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Evaluation of steady-state ground resistance by field measurement and CDEGS computation

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ABSTRACT

In addition to the soil resistivity and size of the grounding system, grounding system configuration can influence the steady-state resistance (RDC) of a grounding system. The RDC of four to six configurations in three distinct soil conditions (sites 1 to 3) is measured using the fall-of-potential method and computed using the current distribution, electromagnetic fields, grounding, and soil structure analysis (CDEGS) simulation. The RDC value generally decreases as size increases, i.e., when more rods or tapes are added, except for a little variation subject to the electrode arrangement and soil resistivity. The 3 and 4-parallel configurations perform better on low resistivity soil (site 1), while the grid configurations (2×2- and 3-rod grids) are better on high resistivity soil (site 2). The difference between the measured and computed values at high soil resistivity sites (sites 2 and 3) is large, ranging from 18% to 66% for site 2 and from 35% to 53% for site 3. The difference is lower and more consistent at site 1, where five out of six configurations achieve less than 10%. At all sites, the difference between computed and measured RDCs generally decreases as the area of the electrode increases, except for some cases at site 2.

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1. INTRODUCTION

A grounding system is an essential aspect of electrical installations that involves connecting the electrical system to the earth's conductive surface. A proper grounding system is designed to provide a low-impedance path for the fault current to flow and protect the system from electrical faults and hazards. Grounding systems help to prevent damage to electrical equipment [1]–[5], reduce the risk of electric shock and electrocution [6], [7], and ensure the safe and reliable operation of electrical systems [8], [9]. Many electrical standards [10]–[14] emphasise low ground resistance values in order to provide an effective path for currents to the ground. To attain low ground resistance values at steady-state conditions (RDC), many studies [15]–[17] found that there are two primary factors that have to be considered; the size of the grounding system and soil resistivity. Generally, the RDC is proportional to soil resistivity and inversely proportional to the size of the grounding system.

There are various approaches used in obtaining RDC values. Harid [18] used field measurement and analytical methods. For the four tower footings considered, the calculated RDC using a mathematical expression is 60 Ω, but through field measurement they obtained 55.3 Ω to 108.2 Ω. Meanwhile, Nor *et al.* [19] compared field measurement with the computational finite element method (FEM) for 2-, 3-, and 4- rod configurations. They obtained RDCs of 130.53 Ω, 105.57 Ω, and 80.33 Ω, respectively, from the measurement, and RDCs of 126.2 Ω, 94.6 Ω, and 76.2 Ω, respectively, from the FEM simulation. The study performed by Abdullah *et al.* [20] on a 4-mesh grid with rods grounding system also obtained a slightly higher RDC of 6.41 Ω through measurement in comparison to 6.3 Ω through FEM. Comparisons between measured and FEM were also done by Cvetković *et al.* [21]. They found measured RDCs of 38.5 Ω and 50 Ω for a single vertical and a single horizontal rod, respectively. The corresponding computed RDCs (using FEM) were found to be 43.98 Ω and 47.52 Ω, respectively. Jovanović *et al.* [22] expanded the research carried out by [21], in which a grid electrode was included. They obtained a measured RDC of 0.65 Ω, and a computed RDC of 1.02 Ω for the grid electrode [22]. In a recent study by Hizamul-Din *et al.* [23], the RDC of two new types of electrodes (spiked strip and linear array) was compared to that of the conventional strip electrode through field experiments and FEM simulations. The results showed that both spiked strip and linear array electrodes outperformed the conventional strip electrode. The linear array electrode obtained the lowest RDCs of 72.7 Ω and 65.8 Ω from measurement and simulation, respectively.

From all the observations, also portrayed in Figure 1, it can be seen that some studies found a relatively large and inconsistent difference between the measured and computed RDCs. The difference can be high, although the RDC is low. Similarly, those with a higher RDC may result in only a small difference between the measured and computed RDC values. According to [10] this is due to factors such as stray alternating currents, coupling between test leads, and buried metallic objects, but these factors have not been thoroughly investigated. Therefore, this paper aims to investigate the effects of surface area, soil resistivity, and grounding system configurations on the percentage error between the measured and computed RDC values by evaluating the performance of four to six grounding systems at three different sites using both field measurement and computational methods. The obtained RDC values will be analysed in relation to soil resistivity, total surface area, and grounding system configuration, including parallel and grid configurations.

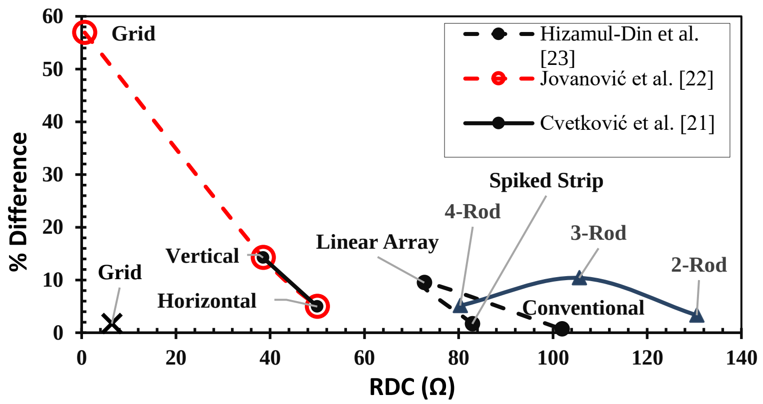

Figure 1. Plot of the percentage difference against RDC in various studies

2. METHOD

2.1. Soil resistivity

The wenner 4-point method [10], [14] was used to measure soil resistivity at three different sites. Multiple traverses were made at each site to collect sufficient data on the soil. For each site, all the traverses were averaged and then input into computer software for profiling. The RESAP module of a commercial software package called current distribution, electromagnetic fields, grounding, and soil structure analysis (CDEGS) [24] was used to interpret the measured soil resistivity data into a two-layer. According to [11], a two-layer structure is adequate since it is a good approximation of many soil structures.

2.2. Grounding system configurations

Figure 2 presents the six configurations of ground electrodes used in the study. Specifically, configuration in Figure 2(a) is a conventional 16 mm-diameter copper rod electrode of 1.8 m in length. The other five configurations consist of conventional rod electrodes connected by a 25 mm-wide, 3 mm-thick copper tape electrodes. All ground electrodes were installed to a depth of 0.3 m below the earth's surface. As it was highlighted in IEEE Std. 142 [12] that using multiple electrodes with a spacing of less than 3 m may not be the most cost-effective use of materials, the spacing between the rod and another rod was then maintained at 2 times the rod electrode's length, i.e., 3.6 m.

The installation and test begin with configuration in Figure 2(a). Then, one more rod was added at a distance of 3.6 m and connected with copper tape to form configuration in Figure 2(b). The connection with one more rod is repeated to form configuration in Figure 2(c). Next, configuration in Figure 2(d) was formed by connecting the third rod at 3.6 m away from both the first and second rods to form an equilateral triangle. Subsequently, this third rod, together with the tapes used in connecting it to the first and second rods, were all removed. The removed rod was reinstalled with another rod, but in a straight line with the previous two rods in configuration showed in Figure 2(b). In the same manner, configuration in Figure 2(e) was then formed by installing the fourth rod aligned with the first three. To construct configuration in Figure 2(f), the third and fourth rods in configuration E were taken out of the ground together with the tape that connected them. They were then, one after another, installed 3.6 m away and opposite to the first and second rods, before finally being connected using the copper tape.

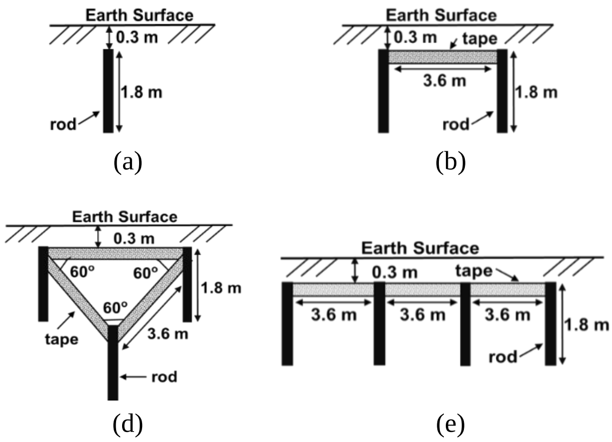

Figure 2. Grounding system configurations; (a) single road, (b) 2-parallel rods, (c) 3-parallel rods, (d) 3-rod grid, (e) 4-parallel rods, and (f) 2×2 rod grid

2.3. Grounding system size

For each configuration, the surface area of the copper rod electrode and copper tape electrode was calculated using (1) and (2), respectively. Table 1 presents the six configurations of the grounding system used in the study, with their calculated surface area due to the copper rod electrode and copper tape electrode, respectively.

$$Area_{Rod} = 2\pi r^2 + 2\pi rl \quad (1)$$

$$Area_{Tape} = 2(wh + wL + hL) \quad (2)$$

In (1), r is the radius, and l is the length of the rod. In (2), w, h, and L are the width, height, and length of the copper tape electrode, respectively. Generally, the total area of the grounding system increases from configurations A to F. It is noted that configurations C and D have equal rod surface areas due to the same number of rods used, as do configurations E and F. Meanwhile, the tape areas are equal for configurations D and E.

Table 1. Grounding system size, i.e., calculated surface area

Conf.	Surface area of rod (m^2)	Surface area of tape (m^2)	Total surface area (m^2)
A	0.0909	0.0000	0.0909
B	0.1818	0.2018	0.3835
C	0.2726	0.4034	0.6760
D	0.2726	0.6050	0.8776
E	0.3635	0.6050	0.9685
F	0.3635	0.8066	1.1701

2.4. Grounding resistance: field measurement

The RDC measurements for each of the grounding system configurations shown in Figure 2 at all sites were conducted with a Fluke 1623-2 instrument using the fall of potential method (FOP) [10], [13], [14].

All six grounding system configurations considered in this study underwent the FOP tests on the same day, thereby minimising any potential variations in soil resistivity.

2.5. Computational method

The RDC values were computed for each configuration at each site by using the MALZ-CDEGS module [24]. During the RDC simulations, the soil resistivity profile of the site, electrode dimensions, and material characteristics were all keyed in to model the grounding system under test. The flow is illustrated in Figure 3.

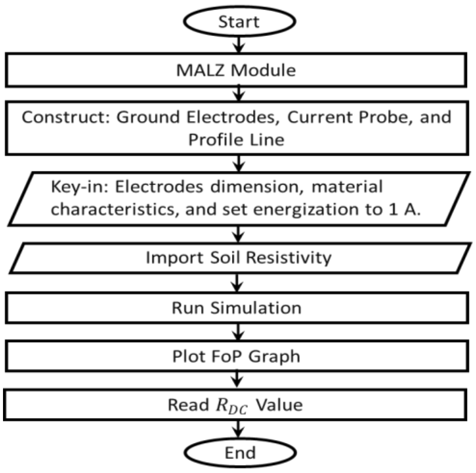

Figure 3. Flowchart of RDC simulation using the MALZ-CDEGS module

3. RESULTS AND DISCUSSION

3.1. Soil resistivity

The obtained soil profiles for the three sites are shown in Table 2. It can be seen that the resistivity value for site 2 is higher than site 1 for both layers, with a difference of 50% for the top layer ($\rho 1$) and 40% for the bottom layer ($\rho 2$). Similarly, the resistivity of site 3 is higher than that of site 1, by 55% and 71% for the top and bottom layers, respectively.

Table 2. Two-layer soil resistivity profile by CDEGS

Site	Soil resistivity profile			
	$\rho 1$ (Ωm)	$\rho 2$ (Ωm)	$h1$(m)	$h2$(m)
1	45.48	231.19	1.88	Infinite
2	91.45	383.13	0.64	Infinite
3	100.93	788.77	7.21	Infinite

In terms of the height of the soil layer, it is worth noting that the depth of the top layer, $h1$, at site 2 was only 0.64 m. As shown in Figure 2, all ground electrodes used in this study were installed 0.3 m below the earth's surface; thus, the contact between the ground electrodes and soil is up to 2.1 m below the earth's surface. As seen in Table 3, the bottom layer for site 2 has a greater impact on determining the RDC values of the grounding systems as compared to the top layer, and for configurations B to F, the top layer may still have an effect on the RDC values, particularly for configurations D, E, and F. Meanwhile, the influence of the top layer is definitely more significant than the bottom layer at sites 1 and 3 due to the depth (h) of 1.88 m and 7.21 m, respectively, as also observed in another study by Muhammad *et al.* [2]. At these sites, almost all electrode parts (for site 1) and all electrodes (for site 3) are fully in contact with the top layer's soil.

3.2. Grounding resistance, RDC

The measured and computed RDC values for all six configurations (note: only four configurations at site 3), at all three sites are tabulated in Table 4, together with the percentage difference of the computed from the measured RDC.

Table 3. Calculated surface area for soil layers at the three sites

Conf.	Site 1				Site 2				Site 3			
	Surface area in top layer (ρ1=45.48 Ωm)		Surface area in bottom layer (ρ2=231.13 Ωm)		Surface area in top layer (ρ1=91.45 Ωm)		Surface area in bottom layer (ρ2=383.13 Ωm)		Surface area in top layer (ρ1=100.93 Ωm)		Surface area in bottom layer (ρ2=788.77 Ωm)	
	(m^2)	(%)	(m^2)	(%)	(m^2)	(%)	(m^2)	(%)	(m^2)	(%)	(m^2)	(%)
A	0.0798	87.8	0.0111	12.2	0.0173	19	0.0736	81	0.0909	100	0	0.0
B	0.3601	93.9	0.0234	6.1	0.2363	62	0.1472	38	0.3835	100	0	0.0
C	0.6406	94.8	0.0354	5.2	0.4552	67	0.2208	33	0.6760	100	0	0.0
D	0.8418	95.9	0.0358	4.1	0.6568	75	0.2208	25	0.8776	100	0	0.0
E	0.9212	95.1	0.0473	4.9	0.6741	70	0.2944	30	0.9685	100	0	0.0
F	1.1224	95.9	0.0477	4.1	0.8757	75	0.2944	25	1.1701	100	0	0.0

Table 4. Measured and computed (CDEGS) RDC values, and the percentage difference between them for all configurations at the three sites

Conf.	Site 1			Site 2			Site 3		
	Measured (Ω)	CDEGS (Ω)	Difference (%)	Measured (Ω)	CDEGS (Ω)	Difference (%)	Measured (Ω)	CDEGS (Ω)	Difference (%)
A	24.3	30.5	-25.51	253.8	122.2	51.85	114.2	54.5	52.28
B	12.12	13.3	-9.74	116.1	39.5	65.98	46.8	22	52.99
C	9.3	9.85	-5.91	78.3	28	64.24	28.4	15.7	44.72
D	9.2	9.81	-6.63	53.7	28	47.86	---	---	---
E	7.74	8.11	-4.78	51.1	22.4	56.16	19.44	12.7	34.67
F	7.92	8.36	-5.56	28.1	23	18.15	---	---	---

3.2.1. Effect of grounding system configurations at low soil resistivity site

Figure 4 shows the measured and computed RDCs for the six grounding system configurations at the low soil resistivity site (site 1). Generally, it can be seen that the RDC decreases with increasing size, i.e., the surface area of the grounding electrodes. However, from the tabulation shown in Table 4, it is noticed that for configuration F, despite having a larger area than E as shown in Table 3, the measured and computed values are 0.18 Ω and 0.25 Ω, respectively, higher than those of E. Configuration D, which has a larger area than C, obtained a relatively equal RDC that is only lower by 0.1 Ω and 0.04 Ω, respectively, for measured and computed values when compared to those of C. Additionally, Table 3 reveals that configurations D and F not only surpass C and E in the total surface area but also exhibit larger surface areas in the top layer (lower resistivity). This could be due to the soil in which the grounding system is installed has non-uniform resistivity; thus, a larger area may not necessarily result in lower resistance. The current tends to concentrate in areas of lower resistivity, causing an uneven distribution that contributes to higher overall resistance.

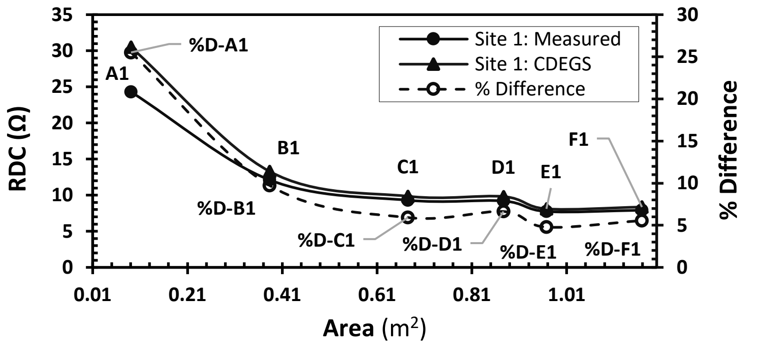

Figure 4. The plot of measured and computed RDC values, together with their percentage difference for the six configurations installed at site 1. Note: %D-X1 refers to the percentage difference between measured and computed RDC for configuration X installed at site 1

Comparing the measured and computed values, the differences between them are all below 10%, except for configuration A (a single rod), which is about 25%. Generally, the plots in Figure 4 show reducing RDC values, both measured and computed, and also reducing percentage differences as the surface area of the grounding electrodes increases. Further, the computed RDC values are noticed to be higher than the measured values for all the configurations installed at site 1.

3.2.2. Effect of grounding system configurations at high soil resistivity site

The RDC values obtained at site 2 (high soil resistivity) are plotted in Figure 5 and tabulated in Table 4. All RDC values, regardless of whether measured or computed, were found to be much higher, at least three times, than those found at site 1. This is expected, which was due to the higher resistivity of soil at site 2, also observed in many studies [2], [25], [26]. The RDC value significantly decreases with the increasing total surface area, i.e., as more rods or tapes are added, except for the computed RDC of configuration D. This exception can be related to the greater impact of the bottom layer at site 2 in determining the RDC values of the grounding system. It can be seen from Table 3 that the surface area of the ground electrodes for configuration D is the same as that of configuration C.

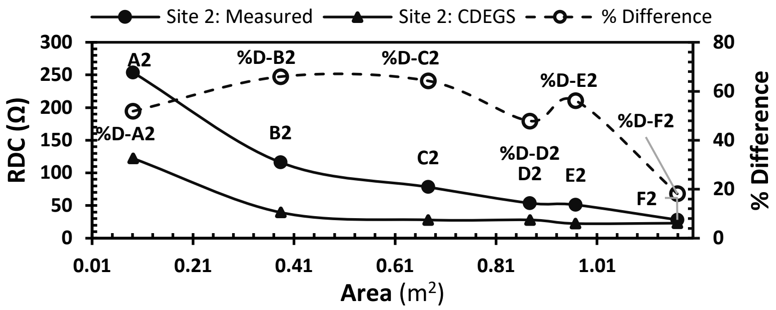

Figure 5. The plot of measured and computed RDC values, together with their percentage difference for six configurations installed at site 2. Note: %D-X2 refers to the percentage difference between measured and computed RDC for configuration X installed at site 2

In terms of differences between the measured and computed values, the differences are much larger than those at site 1. It ranges from 18% to 66%. A similar observation on the large difference of 56% was seen in Jovanović *et al.* [22], in which they used FEM to compute the RDC value of the grid system. Aman *et al.* [27] also obtained an approximately 65% difference in their work. They used two-parallel rod configurations in a soil with a resistivity of about 100 Ωm, which were tested three times within the period of 10 months. In Figure 5, it can be observed that the RDC percentage difference shows an increasing trend as the grounding surface area increases, but only from configurations A to B and configurations D to E. For configurations B to D and E to F, the difference reduces as the grounding surface area increases.

At site 3, only four configurations (A, B, C, and E) are installed, and the RDC performance is shown in Figure 6, with the values also tabulated in Table 4. The RDC values are lower than the corresponding configurations installed at site 2, although the bottom layer of site 3, as shown in Table 2, has the highest resistivity value. This can be attributed to the depth of the top layer (lower resistivity), which entirely (100%) encloses the ground electrodes, as presented in Table 3. The observed pattern of percentage variation across configurations A, B, C, and E shown in Figure 6 aligns closely with that of site 2. The disparity between the calculated and measured RDC values, as outlined in Table 4, falls within the range of 35% to 53%.

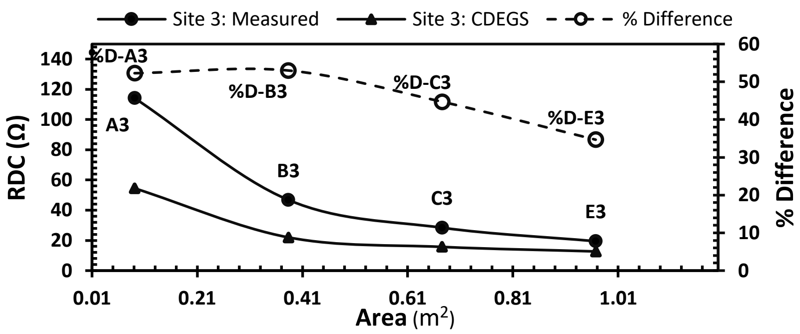

Figure 6. The plot of measured and computed RDC values, together with their percentage difference for four configurations installed at site 3. Note: %D-X3 refers to the percentage difference between measured and computed RDC for configuration X installed at site 3

3.2.3. Effect of soil layer's height

In this section, the effect of the thickness of the soil layers on the percentage difference between measured and computed values will be evaluated by considering the following three cases in the simulation:

a. Case 1: two-layer soil profile as shown in Table 2 is considered.
b. Case 2: uniform soil, with priority given to the soil layer that largely contains the grounding systems. In this case, the following assumptions are made: i) site 1: the effect of the top layer outperforms that of the bottom, thus 45.48 Ωm is used; ii) site 2: the effect of the top layer is negligible, thus the resistivity of the bottom layer, i.e., 383.13 Ωm is used. However, as can be seen from Table 3, more than 60% of the ground electrodes in configurations B to F lie in the top layer. Therefore, a uniform resistivity equal to the resistivity of the top layer is also considered for comparison purposes; and iii) site 3: the effect of the bottom layer is negligible. The soil resistivity is set to 100.93 Ωm.
c. Case 3: uniform soil, with the soil resistivity automatically computed by CDEGS. Soil resistivities of 107.35 Ωm, 227.5 Ωm, and 120.46 Ωm are used for sites 1, 2, and 3, respectively.

- Comparison between cases 1, 2, and 3

Figure 7 compares the three cases in terms of the percentage difference between the measured and computed RDCs at site 1. It is observed that case 1 yielded the lowest percentage difference for all configurations, except configuration A. Case 3 shows a similar trend to that of case 1, but with a two-fold higher percentage difference, and the difference reduces as the area increases. In contrast, case 2 shows a completely opposite trend to that found in cases 1 and 3. The highest RDC difference amongst the three cases also came from case 2 for all configurations, except configuration A.

The lowest percentage difference observed for site 1 can be due to having the lowest soil resistivity as compared to sites 2 and 3. This is similar to the observation by Salam *et al.* [28] on the soil resistivity and ground resistance near an electrical substation. They obtained only a little difference of 2.25% between measured and simulated (using Cymgrd software) RDC values for the grid with rods installed in the wet soil (low resistivity) site. In contrast, a significant difference (19.42%) was observed for the grid without rods at the dry site (high resistivity).

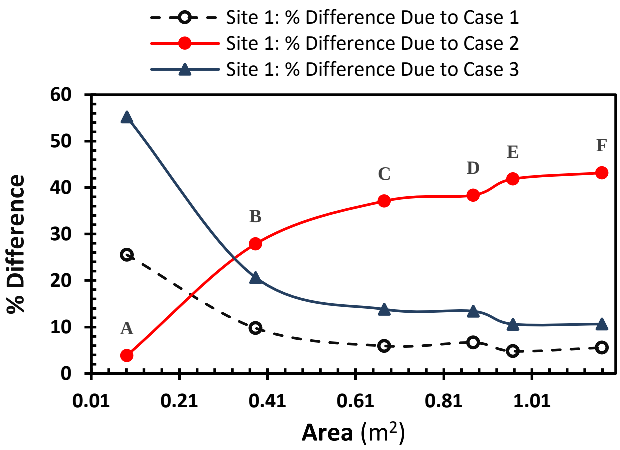

Figure 7. Percentage difference between measured and computed RDC for cases 1, 2, and 3 at site 1

Similar to Figure 7, Figure 8 shows the comparison between measured and computed RDC values, but performed for site 2. The percentage difference for cases 1 and 3 is close for all the configurations considered. Meanwhile, the percentage difference for case 2 (bottom layer) is lower than in the other cases. Note that an additional plot considering the top layer soil resistivity (i.e., based on the larger surface area of the grounding system location) has been included. The added plot shows a much higher percentage difference than when the soil is assumed to have the bottom layer's resistivity (i.e., based on the soil layers' depth). This suggests that the assumption on soil resistivity should follow the resistivity of the soil layer based on depth. The percentage difference between measured and computed RDCs performed for site 3 is shown in Figure 9. The trend for all cases is similar for all configurations due to the large height of the top layer, indicating that a uniform soil layer is more suitable when the soil layer's height is large, i.e., substantially higher than the vertical length of the ground electrode after installation.

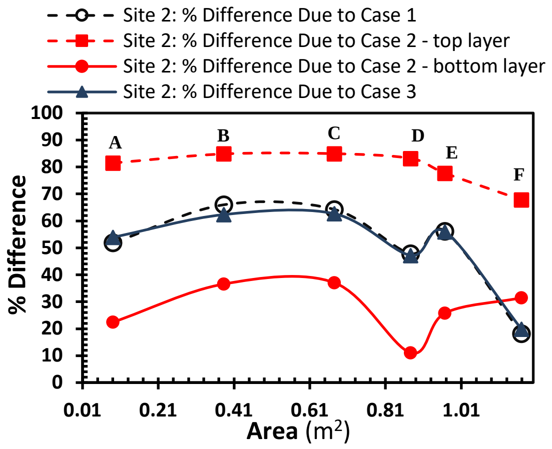

Figure 8. Percentage difference between measured and computed RDC for cases 1, 2, and 3 at site 2

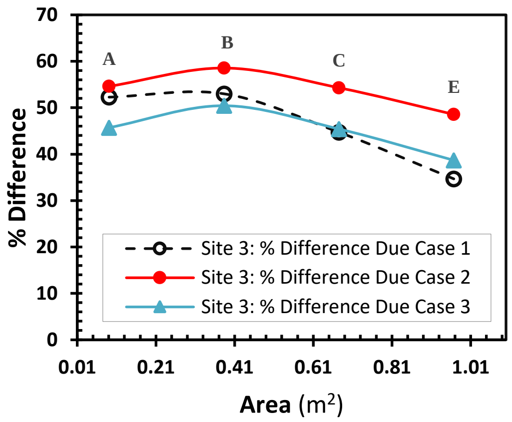

Figure 9. Percentage difference between measured and computed RDC for cases 1, 2, and 3 at site 3

Table 5 presents a summary of the percentage differences between the measured and computed RDC values for all three sites, considering the three scenarios defined in subsubsection 3.2.3. It can be seen that case 1 gives the lowest difference between the measured and computed RDC for 2 sites, i.e., sites 1 and 3, while cases 2 and 3 each give the lowest difference just for one site. This is consistent with the findings of Nassereddine *et al.* [29], who compared the two-layer soil profile computed using CDEGS, with a single uniform layer that was calculated by taking the average of apparent soil resistivities. Their findings indicated that the use of a single-layer apparent soil structure can result in a more expensive and non-compliant system. Similarly, in the study conducted by Dawalibi and Barbeito [30], it was observed that a relatively high level of accuracy is achieved when utilising multi-layer soil structure models, in contrast to the results obtained when uniform soil models are employed.

Table 5. Summary of the percentage difference between measured and computed RDC for cases 1, 2, and 3 at all sites

Case	% difference		
	Site 1	Site 2	Site 3
1	6 to 26	18 to 66	35 to 52
	Lowest	Highest	Lowest
2	4 to 43	11 to 37	49 to 55
	Highest	Lowest	Highest
3	11 to 55	20 to 63	39 to 46
		Highest	Lowest

4. CONCLUSION

The RDC performance of four to six grounding system configurations at three sites with different soil resistivity profiles was evaluated through both field measurement and computational methods. As expected, higher soil resistivity resulted in a higher RDC. This is also true when the number of rods, which indicate the grounding system size, i.e., surface area, is increased. Further analysis of the results of sites 1 and 2 shows that grounding system configuration, i.e., the arrangement of the electrodes, also affects the RDC of grounding systems. Specifically, grid grounding systems (2×2 rod grid and 3-rod grid) can be recommended to be installed at sites with high soil resistivity, while parallel rod grounding systems (3- and 4-parallel rods) can be employed in areas with low soil resistivity. In terms of the difference between measured and computed RDCs, the values are lower and more consistent for the low resistivity site 1. Further, the computed RDC values are higher than the measured values at the low resistivity site, and vice versa for the ground electrodes installed at the high resistivity sites. From the three soil resistivity scenarios considered, it is also recommended that the assumption on soil resistivity follow the resistivity of the soil layer based on depth. For a more conclusive result, further study may consider a larger number of grounding system configurations and sites with diverse soil characteristics.

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REFERENCES

[1] A. G. Morinec, "Power quality considerations for CNC machines: grounding," in *Conference Record of Industrial and Commercial Power Systems Technical Conference*, 2000, pp. 7–14, doi: 10.1109/icps.2000.854351.
[2] U. Muhammad, N. M. Nor, A. M. Ramli, and N. N. Ahmad, "Effect of ground electrodes on the susceptibility to damage of customer premises equipment (CPE) under impulse conditions," *Energies*, vol. 15, no. 3, 2022, doi: 10.3390/en15031247.
[3] S. A. Saleh *et al.*, "Experimental assessment of grounding system impacts on ground currents and transient overvoltage," *IEEE Transactions on Industry Applications*, vol. 58, no. 5, pp. 5987–6001, 2022, doi: 10.1109/TIA.2022.3189614.
[4] P. Barker, "Overvoltage considerations in applying distributed resources on power systems," in *Proceedings of the IEEE Power Engineering Society Transmission and Distribution Conference*, 2002, vol. 1, pp. 109–114, doi: 10.1109/PESS.2002.1043188.
[5] K. Switzer, *Practical guide to electrical grounding*. Solon, Ohio, USA: ERICO, 1999.
[6] A. Albert and M. R. Hallowell, "Safety risk management for electrical transmission and distribution line construction," *Safety Science*, vol. 51, no. 1, pp. 118–126, 2013, doi: 10.1016/j.ssci.2012.06.011.
[7] A. D. Adebayo and C. J. Ujam, "Analysis of electrical grounding design of substation and lines," *International Journal of Scholarly Research in Engineering and Technology*, vol. 2, no. 1, pp. 31–40, 2023, doi: 10.56781/ijsret.2023.2.1.0016.
[8] Y. Khan, F. R. Pazheri, N. H. Malik, A. A. Al-Arainy, and M. I. Qureshi, "Novel approach of estimating grounding pit optimum dimensions in high resistivity soils," *Electric Power Systems Research*, vol. 92, pp. 145–154, 2012, doi: 10.1016/j.epsr.2012.06.003.
[9] S. C. Malanda, I. E. Davidson, E. Singh, and E. Buraimoh, "Analysis of soil resistivity and its impact on grounding systems design," *2018 IEEE PES/IAS PowerAfrica, PowerAfrica 2018*, pp. 324–329, 2018, doi: 10.1109/PowerAfrica.2018.8520960.
[10] IEEE Std 81, "Guide for measuring earth resistivity, ground impedance, and earth surface potentials of a grounding system," *IEEE Std 81-2012 (Revision of IEEE Std 81-1983) - Redline*, pp. 1–192, 2012.
[11] IEEE Std 80, "Guide for safety in AC substation grounding," *Group*, pp. 1–192, 2000.
[12] IEEE, "Recommended practice for grounding of industrial and commercial power systems," pp. 142–1991, 1992.
[13] IEEE Std 81, "Guide for measurement of impedance and safety characteristics of large, extended or interconnected grounding systems," *IEEE Std 81.2-1991*, 1991.
[14] Telecommunications Industry Association, "Code of practice for protective earthing of electrical installations. BS 7430: 2011," 2011.
[15] S. Sekioka, T. Sonoda, and A. Ametani, "Experimental study of current-dependent grounding resistance of rod electrode," *IEEE Transactions on Power Delivery*, vol. 20, no. 2, pp. 1569–1576, 2005, doi: 10.1109/TPWRD.2004.838660.
[16] S. Tomaškovičová, T. Ingeman-Nielsen, A. V. Christiansen, I. Brandt, T. Dahlin, and B. Elberling "Effect of electrode shape on grounding resistances—Part 2: Experimental results and cryospheric monitoring" *Geophysics*, vol. 81, no. 1, pp. WA169-WA182 2016, doi: 10.1190/geo2015-0148.1.
[17] M. Kizhlo and A. Kanbergs, "Research of the parameter changes of the grounding system," *WNWEC 2009 - 2009 World Non-Grid-Connected Wind Power and Energy Conference*, pp. 1–4, 2009, doi: 10.1109/WNWEC.2009.5335821.
[18] N. Harid, "Experimental investigation of impulse characteristics of transmission line Tower footings," *Journal of Lightning Research*, vol. 4, no. 1, pp. 36–44, 2012, doi: 10.2174/1652803401204010036.
[19] N. M. Nor, M. Trlep, S. Abdullah, and R. Rajab, "Investigations of earthing systems under steady-state and transients with FEM and experimental work," *International Journal of Electrical Power and Energy Systems*, vol. 44, no. 1, pp. 758–763, 2013, doi: 10.1016/j.ijepes.2012.08.031.
[20] S. Abdullah, N. M. Nor, R. Rajab, and M. Trlep, "Analysis of 4 mesh grid grounding systems by FEM simulations and field tests," *Applied Mechanics and Materials*, vol. 793, pp. 159–163, 2015, doi: 10.4028/www.scientific.net/amm.793.159.
[21] N. N. Cvetković, D. B. Jovanović, A. T. Ristić, M. S. Stojanović, and D. D. Krstić, "Comparison of different models for determining the grounding rod resistance," *Electrotechnica & Electronica (E+E)*, vol. 50, no. 9-10, pp. 35–39, 2015.
[22] D. B. Jovanović, N. N. Cvetković, A. T. Ristic, and V. B. Stanković, "Different calculation methods and experimental validation for various ground electrode types," *2015 9th International Symposium on Advanced Topics in Electrical Engineering, ATEE 2015*, pp. 337–342, 2015, doi: 10.1109/ATEE.2015.7133827.
[23] H. H. Hizamul-Din, N. M. Nor, A. Mahmud, N. N. Ahmad, and N. F. Idris, "Investigations on the performance of various horizontal ground electrodes," *Energies*, vol. 14, no. 4, 2021, doi: 10.3390/en14041036.
[24] "Current distribution, electromagnetic interference, grounding and soil structure analysis (CDEGS)." SafEngServices & technologies ltd., 2023. https://www.sestech.com/Product/Package/CDEGS
[25] A. Galván D., G. Pretelín G. and E. Gaona E., "Practical evaluation of ground enhancing compounds for high soil resistivities," *2010 30th International Conference on Lightning Protection (ICLP)*, Cagliari, Italy, 2010, pp. 1-4, doi: 10.1109/ICLP.2010.7845889.
[26] F. Sinchi-Sinchi, C. Coronel-Naranjo, A. Barragán-Escandón, and F. Quizhpi-Palomeque, "Soil treatment to reduce grounding resistance by applying low-resistivity material (LRM) implemented in different grounding systems configurations and in soils with different resistivities." *Applied Sciences*, vol. 12, no. 9, 2022, doi: 10.3390/app12094788.
[27] F. Aman, N. M. Nor, and N. N. Ahmad, "Impulse characteristics of ground electrodes over time (10 months)," in *2022 57th International Universities Power Engineering Conference: Big Data and Smart Grids, UPEC 2022 - Proceedings*, 2022, pp. 1–4, doi: 10.1109/UPEC55022.2022.9917948.
[28] M. A. Salam, Q. M. Rahman, S. P. Ang, and F. Wen, "Soil resistivity and ground resistance for dry and wet soil," *Journal of Modern Power Systems and Clean Energy*, vol. 5, no. 2, pp. 290–297, 2017, doi: 10.1007/s40565-015-0153-8.
[29] M. Nassereddine, J. Rizk, and G. Nasserddine, "Soil resistivity data computations; single and two - layer soil resistivity structure and its implication on earthing design," *International Scholarly and Scientific Research & Innovation*, vol. 7, no. 1, pp. 885–890, 2013.
[30] F. Dawalibi and N. Barbeito, "Measurements and computations of the performance of grounding systems buried in multilayer soils," *IEEE Transactions on Power Delivery*, vol. 6, no. 4, pp. 1483–1490, 1991, doi: 10.1109/61.97681.

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