single rod is investigated, with a ring placed around the electrode under test, while the grid as a remote earth is investigated and analysed using impulse currents of positive polarity. The effect of impulse polarity is presented in Section 4 of this paper.

3.1 Voltage and current traces

Fig. 5*a* shows the voltage and current traces for single rod using the ring as remote earth at a 50 kV charging voltage and Fig. 5*b* shows the voltage and current traces for single rod using the grid as the remote earth at 60 kV charging voltage for positive impulses. It can be seen from Fig. 5*a* that the voltage and current traces have a similar fast rise time to Fig. 5*b*.

Furthermore, Fig. 6 shows the current and voltage traces at higher charging voltage which is at 120 kV for single rod using: (a) ring as remote earth and (b) grid as remote earth. From Fig. 6*b*, it can be seen that, at a higher injected voltage with the grid as remote earth, more oscillations on the current signal is generated in comparison with Fig. 5*b*, with a lower charging voltage of 60 kV. However, these oscillations and the factors affecting it are unknown to the authors. The increase in oscillations on current traces with increasing voltage/current for both types of remote earth configurations can be seen clearly in Figs. 7*a* and *b* for ring and grid remote earth, respectively. In addition, Figs. 7*a* and *b* show that the current decays faster at higher charging which could be caused by the pre-dominantly resistive behaviour of the earthing systems configured at higher voltage/current levels. The authors sense that this could also be caused by its high resistivity values. When the Wenner method is performed for soil resistivity data, soil resistivity is found to be below 331 Ωm (refer to Table 2). The authors of [16, 20] suggest that for high soil resistivity, above 1000 Ωm, the capacitive effects become significant, which can be the cause of oscillations in the current traces. The soil resistivity values found in this study are below 331 Ωm, which is below 1000 Ωm. The authors have concluded that the relationship between high resistivity values with increased oscillations and increasing currents requires further study in future.

Fig. 8 shows the time to current peak for a single rod with the ring placed as remote earth and grid as remote earth at different charging voltages. It is observed in Fig. 8 that the time to peak decreases as the charging voltages increases. Similar results are established by Mohamad Nor *et al.* [17] where the time to peak current is found to decrease with increasing currents. This time relation with voltage/current levels could be due to the rate of propagation of ionisation where at low voltage/current, a slower rate of ionisation propagation as compared with high voltage/current levels. Thus, better conduction would be expected at higher voltage/current magnitudes.

3.2 $R_{impulse}$ calculated

The impulse resistance, R_{impulse} is calculated from the voltage and current signals captured by two DSOs. Many publications [14, 17, 18] use (1) to obtain the value of R_{impulse} so that inductive effects can be minimised. In this approach, $V_{\text{at}}\ I_{\text{peak}}$ value is taken at the time when the current is at its peak

$$R_{\text{impulse}} = \frac{V_{\text{at}} I_{\text{peak}}}{I_{\text{peak}}}. \tag{1}$$

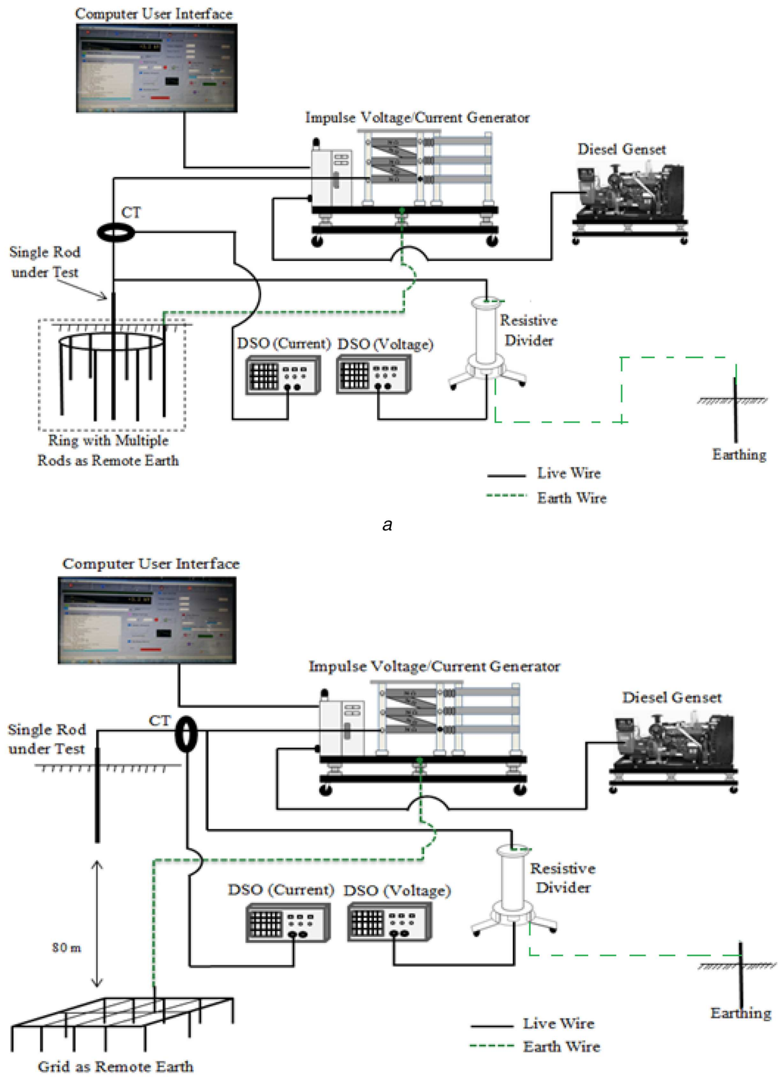
Fig. 9 shows the plotted R_{impulse} values against the current. As expected, it can be seen from this plot that impulse resistance for a single rod with the separate grid as remote earth and ring around the single rod as remote earth decrease as the current magnitude increases. This is similar to those found in other publications [2–4, 6, 7, 14, 17, 18]. The values of R_{impulse} of the single rod using both types of remotes are also found to be close. This shows that both types of remote earth configurations are acceptable for the field measurements on earthing systems under high impulse conditions.

4 Effect of impulse polarity

The results presented in Section 3 have shown that the arrangement of the remote earth did not affect the results. In this section, the effect of impulse polarity on single rod with ring electrode around the electrode under test as the remote earth is investigated.

4.1 Voltage and current traces under negative polarity

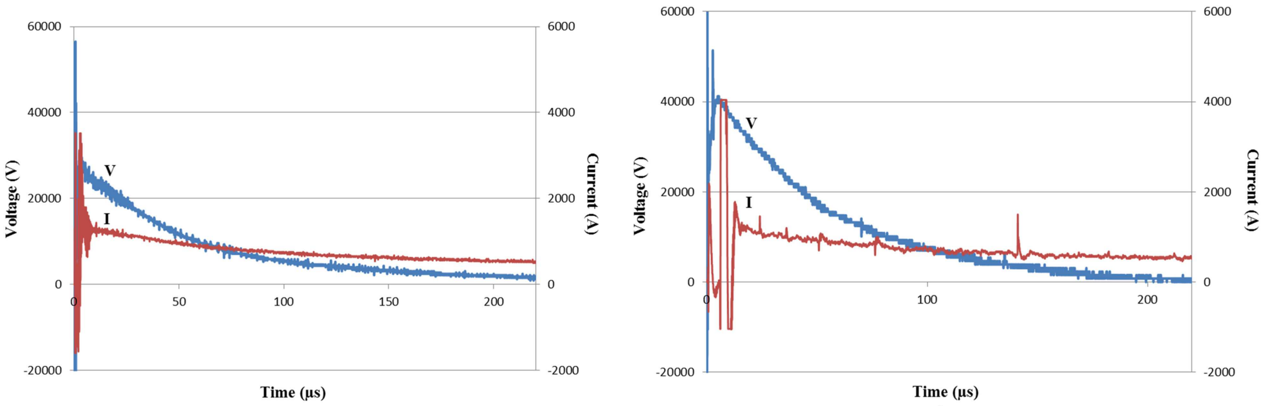
Fig. 10 shows voltage and current traces of a single rod electrode earthing system at applied voltages of 100 kV under negative impulse polarity. Similar voltage and current traces as in Fig. 10 are seen at different voltage levels where voltage and current traces



a

b

Fig. 4 *Test set-up for impulse tests for different remote earth*
(a) Single rod using ring as remote earth, ***(b)*** Single rod using grid as remote earth



a

b

Fig. 5 *Voltage and current traces for single rod at low charging voltage*
(a) Ring as remote earth at 50 kV charging voltage, ***(b)*** Grid as remote earth at 60 kV charging voltage

have fast rise and decay time. Some oscillations, as observed in positive polarity are also observed on the current traces at a lower voltage level (refer to Fig. 11). These oscillations are thought to be present due to some capacitive effects in the soil that exists between the soil grains, and the contact between the soil and the rods. Furthermore, similar to current traces for all levels of applied voltage shown in Fig.7, it is found that peak current occurs at similar times to peak voltage, due to the predominant resistive behaviour of the earthing systems.

On the other hand, oscillations on current traces are seen to be higher in negative polarity in comparison with a positive polarity (see Figs. 7 and 11). This could occur due to lower currents in negative in comparison with positive polarity thus achieving the less resistive effect. The levels of oscillations on current traces are found be independent of voltage/current levels. This trend is different than observed when a single rod is used under positive impulse polarity. The authors suggest that different characteristics

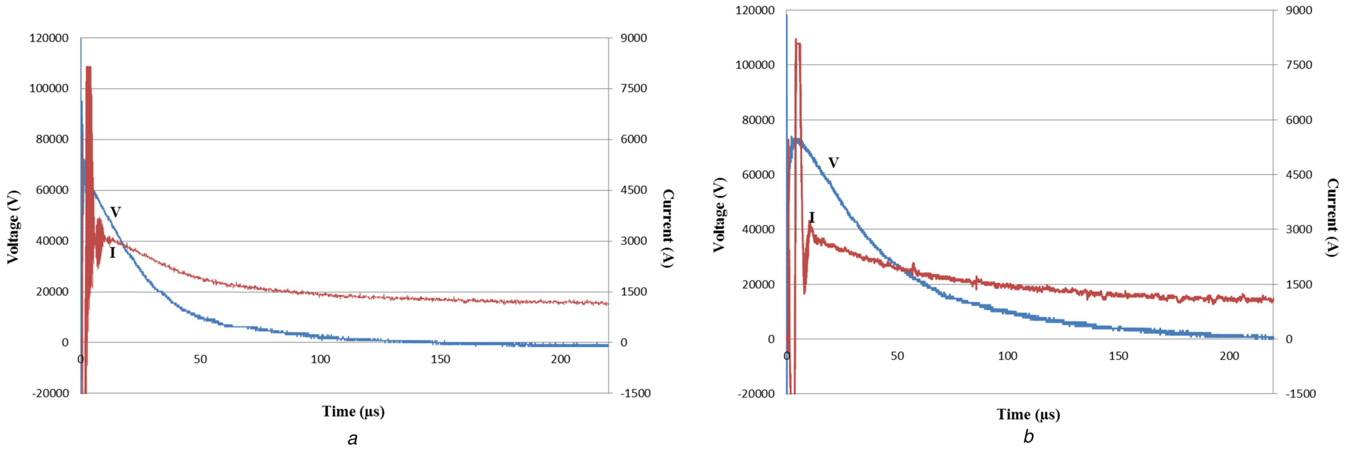


Fig. 6 *Voltage and current traces for single rod at 120 kV charging voltage*
(a) Ring as remote earth, ***(b)*** Grid as remote earth

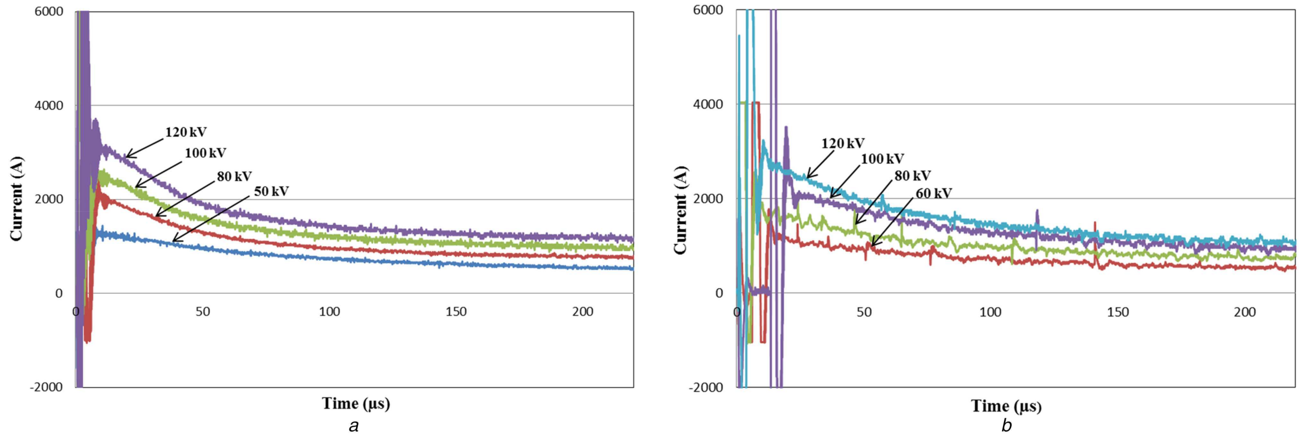


Fig. 7 *Current traces for single rod at different charging voltages*
(a) Ring as remote earth, ***(b)*** Grid as remote earth

Table 2 Soil resistivity data for the field sites with earthing systems

Earthing system	1st layer soil, Ω m	2nd layer soil, Ω m	Thickness, m
grid	331.1637	107.4214	0.9948738
single rod and ring	68.06359	277.0916	0.8890206

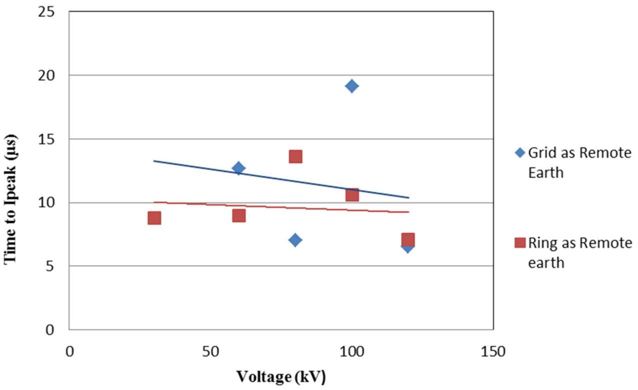


Fig. 8 *Time to current peak for single rod with different remote earth*

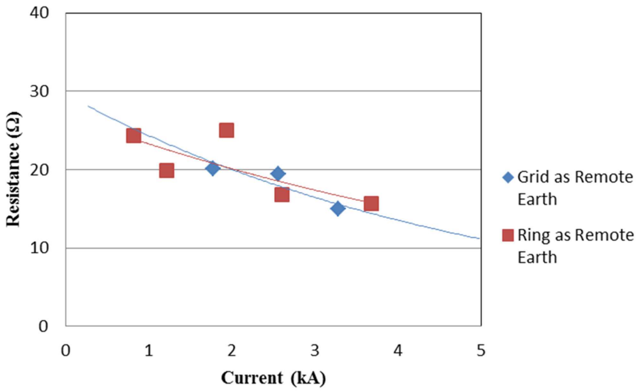


Fig. 9 *Earth resistance values with increasing currents for single rod with different remote earth*

of earthing systems between positive and negative impulse polarities require further study in the future.

4.2 Impulse resistances

A similar earth resistance measurement as (1) is adopted to obtain for impulse resistance under negative polarity. Fig. 12 shows resistance values for different impulse current magnitudes and voltages, respectively. A significant reduction in impulse resistance is observed as the current magnitudes are increased for positive and negative polarities. Furthermore, it is also observed that, for all values of impulse currents, earth resistance for positive polarity is lower than earth resistance at negative polarity. A similar observation was seen by the authors of [11, 13–15].

Since the reduction in impulse resistance is associated with thermal and ionisation processes [3–17], it is expected that some polarity effect would occur in discharges in the soil. This observation is further supported by studies [11, 13–15] establishing

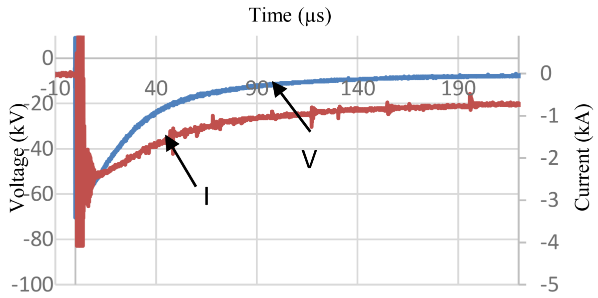


Fig. 10 *Typical voltage and current traces for single rod earthing system at 100 kV under negative polarity*

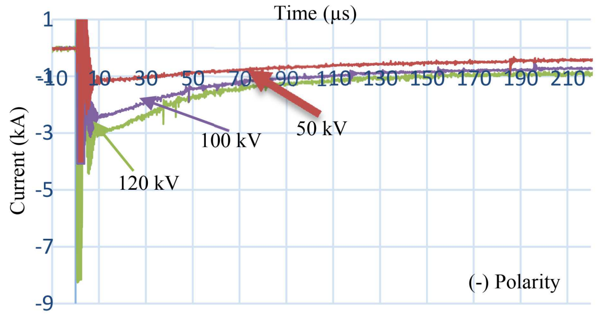


Fig. 11 *Current traces for single rod under negative polarity*

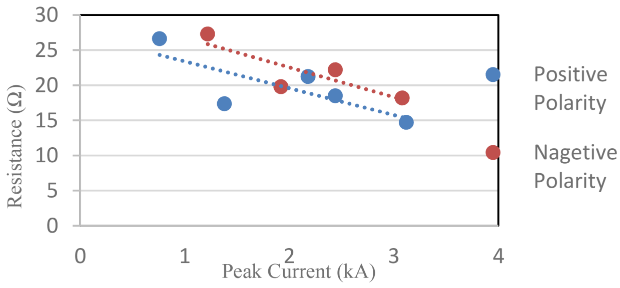


Fig. 12 *Single rod electrode resistance versus current pea*

that the characteristic properties of soil are affected by impulse polarities. The authors of [11, 12], explained that for positive polarity applied voltages, current propagation starts from the test electrode to the soil, while for negative polarity applied voltages, current starts propagating from the soil to the test electrode. Thus, less discharge in soil occur due to few streamers propagation and conduction processes are expected to appear in negative polarity, in comparison with positive polarity, which resulted in the production of lower current magnitudes in negative polarity. This polarity effect again shows that the soil ionisation process would occur in the soil when earthing systems are subjected to high impulse conditions.

5 Conclusion

The results presented in this study highlight the importance of selecting proper remote earth during impulse test, so that accurate measurement can be obtained. It is observed that at a low-charging voltage of 30 kV, the ring remote earth R_{impulse} value is almost similar to the R_{DC} value. This shows that the ionisation in soil may not have taken place at low voltage/current. At higher current magnitudes, R_{impulse} values are found to be lower than that of R_{DC} for single rod using both remote earth. The R_{impulse} values for a single rod with two different remote earth are found to be similar. The results suggest that both locations and characteristics of the remote earth are acceptable for the impulse tests on earthing systems by measurements. This study also shows that researchers can choose which method is easy for the measurements in future whether to have separate remote earth or by constructing the remote earth surrounding it, depending on their set-up.

As for the impulse polarity, it is observed that current traces under negative polarity have higher oscillations than that under impulse polarity. The current magnitudes are found to be lower, hence higher earth resistance values are observed under negative impulse polarity. These results correspond to those published previously in which the earth resistance values under negative impulse are always higher than that under positive impulse.

6 Acknowledgment

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