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Review

Review: Factors Affecting the Performance of Ground Electrodes under High Impulse Currents

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Abstract: Most studies have observed that the impedance values of ground electrodes under high impulse conditions (Z_{imp}) are lower than the resistance values under steady-state conditions (R_{DC}). It has been suggested that this is due to the ionisation process in soil, where streamers will propagate away from the electrodes, causing an increase in the ionisation zone, thus reducing the Z_{imp} values. The percentage difference between Z_{imp} and R_{DC} is found to be dependent on several factors. This paper aims to review and present the findings of previously published work on the percentage difference between Z_{imp} and R_{DC} in relation to various factors.

Keywords: impulse impedance; steady-state resistance values

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1. Introduction

The impulse characteristics of grounding systems are known to be different from those assessed under steady-state conditions. This is caused by the soil ionisation process, which occurs when the electric field (E) is higher than the critical electric field (E_c) inside the soil. These E_c values, which determine the onset of ionisation in soil, were summarised using information from 27 publications in [1], with values ranging from 0.13 kV/cm to 41 kV/cm for various soil resistivities and electrode configurations; most of the E_c values in these studies were obtained via laboratory tests. It can be seen in a study by Mohamad Nor et al. [2] that Ec was lower in a hemispherical container, which had a non-uniform electric field, in comparison to the uniform electric field of a parallel plate. In [2], E_c was found to be independent of the soil's grain size and moisture content. Moreover, a higher E_c value was seen under negative impulse polarity than positive impulse polarity because, as expected, air discharge occurred at higher voltage levels under the former. On the contrary, He et al. [3] observed that E_c values were affected by the soil's grain size, where the smaller the soil grain size, the higher the E_c value. They [3] also found that the E_c values decreased with increasing water content, contrary to the findings of Mohamad Nor et al. [4].

He et al. [3] expanded upon existing work on the effects of soil temperature and density, and found that E_c decreases with increasing soil temperature and increases with increasing soil density. Although the E_c values contribute to knowledge regarding the initiation of the ionisation process, studies pertaining to the E_c of various factors affecting soil appear to be limited. Furthermore, in several studies, E_c is not established due to unclear observation of the initiation of the ionisation process, as well as a lack of consistency in the measurements used between studies for determining E_c. In [4], E_c was determined when the second current peak started to occur, and its voltage was applied to an equation in which the configuration of a hemispherical container was known. In [2], in a parallel-plate test cell, E_c was calculated from the voltage level at which breakdown occurred in a parallel plate filled with soil, instead of via observation of the second current peak, as seen in [4]. This was defined as the moment that ionisation began, and was followed instantaneously by breakdown; hence, the study evaluated E_c based on the breakdown of soil. Similarly, in Ref. [5], based on the configuration of the test cell, the breakdown voltage was used to calculate the starting gradient. Some studies calculate E_c from the breakdown voltage [2,6–8], which may result in E_c being higher than when it was measured at the initiation of the second current peak. This, again, leads to inconsistencies in the evaluation of E_c. In some studies, namely [2,4,8], the 'up and down method' is used, while in others, no specific test method is mentioned or presented for obtaining E_c or $E_{breakdown}$. Furthermore, E_c is not easily established in some studies, which could be caused by non-observable breakdown or a lack of two current peaks; this may occur due to low soil resistivity, low current magnitudes or a large cross-sectional area, which could prevent the electric field from increasing in the soil. Hence, the method of obtaining E_c is not as widely discussed as the method of measuring Z_{imp} in relation to the R_{DC} values, whereby the latter of which is more straight forward.

Due to all of these inconsistencies, the unclear determination of E_c and the fact that the percentage difference between Z_{imp} and R_{DC}, for various factors affecting the characteristics of soil, can be more widely obtained than E_c, in this study, the percentage difference between Z_{imp} and R_{DC} is presented.

2. Factors Affecting the Soil Characteristics under High Impulse Conditions

Many studies have focused on the factors that contribute to soil characteristics under high impulse currents, and have found that the performance of grounding systems is affected by soil resistivity, ground electrode configuration, current response time, magnitude, the point of impulse current injection and impulse polarity. However, so far, not all of these effects have been reviewed, and the percentage difference between Z_{imp} and R_{DC} has not been compared from one study to another. In this paper, in order to obtain clarification on the percentage difference between Z_{imp} and R_{DC} in relation to these factors, the results from the literature are reviewed and discussed. Equation (1) is used to calculate the percentage difference between Z_{imp} and R_{DC} for all of the results obtained in previously published work. Since many studies have presented plots of Z_{imp} versus current magnitudes, the average Z_{imp} is considered in order to establish a single value of Z_{imp}, which is applied in Equation (1).

$$\% \text{ difference between } Z_{imp} \text{ and } R_{DC} = \left(\frac{R_{DC} - Z_{imp}}{R_{DC}}\right) \times 100\% \quad (1)$$

2.1. Soil Resistivity

One of the most important parameters in the design of grounding systems is soil resistivity, where R_{DC} changes with moisture content, soil composition, soil grain size, compression, chemical content and temperature. Much work [4–18] has been published on the effect of soil resistivity on the percentage difference between Z_{imp} and R_{DC} when ground electrodes are installed under varying soil resistivity and subjected to high impulse currents; however, no conclusive or summarising work can be found based on the published work. This paper summarises the published results, as shown in Figures 1 and 2, from work based on field and laboratory approaches, respectively.

2.1.1. Field Measurements

In studies of grounding systems under high impulse conditions using field measurements, R_{DC} values are mostly obtained using measurements [9–12], while in Ref. [13], R_{DC} is calculated based on the soil resistivity value obtained using the Wenner Method. Chen and Chowdhuri [9] performed tests on two rod electrodes of different diameters, with R_{DC} ranging from 220 Ω to 327 Ω. Rod (i) had a diameter of 0.95 cm, with a burial depth of 22.86 cm, and rod (ii) had a diameter of 1.59 cm, with a burial depth of 30.48 cm. The tested rod electrodes were installed at two sites, and it was found that the higher the R_{DC} values, the higher the percentage difference between Z_{imp} and R_{DC} for both electrodes (see Figure 1). When Reffin et al. [14] carried out studies on the effect of soil resistivity using 2 m × 2 m mesh electrodes installed at four different sites, giving R_{DC} values ranging from 12.9 Ω to 62.6 Ω, they found that the higher the R_{DC} value, the higher the percentage difference between Z_{imp} and R_{DC}. Abdul Ali et al. [15] observed that the percentage differences between an average Z_{imp} and R_{DC} for six different electrodes, installed at two sites with high soil resistivity, were higher in high-R_{DC} ground electrodes subjected to impulse currents up to 5 kA. Oettle and Geldenhuys [7] found that the percentage difference between Z_{imp} and RDC was approximately 57% for an electrode with an RDC of 834 Ω, while the percentage differences between Z_{imp} and R_{DC} were close (between 32% and 36%) for the other three electrodes, despite large variation in the R_{DC} values of 53.5 Ω, 240 Ω and 635 Ω. He et al. [16] conducted impulse tests on a number of electrodes whose soil resistivity values changed from 100 Ωm to 5103 Ωm. They observed that the higher the soil resistivity, the higher the impulse resistance value. The impulse coefficient, measured as the ratio of Z_{imp} to R_{DC}, was found to decrease with increasing soil resistivity, which was reflected in the percentage difference between Z_{imp} and R_{DC}, calculated using Equation (1); the higher the soil resistivity, the higher the percentage difference between Z_{imp} and R_{DC}. However, this is not included in Figure 1, since only the soil resistivity values were presented, and not in the form of R_{DC} values; hence, the relationship between R_{DC} and the percentage difference between Z_{imp} and R_{DC} could not be plotted in the figure.

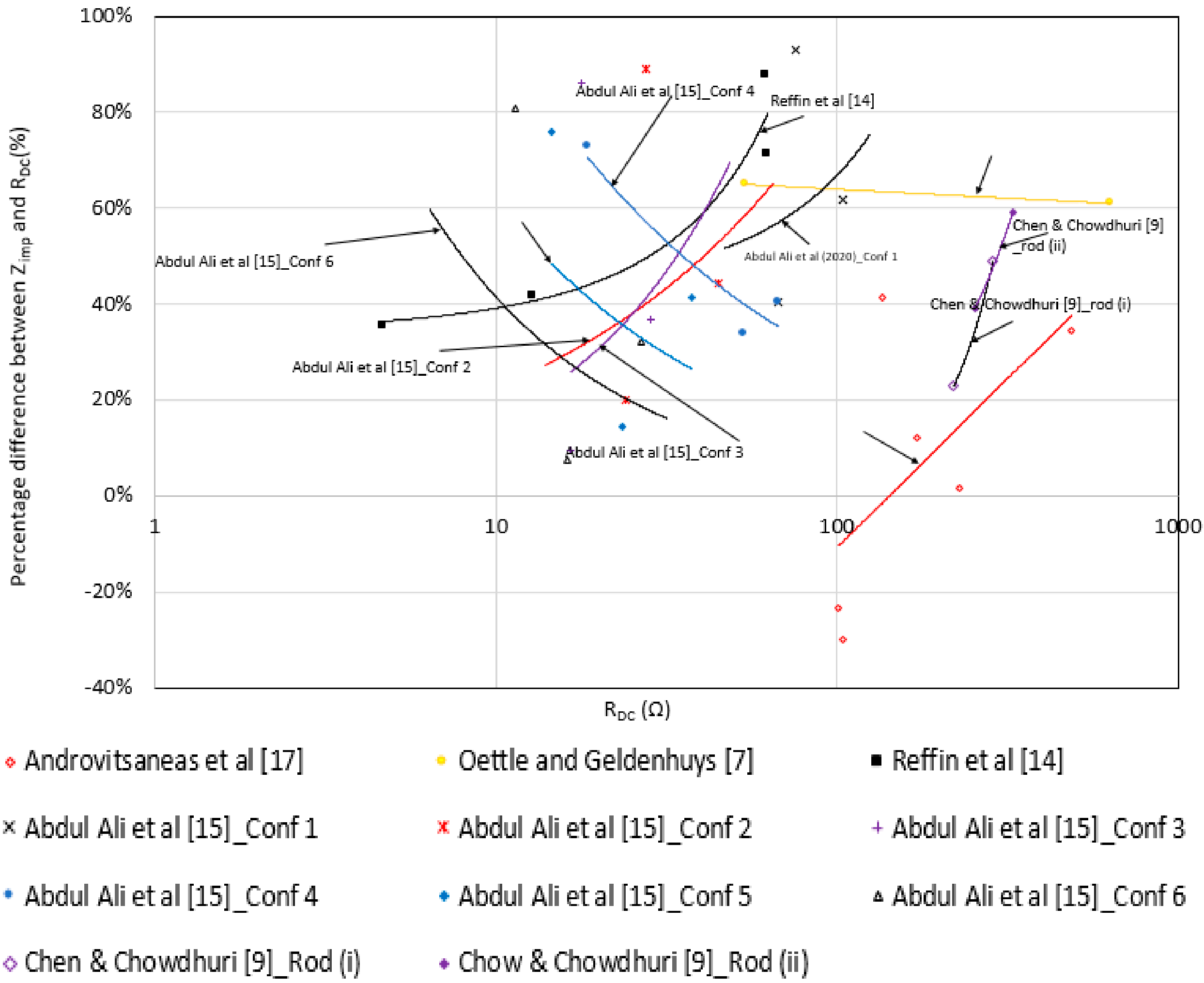

Figure 1. Percentage differences between Z_{imp} and R_{DC} for electrodes at various soil resistivities based on field measurements.

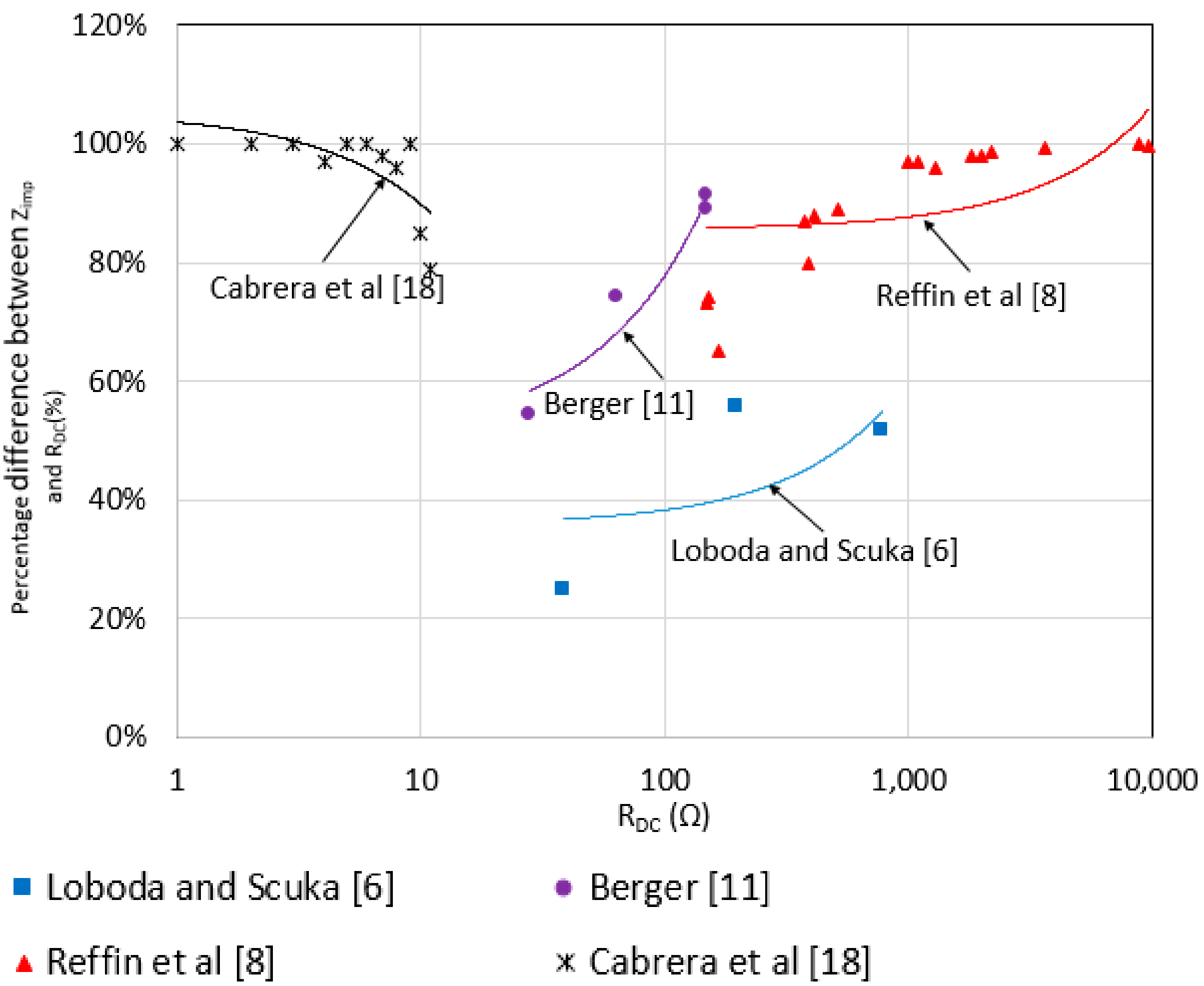

Figure 2. Percentage differences between Z_{imp} and R_{DC} for electrodes at various soil resistivities based on laboratory measurements.

In Ref. [17], electrodes installed in natural soil, encased in concrete and bentonite, were tested in July and November. Higher R_{DC} values were seen for ground electrodes measured in summer (July) in comparison to those measured in autumn (November). The higher the R_{DC} values (the highest were seen in July), the higher the observed percentage difference between Z_{imp} and R_{DC}. It was also noticed that for ground electrodes tested in November, whose RDC values were 135 Ω and below, the percentage difference between Z_{imp} and R_{DC} was negative, indicating that Z_{imp} was higher than R_{DC}. This shows that the soil resistivity underwent seasonal changes, and significantly affected the percentage difference between Z_{imp} and R_{DC}.

2.1.2. Laboratory Measurements

In order to evaluate the percentage difference between Z_{imp} and R_{DC} at various soil resistivities, the R_{DC} values from the published papers had to be known so that the relationship between soil resistivity (R_{DC}) and Z_{imp} could be calculated. The results are plotted in Figure 2. It can be seen from the figure that for most of the published work, there is a clear relationship between R_{DC} and the percentage difference between Z_{imp} and R_{DC}, where the higher the R_{DC} value, the higher the percentage difference between Z_{imp} and R_{DC}; the exception is Ref. [18], where the percentage difference between Z_{imp} and R_{DC} is independent of the R_{DC} values.

Loboda and Scuka [6] used cylindrical test cells filled with soils of three different resistivities, giving R_{DC} values of 38.6 Ω, 195.7 Ω and 782.8 Ω. The percentage difference between Z_{imp} and R_{DC} was found to be close for the electrodes with R_{DC} values of 195.7 Ω and 782.8 Ω, and 50% lower for the electrode with a much lower R_{DC} value (38.6 Ω). This shows that low soil resistivity resulted in a low percentage difference. Similarly, when Berger [11] carried out tests on a hemispherical model, he found that the higher the R_{DC} value, the higher the observed percentage difference between Z_{imp} and R_{DC}. For R_{DC} values ranging between 27 Ω and 150 Ω, the percentage differences between Z_{imp} and R_{DC} were found to be between 54% and 92%. On the other hand, Cabrera et al. [18] found that the percentage difference between Z_{imp} and R_{DC} was close to 100% for soil in a cylindrical test cell, with an R_{DC} value above 2000 Ω. This may be because the measurement of Z_{imp} was based on the Rarc, which was obtained from the voltage and current waveforms about 1µs after breakdown. During breakdown, it can be expected that there will be a large current flow, causing a significant drop in Z_{imp} values. Another recent study on the effect of soil resistivity on the percentage difference between Z_{imp} and R_{DC} was conducted in Ref. [8], where they found that, like in [18], almost all ground electrodes produced a percentage difference between Z_{imp} and R_{DC} close to 100%. This could be due to the boundary conditions of the test cell, which enabled full discharge of the current in the soil, unlike in the case of field tests, in which the large area allows a large amount of the current to dissipate into the soil. There are also several published studies [4,5] that show Z_{imp} at various soil resistivities. However, no R_{DC} values are presented in these studies; hence, the percentage difference between Z_{imp} and R_{DC} is not included in Figure 2.

2.2. Electrode Configurations

Variation in the configuration of ground electrodes under high impulse conditions is one of the most commonly investigated topics, whether using laboratory or field approaches. Due to the large number of studies using both approaches, this paper is divided into two sub-sections (laboratory and field measurements), and the results from the published work are plotted in Figures 3 and 4, respectively.

2.2.1. Field Study

Chen and Chowdhuri [9] installed two electrodes at two sites with different soil resistivities, where RDC ranged from 220 Ω to 320 Ω, and they were subjected to high impulse conditions. The authors observed that the higher the RDC value, the higher the observed percentage difference between Z_{imp} and RDC. Stojkovic et al. [19] performed tests on three large electrodes, and there was a clear trend whereby the percentage difference between Z_{imp} and R_{DC} was higher in the grid electrodes with high R_{DC} values. Due to the presence of inductive components in the large grid electrodes, it was noticed that the percentage difference between Z_{imp} and RDC was negative for all of the electrodes [19], indicating that Z_{imp} was higher than R_{DC}. A clear relationship between R_{DC} and the percentage difference between Z_{imp} and R_{DC} was also seen in Ref. [10], in which rod and wire electrodes were subjected to high impulse conditions. The rod electrode with a higher R_{DC} was found to produce a higher percentage difference between Z_{imp} and R_{DC} than the wire electrode. A similar observation was made in a study by Vainer [20], where the percentage difference between Z_{imp} and R_{DC} was higher in a ground electrode with a high R_{DC} value. For the ground electrode with a low R_{DC} value of 1.7 Ω, Z_{imp} was found to be higher than R_{DC}, thus producing a negative percentage difference between Z_{imp} and R_{DC}. Ametani et al. [12] also obtained a negative percentage difference between Z_{imp} and R_{DC} for ground electrodes with R_{DC} values of 12 Ω and 6 Ω, but Z_{imp} was lower than R_{DC} for the ground electrode with an R_{DC} of 16 Ω. In Ref. [21], the percentage difference between Z_{imp} and R_{DC} was also found to be negative for ground electrodes with a low R_{DC} value of 3.2 Ω. A concrete pole was used in their study [21]; however, it did not follow the same trend, with a very low percentage difference observed between Z_{imp} and R_{DC} at an R_{DC} of 39 Ω. He et al. [16], Towne [22], Hizamul-Din et al. [23], Harid et al. [24] and Elmghairbi et al. [25] found the same relationship, whereby the higher the R_{DC} value, the higher the percentage difference between Z_{imp} and R_{DC}. In Ref. [24], for a ground electrode consisting of a circular ring 60 m in diameter with eight vertical rods, with an R_{DC} of 18 Ω, Z_{imp} was found to be higher than R_{DC}. A negative percentage difference between Z_{imp} and R_{DC} was also seen in Ref. [25] for electrodes with much lower R_{DC} values of 5 Ω and 4 Ω. Mohamad Nor et al. [26] found that the percentage difference between Z_{imp} and R_{DC} was −2200% at an R_{DC} of 0.3 Ω, which was due to the inductance components of the large grid of the gas insulated sub-station (GIS); meanwhile, for a smaller test grid with a larger R_{DC} value of 7 Ω, the percentage difference was found to be −12%.

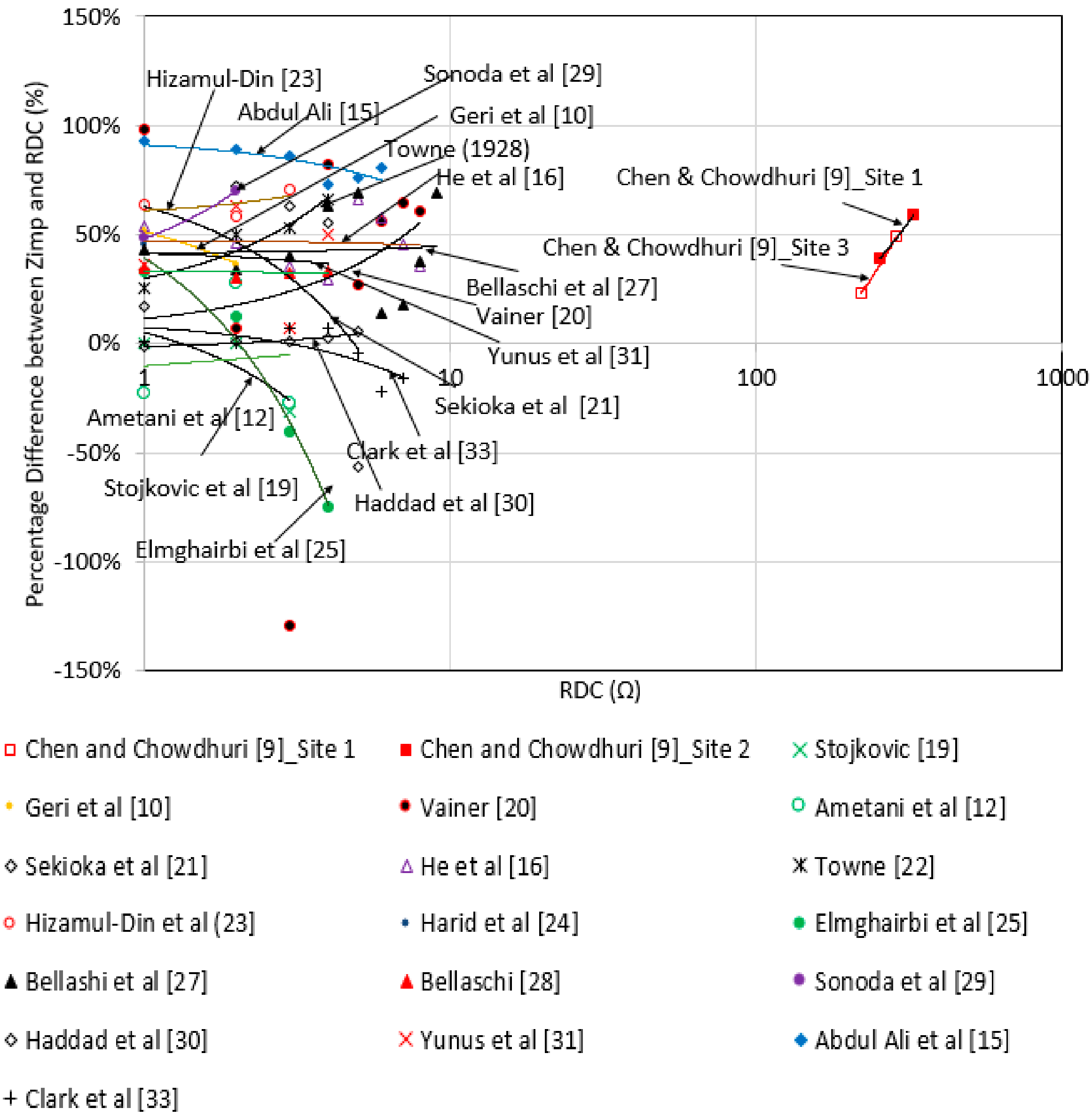

Figure 3. Percentage differences between Z_{imp} and R_{DC} for electrodes with various configurations based on field measurements.

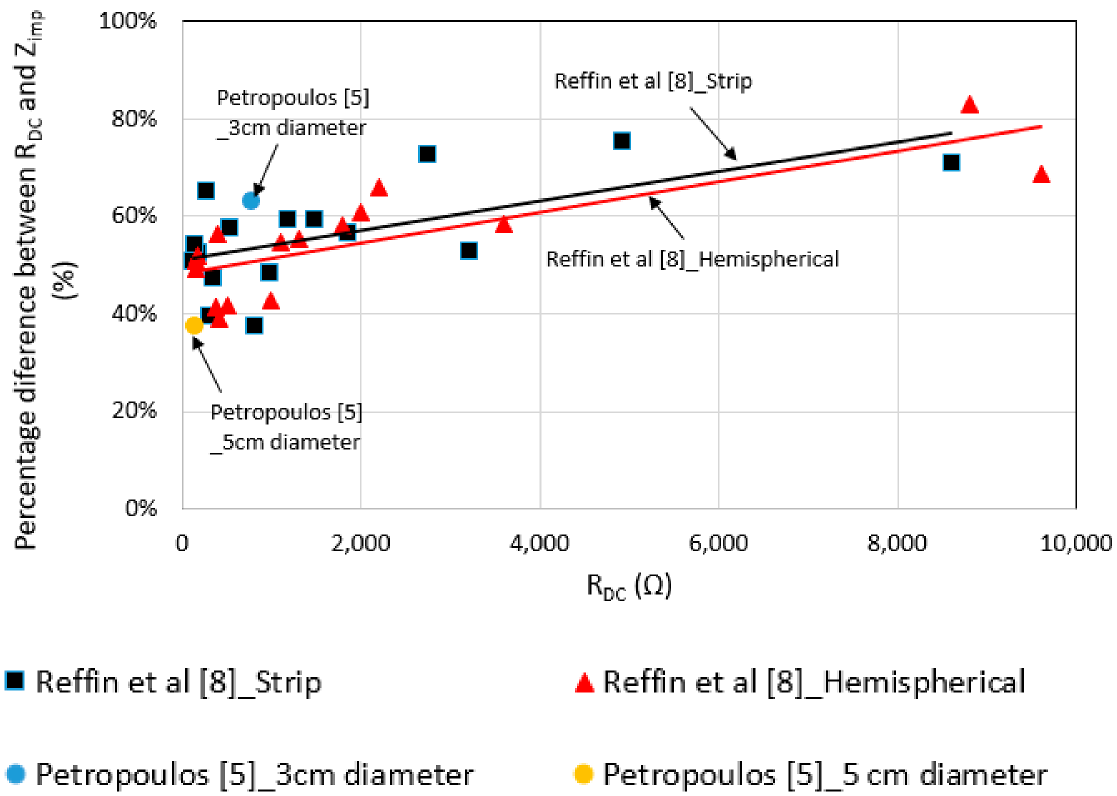

Figure 4. Percentage differences between Z_{imp} and R_{DC} for electrodes with various configurations based on laboratory measurements.

In some studies, namely [7,15,27–33], the percentage difference between Z_{imp} and R_{DC} was not influenced by the R_{DC} values. In Ref. [33], close percentage differences between −22% and 7% were seen for all of the electrodes, with R_{DC} values ranging from 36 Ω to 183 Ω, when tested using a low-impulse-voltage generator with a magnitude of up to 400 V. On the other hand, when these electrodes were tested at much higher current magnitudes, up to 7 kA, two current peaks were observed. When Z_{imp} was measured from the second current peak, referred to as post-ionisation resistance, it was found that the higher the R_{DC} value, the higher the percentage difference between Z_{imp} and R_{DC}.

2.2.2. Laboratory Study

There have been numerous studies on the effects of electrode configuration on Z_{imp} values. However, since this paper aims to evaluate the relationship between R_{DC} and the percentage difference between Z_{imp} and R_{DC}, the values of R_{DC} and Z_{imp} in the test cell had to be known, and were found to be limited. In Ref. [5], although several ground electrodes were used with the Z_{imp} values, only hemispherical test cells with inner electrodes 3 cm and 5 cm in diameter provided information on R_{DC}. The percentage differences between Z_{imp} and R_{DC} were found to be 63% and 38%, respectively, at R_{DC} values of 1360 Ω and 770 Ω, indicating that the higher the R_{DC} value, the higher the percentage difference between Z_{imp} and R_{DC}. When Reffin et al. [8] investigated four types of soil in hemispherical containers, containing varying amounts of water, with two types of active electrode used, hemispherical and strip electrodes, they found that the higher the R_{DC} value, the higher the percentage difference between Z_{imp} and R_{DC}.

2.3. Impulse Polarity

2.3.1. Field Study

The effect of impulse polarity can be limited by the manufacturer's design of the impulse generator, which is designed to produce only positive impulse polarity. This paper aims to list and review the results obtained from previous investigations on the percentage difference between Z_{imp} and R_{DC} when subjected to both impulse polarities. Figure 5 presents selected results from the literature on field measurements of different impulse polarities. It can be seen that the higher the R_{DC} value, the higher the percentage difference between Z_{imp} and R_{DC} for all electrodes. Androvitsaneas et al. [17] found that for ground rods installed in natural soil and encased with concrete and bentonite, higher Z_{imp} values were found under negative than positive impulse polarity. When the average Z_{imp} value was considered, it was noticed that the percentage difference between Z_{imp} under positive and negative impulse polarity was largest for the ground rod installed in natural soil (with the highest R_{DC} of 486 Ω, which represents an approximately 12% difference), while the Z_{imp} values between the positive and negative impulse polarities were found to be close for the ground rod encased with concrete and bentonite during summer, with RDC values of 135 Ω and 170 Ω, respectively. No impulse polarity effect on the Z_{imp} values was seen for any of the three electrodes during autumn, when the electrodes had lower R_{DC} values. A similar trend was seen in Ref. [34], when high current tests were carried out on a mesh ground electrode with an R_{DC} value of 3.6 Ω under both positive and negative impulse polarities. The Z_{imp} values were found to be close for both impulse polarities.

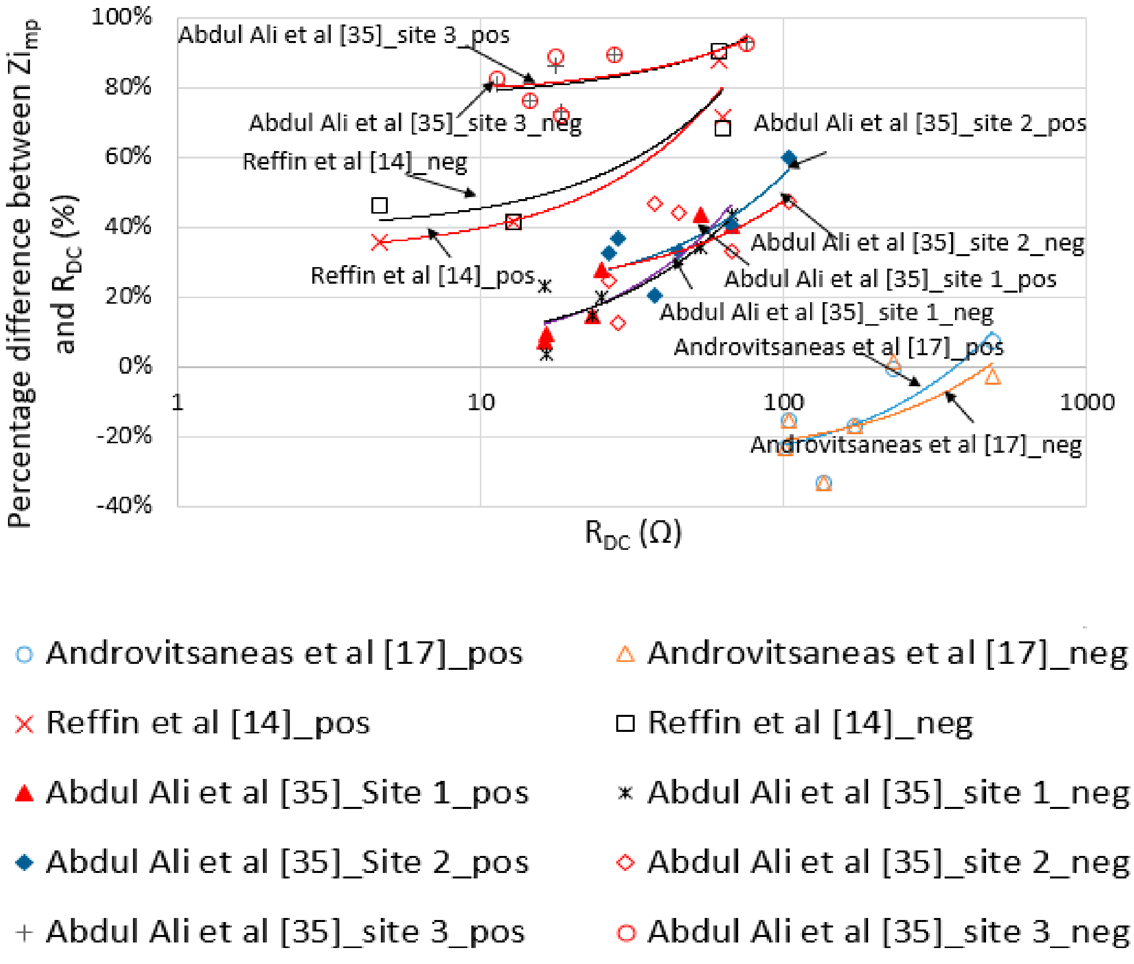

Figure 5. Percentage differences between Z_{imp} and R_{DC} for electrodes under different impulse polarities based on field measurements.

In another study, Bellaschi [27] carried out impulse tests on practical ground electrodes under both impulse polarities; however, the ground electrodes subjected to positive impulse polarity had different configurations than those subjected to negative impulse polarity. Therefore, in this study, no direct comparison could be made of the performance of the ground electrodes subjected to positive and negative impulse polarities [27]. In Ref. [14],

Z_{imp} was found to be 10% higher under negative impulse polarity than positive impulse polarity for a ground electrode with a high R_{DC} value of 62.6 Ω. The difference in the average Z_{imp} between positive and negative impulse polarities was found to be approximately 10%, and the difference was more significant with lower current magnitudes. On the contrary, at a slightly lower R_{DC} value of 61.6 Ω, Z_{imp} under positive impulse polarity was found to be 20% higher than under negative impulse polarity for all current magnitudes.

In Ref. [35], a similar observation, whereby Z_{imp} was higher under negative impulse polarity than under positive impulse polarity, was clearly seen in a ground electrode with a high R_{DC}. In a separate study by the same authors [36], the same configurations as those presented in [35] were used, but the ground electrodes were installed in high-resistivity soil of 1464.4 Ωm and 443.4 Ωm, at heights of 8.14 m and infinity for the upper and lower layers, respectively. It was noticed that despite having high R_{DC} values for six electrodes, ranging from 253 Ω to 833.78 Ω, no impulse polarity effect was seen on Z_{imp}. This is thought to be due to the high Z_{imp}, which was measured before the occurrence of breakdown in the soil, where low current magnitudes below 2 kA were noted. In terms of breakdown voltage, the authors found that the breakdown voltage under negative impulse polarity was higher than that under positive impulse polarity. Nevertheless, Ref. [37] found that for a rod electrode with an R_{DC} value of 67.8 Ω, the Z_{imp} value obtained under negative impulse polarity was 11% higher than that obtained under positive impulse polarity. An impulse polarity effect was only noticed in two studies [14,17], and this effect was not influenced by the R_{DC} values; in Ref. [17], an impulse polarity effect was seen under high R_{DC}, while in Ref. [14], an impulse polarity effect was seen under low R_{DC}.

2.3.2. Laboratory Study

Many laboratory studies did not include the R_{DC} values in their measurements; however, the differences in Z_{imp} values between positive and negative impulse polarities were noted for various soil resistivities. A number of investigations on the characteristics of soil under two impulse current polarities were carried out [5,18,35,38–40]. In [18], various types of soil were used, with the soil resistivity values ranging between 2.4 kΩm and 8.5 GΩm. The results of soil characteristics under positive impulse polarity are presented in Figure 2. Despite an obvious difference in the effects of impulse polarity on breakdown voltage and breakdown electric field, in high-resistivity soil, the arc resistance (R_{arc}) values were found to be close for all soil types, regardless of impulse polarity. This may be due to the high current in the test samples; the current magnitudes were measured at the second peak of the current, which occurred about 1 µs after breakdown in the peak current, and were used for R_{arc}. Hence, much lower Z_{imp} values were seen in comparison to R_{DC}; this caused the percentage difference between Z_{imp} and R_{DC} to be close to 100% in most test samples, making the impulse polarity effect insignificant. Due to their closeness, the results between positive and negative impulse polarity are not presented in this section. Similarly, Petropoulos [5] found that there was an impulse polarity effect on the starting gradient (E_o), where higher E_o was seen under negative than positive impulse polarity, while no impulse polarity effect was seen on Z_{imp} values, except at the tail of the Z_{imp} traces (plotted as the ratio of instantaneous voltage to current), where Z_{imp} was found to be higher under negative than positive impulse polarity.

In Ref. [38], impulse resistance values were based on pre-ionisation resistance (R_1) and post-ionisation (R_2), due to two current peak observations. It was noticed that in medium-grain-size sand with 3% water content in a hemispherical container, the average R_1 value under negative impulse polarity was 46% higher than under positive impulse polarity. On the other hand, for the same test sample, the average R_2 value under negative impulse polarity was 60% higher than under positive impulse polarity. They [38] also found that the breakdown voltage was higher under negative impulse polarity than under positive impulse polarity for sand with 1% and 5% water content. However, these results were not included in this study since there was no R_{DC} value available.

Similarly, the results from Ref. [39] could not be presented in this work due to the lack of data on soil resistivity and R_{DC} values; hence, the relationship between Z_{imp} and R_{DC} could not be determined. However, it was noticed in Ref. [39] that the Z_{imp} values were close for both positive and negative impulse polarities. Furthermore, a higher breakdown voltage was seen under negative impulse polarity than under positive impulse polarity. Different observations were made when impulse tests were carried out by the same authors [40] on the same test cell, but were instead filled with dry soil; Z_{imp} values were noted in the mega-ohm range, and Z_{imp} under negative impulse polarity was found to be higher than Z_{imp} under positive impulse polarity. The difference was approximately 16%, and was found to be more significant at higher current magnitudes, which is a result similar to that found in Ref. [35]. Since no soil resistivity or RDC data are available in this work [40], the relationship between Z_{imp} and R_{DC} is not presented in the present paper.

2.4. Current Rise Times

In many studies, it can be seen that the voltage probe is parallel to the ground electrode whether the tests are carried out in the laboratory or using field measurements. In Refs. [41,42], this arrangement was shown to cause an inductive effect, which resulted in changes in the voltage amplitude, and in the rise and tail times of the ground electrode under study. The voltage traces that are now applied to ground electrodes would be expected to change the current response times of the ground electrode being tested, and thus, the impulse impedance values. Though several proposed methods of measurement have been adopted to reduce these inductive effects—particularly in investigations of non-linear test load, such as in a surge arrester [41,42]—so far, no specific measurements have been proposed for the arrangement of impulse tests on ground electrodes to reduce these self- and mutually inductive effects. However, a few studies [6,13,43] have been conducted on the effect of current rise times on the behaviour of ground electrodes. Loboda and Scuka [6] performed tests with three current rise times (2–3 μs, 6–7 μs and 8–12 μs) on six test samples in cylindrical test cells. They [6] found that the current rise times had no influence on the Z_{imp} values. Liew and Darveniza [13] used an ionisation model to explain their experimental results obtained using field measurements, and they found that higher Z_{imp} values were observed under short current rise times. This is explained by the ionisation model, which showed that less time was available for full ionisation under shorter current rise times, while under slower current rise times, there was more time for the ionisation process to take place in soil; hence, it produced low Z_{imp}. A similar observation was made by Yang et al. [43], where a shorter current rise time of 2.6 μs produced higher Z_{imp} than a longer time of 8 μs due to the higher frequency under the shorter time response; hence, a higher inductive effect, and therefore, higher Z_{imp}, was expected in 2.6 μs than in 8 μs.

2.5. Point of Injection

As is generally known, under high impulse conditions, the inductive effect in a ground electrode is significant due to its fast, steep responses with high frequency. Due to the high inductive effect in ground electrodes, which can delay the current response and increase the Z_{imp} value, the point of injection can affect the characteristics of the ground electrode. However, studies on the effect of point of injection can only be conducted using field measurements, and such studies are found to be limited. Stojkovic et al. [19] injected two grids of 10 m × 10 m, with no mesh and with four meshes, where each mesh measured 5 m × 5 m and was placed in one of two locations: at the corner or at the midpoint of an edge. The authors noticed that there was no influence of point of injection on the impulse impedance and voltage/current shapes. It was noticed that Z_{imp} was higher than R_{DC}, with a percentage difference of −18% to −85%. On the contrary, Ametani et al. [12] found that the point of injection affected the impulse impedance and voltage/current shapes of grid electrodes. They injected five ground electrodes: (i) a single counterpoise measuring 30 m in length, (ii) a cross-shaped counterpoise measuring 30 m in length and crossed with a 20 m long electrode, (iii) Mesh I measuring 10 m × 10 m with 4 meshes, (iv) Mesh II measuring 10 m × 20 m with 8 meshes and (v) Mesh III measuring 24.8 m × 34.1 m with 16 meshes. Different Z_{imp} and voltage/current amplitudes were seen when these electrodes were injected in various nodes. For (i) single and (ii) cross-shaped counterpoises, when the injected point was at the node closest to the source, the voltage amplitude and impulse impedance were at their highest in comparison to those at the other nodes. The electrode (v) with Mesh III showed a more obvious effect when impulse voltage was applied in various nodes due to its large grid size. It was observed that the highest voltage and impedance values occurred when impulse voltage was injected in the centre of Mesh III, while injection at the midpoint of the edge of Mesh III produced the smallest voltage and impulse impedance values. Similarly, in Ref. [20], when three grids measuring 20 m × 20 m, 40 m × 40 m and 60 m × 60 m were subjected to impulse currents at their corners and their centres, significant differences in the effect of point of injection on large ground grids were observed. Another major contribution of their work was that the effect of point of injection was more significant for the grid measuring 40 m × 40 m installed in lower-resistivity soil (100 Ωm) than that installed at 1500 Ωm, with higher Z_{imp} produced at the corner injection point of the grid installed at 100 Ωm. These results are similar to those found in Ref. [29], where higher Z_{imp} values were obtained for both grid electrodes (10 m × 10 m and 20 m × 20 m) when they were injected in the corners than when they were injected in the centre. It was also clear [29] that the peak voltage applied in the corners was higher than the peak voltage applied in the centre of the ground electrodes. Yang et al. [43] observed a similar trend in Z_{imp}, where higher Z_{imp} values were seen when the ground grid was injected at the edge of the grid (corner) than when the grid electrode was injected in the centre. This can be explained by greater dissipation over a larger effective area when the ground electrode was injected in the centre, thus producing lower Z_{imp} than when it was injected at the edge (corner). All of these studies show that there is a need to consider the point of injection in the design of grounding systems, so that the current can be effectively discharged to the ground without creating high potentials in the ground electrodes.

3. Conclusions

This paper involved a review of published work on the relationship of R_{DC} with the percentage difference between Z_{imp} and R_{DC}. The following can be seen from the reviewed studies:

(i) Most of the studies show that, the higher the soil resistivity (and, hence, the R_{DC} values), the higher the percentage difference between Z_{imp} and R_{DC}. This is seen in work conducted using field and laboratory approaches (see Figures 1 and 2). A negative percentage difference is found in several studies indicating that Z_{imp} values are higher than R_{DC} values, particularly for soil mixed with enhancement materials.

(ii) Much of the published work investigates the effect of ground electrode configuration on the performance of grounding systems under fast impulses using field measurements. The percentage difference between Z_{imp} and R_{DC} is found to be negative (where Z_{imp} is higher than R_{DC}) in ground electrodes with R_{DC} values below 10 Ω (see Figure 3). Very few studies present work related to the performance of various ground electrodes under different impulses using a laboratory approach. The results gathered from the literature show that the higher the R_{DC} value, the higher the percentage difference between Z_{imp} and R_{DC}, as shown in Figure 4.

(iii) Several published studies have investigated the effect of impulse polarity on ground electrodes using both field and laboratory approaches. It can be seen in Figure 5 that, according to field measurements, the percentage difference between Z_{imp} and R_{DC} increases with increasing R_{DC} for all of the tested electrodes. However, no clear relationship can be seen between the effects of impulse polarity on various R_{DC} values. Several studies using laboratory approaches could not be presented in this paper due to the unavailability of data relating R_{DC} values to the percentage difference between Z_{imp} and R_{DC} values.

(iv) When work on the effect of current rise times on the performance of grounding systems was reviewed, it was observed that, for results obtained using a laboratory approach, there was no current rise time effect. On the other hand, for work conducted using field measurements, a rather consistent result was seen where higher Z_{imp} values were obtained under short current rise times.

(v) A very limited number of studies were found that investigated the effect of point of impulse injection on ground electrodes using experimental work. Furthermore, it was found that lower Z_{imp} values occur when ground electrodes are injected in the corner rather than in the centre. In general, the differences in the results for different points of injection are more obvious on large ground grids (with lower R_{DC} values).

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