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Analytic on Various Grounding Configurations in Uniform Layer Soil

Mohd Shahriman B. Mohd Yunus, Mohd Hanif B. Jamaludin, Norain Bt. Bahror

Abstract**—**The performance of an embedded grounding system is very important for the safe operation of electrical appliances and human beings. In principle, a safe grounding system has two objectives, which are to dissipate fault current without exceeding any operating and equipment limits and to ensure there is no risk of electric shock to humans in the vicinity of earthed facilities. The case studies in this paper present the calculating grounding resistance for multiple configurations of vertical and horizontally by using a simple and accurate formula. From the analytic calculated results, observed good/empirical relationship between the grounding resistance and length of the embedded grounding configurations. Moreover, the configurations of vertical and horizontal observed effectiveness of grounding resistance and good agreement on the reduction of grounding resistance values especially for vertical configuration.

Keywords**—**Grounding system, grounding resistance, soil resistivity, electrode geometry, configurations.

I. Introduction

THE quality and performance of grounding systems are a major concern in today's power system design. The main objectives of a good grounding system are [1]-[5]:

1. To assure reliable operation of electrical devices.
2. To provide safety during normal fault conditions.
3. To protect personnel against electrical risks.
4. To dissipate lightning strokes.

According to Ohm's law, grounding resistance is defined as the ratio between the potential of the grounding device (V) and a current flowing into the earth through the grounding device (I), which is related to the soil characteristic and the size and shape of the grounding device. Grounding of either a system or equipment involves the provision of a connection to the general mass of ground. This connection should have resistances lower than the design value and should be capable of carrying the expected maximum fault current. The poor grounding system is very dangerous and increases the risk to the human and equipment, where this factor exposes the risk of hazard such as electrical shock or malfunction, that cause fire in particular areas. Also, leads to the power quality issues such as harmonics, power factor, etc. [6].

The performance of ground resistance is very important in electrical installation. The grounding resistance, R, is dependent on two main factors [7]-[11]:

a) Electrode geometry of the configuration
b) The soil resistivity, ρ

The electrode geometry or area (m^2) and soil resistivity, ρ, are very important in determining the grounding resistance. As revealed by [12], the effects of ground configuration on grounding performance are highly dependent on soil structure type and characteristics where most efficient design in soil structures with high resistivity top layer, ground rods is effective only if it penetrates a low resistivity bottom layer to a significate depth (relative to rod length). Therefore, to achieve the minimum value of ground resistance, R, the current density flowing from the electrode conductor to the ground should be lower. The resistivity of soil varies widely throughout the world and changes dramatically within small areas. Therefore, soil resistivity is mainly influenced by [13]-[17]:

(i) The type of soil such as clay, shale, sandy, etc.,
(ii) Moisture content,
(iii) Amount of electrolytes such as minerals and dissolved salts, and
(iv) Temperature.

According to the ANSI/EEE Std. 80 - 1986 [4], the soil is said to be uniform "when the soil resistivity is constant both laterally and with depth to infinity". Previous formulae were obtained from researchers as [10], [14], [18]-[20] on grounding system analytic. Simple formulas for calculating the grounding resistance proposed in the past [4] as shown in Table I are adopted for case studies. These formulas are based on some idealistic assumptions, such as uniform soil. The purpose of this case study is to continue developing a formula to calculate simply and accurately the grounding resistance hand-calculator for agreement correlation.

TABLE I
Grounding Technique Formula [4]

Grounding type	The formula for calculating grounding resistance, R
Single Ground Rod	$R = \frac{\rho}{2\pi L}\left[\ln\left(\frac{8L}{d}\right) - 1\right]$
Two Ground Rod (S>L)	$R = \frac{\rho}{4\pi L}\left[\ln\left(\frac{8L}{d}\right) - 1\right] + \frac{\rho}{4\pi S}\left(1 - \frac{L^2}{3S^2}\right)$
Four Point Star	$R = \frac{\rho}{8\pi L}\left(\ln\frac{4L^2}{dh} + 2.9 - 2.14\frac{h}{L} + 2.6\frac{h^2}{L^2}\right)$
Six Point Star	$R = \frac{\rho}{12\pi L}\left(\ln\frac{4L^2}{dh} + 6.85 - 6.26\frac{h}{L} + 7\frac{h^2}{L^2}\right)$
Ring of Wire	$R = \frac{\rho}{2D\pi^2}\left(\ln\frac{16D^2}{dh}\right)$

where: R – Grounding resistance (Ω); ρ – Soil resistivity (Ωm); d - diameter of the rod (m); L – Length of rod buried (m); h – Distance of the rod buried from the surface (m); S – Distance between two rods (m); D – Diameter of the ring wire circle (m).

II. Methodology

Steps shown in Fig. 1 are adopted to analyze and compare the ground resistance.

Mohamed Shahriman Mohamed Yunus is with Centre of Excellence for Engineering & Technology, Malaysia (e-mail: mmohdshahriman@yahoo.com).

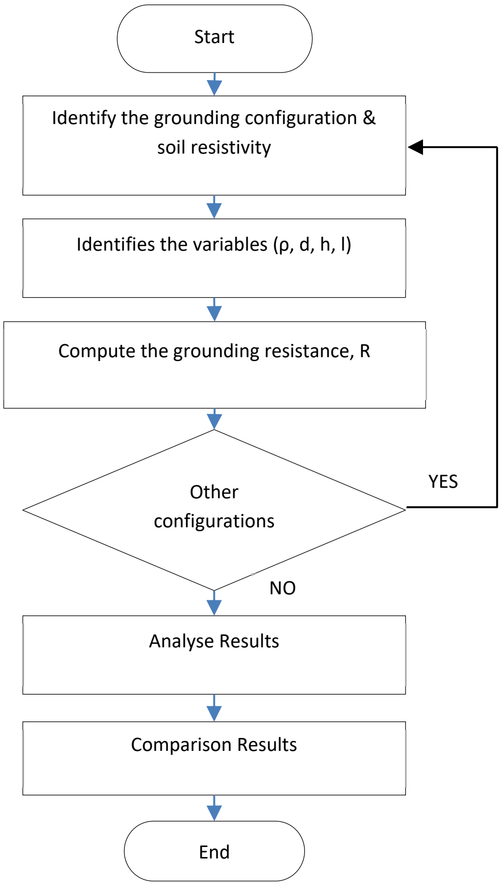

Fig. 1 Analysis procedure for grounding technique

For the case studies, the soil resistivity of 100 Ωm will be used and other variables are dependent on the grounding configurations.

III. Results and Analysis

A. Case Study

1. Case Study 1 – Single Ground Rod

Single Ground Rod is the simplest vertical method. This configuration offers the cheapest and most convenient means of installing an electrode, where this configuration can be manual driving, mechanical driving, and drilling dependent on the soil conditions.

For the technique, an electrode is buried or embedded in a vertical position in the ground. The rod is embedded up to 5.9 m in length and soil resistivity of 100 Ωm is considered in the case study. Fig. 2 shows the resistance values of Single Ground Rod for diameter rods of 0.010 m (d1), 0.016m (d2), 0.020 m (d3) and 0.030 m (d3) respectively.

The results shown in Fig. 2 observed that for the electrode embedded at 0.1 m from the ground surface in the vertical position, the ground resistance for R1 (for diameter rod of 0.010 m) is 538.3 Ω, R2 (for diameter rod of 0.016 m) is 463.5 Ω, R3 (for diameter rod of 0.020 m) is 427.9 Ω and R4 (for diameter rod of 0.030 m) is 363.4 Ω. The resistance coefficient differences of 13.9%, 7.7 %, and 15.1% are observed between R1&R2, R2&R3, and R3&R4 respectively.

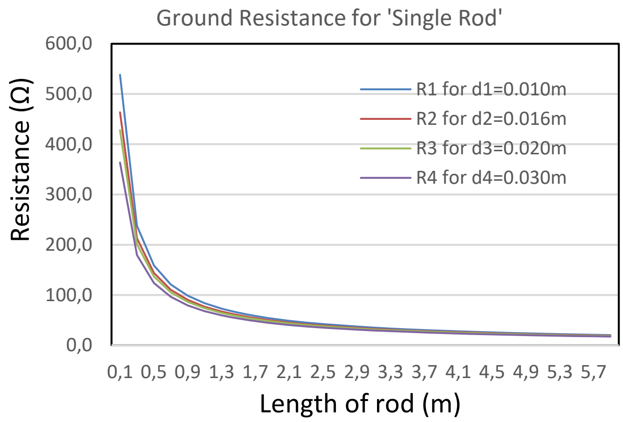

Fig. 2 The ground resistance of Single Ground Rod for diameter rods of 0.010 m, 0.016 m, 0.020 m, and 0.030 m respectively with soil resistivity of 100 Ωm

From the results in Fig. 2, it is observed that for the electrode embedded at 0.1 to 2.1 m, the resistance falls progressively for all diameter sizes. It happens due to the deeper soil with better electrical properties being reached. When the length buried is increased from 2.3 to 3.3 m, there is a minimum difference in the ground resistance, R for the single ground rod of different diameter sizes. However, when the length of the electrode is embedded at 3.5 m, the ground resistance is almost consistent or saturate until the length of the rod is buried at 5.9 m height level from the ground surface. From the results obtained, the ground resistance decreases effectively for 0.1 to 2.1 m length for all different sizes of diameter electrode, however minima decrease with a depth of embedded at 0.1 to 2.1 m. It is observed that there is a good agreement for the higher length of the embedded electrode

2. Case Study 2 –Two-Ground Rod

A two-ground rod is an extension of the single ground rod configuration. The two-ground rod configuration needs another electrode buried in parallel. This configuration requires the mutual separation between two ground electrodes to be two times the driven depth of the ground electrode. The electrode cannot be placed too close due to effectiveness is dropped by interference which causes the net shunt impedance to be greater than their zone of influence.

Fig. 3 obtained the ground resistance values of Two-Ground Rod for diameter rod of 0.010 m (d1), 0.016 m (d2), 0.020 m (d3), and 0.030 m (d4) respectively, with soil resistivity of 100 Ωm.

The case study is performed with soil resistivity 100 Ωm, and the diameter at 0.010 m, 0.016 m, 0.020 m, and 0.030 m, and the distance between 2 rods is 15 m.

From the results shown in Fig. 3, for the electrode embedded at 0.1 m in vertical into the soil, the ground resistance for R1 (for diameter rod of 0.010 m) is 269.7 Ω, R2 (for diameter rod of 0.016 m) is 232.3 Ω, R3 (for diameter rod of 0.020 m) is 214.5 Ω and R4 (for diameter rod of 0.030 m) is 182.2 Ω. The resistance coefficient difference between R1&R2, R2&R3, and R3&R4 is 13.9%, 7.7 %, and 15.1% respectively.

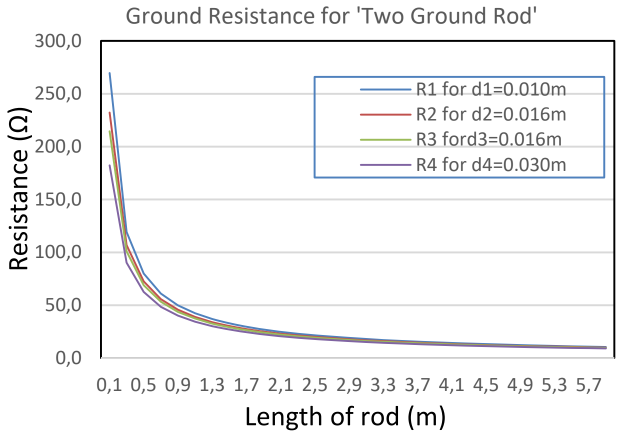

Fig. 3 The ground resistance of Two-Ground Rod for diameter rods of 0.010m, 0.016 m, 0.020 m, and 0.030 m with soil resistivity of 100 Ωm

In Fig. 3, it is observed that there is a good agreement for a higher length of electrode embedded, where at 0.1 to 1.3 m, the resistance falls progressively. It happens due to the deeper soil with better electrical properties being reached. From the results obtained, the ground resistance effectively decreases for all sizes of diameter electrode for 0.1 to 1.3 m length, however progressively decreases with a depth of embedded at 1.5 to 2.3 m. It is observed that there is a good agreement for the higher length of the embedded electrode. Also, observed in Fig. 3, for the length of an electrode at 2.3 m, the ground resistance is consistent or saturate until the length of the rod is buried at 5.9 m height level from the ground surface. From Fig. 3, the ground resistance decreases with increases in the length of the electrode. From the results obtained, the ground resistance is minimum decreases for all different sizes of diameter electrode, however progressively decrease with a depth of embedded at 0.1 to 1.3 m. It is observed that there is a good agreement for a higher length of the embedded electrode.

Fig. 4 obtained the resistance reduction coefficient as compared to Single Ground Rod configuration; Two-Ground Rod has been found to be more effective in reducing grounding resistance with resistance coefficients ranging from 47.4 to 49.9% for all diameter factors.

3. Case Study 3 – Four-Point Star

The Four-Point Star is a horizontal grounding configuration. The technique requires a big area to embed the rod in a horizontal position. To implement this configuration, a hole has to be bored in the area to embed the configuration. The electrode is embedded in a horizontal configuration as '+' pattern in the ground.

Fig. 5 shows the ground resistance of Four-Point Star configuration for a diameter rod of 0.010 m (d1), 0.016 m (d2), 0.020 m (d3), and 0.030 m (d3) respectively with soil resistivity of 100 Ωm and at depth level 0.5 m from the ground surface.

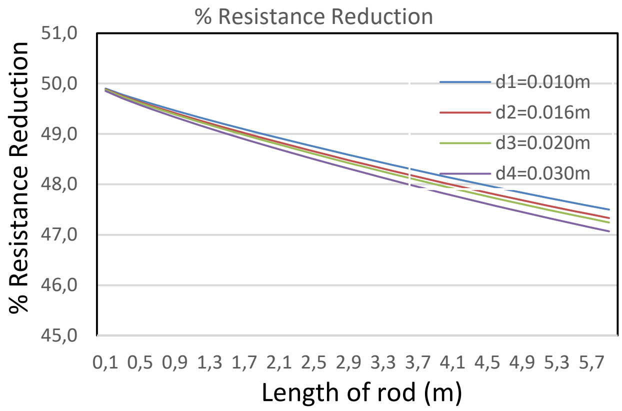

Fig. 4 Percentage reduction between Single Ground Rod and Two Ground Rod

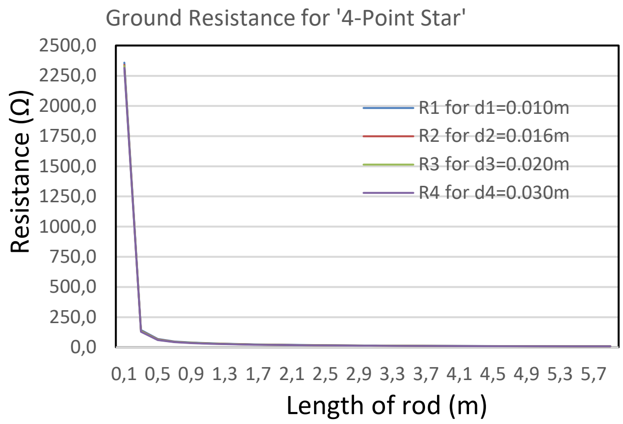

Fig. 5 The ground resistance of Four Point Star for diameter rods of 0.010 m, 0.016 m, 0.020 m, and 0.030 m respectively with soil resistivity of 100 Ωm and at depth level 0.5 m from the ground surface

From the results shown in Fig. 5, for a depth level of 0.5 m from the surface and with electrode length of 0.1 m embedded horizontally into the soil, the ground resistance for R1 (for diameter rod of 0.010 m) is 2358.7 Ω, R2 (for diameter rod of 0.016 m) is 2340.0 Ω, R3 (for diameter rod of 0.020 m) is 2331.1 Ω and R4 (for diameter rod of 0.030 m) is 2314.9 Ω. The resistance coefficients of 0.8%, 0.4%, and 0.7% are obtained for comparison values of R1&R2, R2&R3, and R3&R4 respectively, on different diameter sizes, where they show a minimum reduction of ground resistance.

The grounding resistance values fall progressively when the length of the rod in horizontal is extended from 0.1 m to 1.3 m as observed in Fig. 5 (for the diameter of 0.010 m). It is shown that the ground resistance decreases by extending the length of the rod horizontally in soil. For the length of electrode embedded increased from 1.5 m to 2.1 m, there is a minimum difference in the ground resistance.

The ground resistances decrease as shown in Fig. 5 for a diameter of 0.016 m, 0.020 m, and 0.030 m respectively. However, at electrode length of 2.3 m, the ground resistance is constant or saturate until the length of the electrode rod is embedded at 5.9 m.

The results observed the realistic correlation or a good agreement for ground resistance and length of the electrode, where the ground resistance decreases with increases in length of the rod. By comparing the resistance values for various diameter sizes, it is observed that there is a small difference in values of ground resistance.

4. Case Study 4 – Six-Point Star

The Six-Point Star is another alternative configuration for the 'Star' grounding configuration. The technique requires a big area to embed the electrode in horizontal. The technique is similar as discussed in Subsection III *A* 3 where the electrode is embedded in a horizontal configuration as '*' pattern with an angle of 60° between the rods.

Fig. 6 shows the ground resistance of the Six-Point Star configuration for diameter rod of 0.010 m (d1), 0.016 m (d2), 0.020 m (d3), and 0.030 m (d3) respectively, with soil resistivity of 100 Ωm.

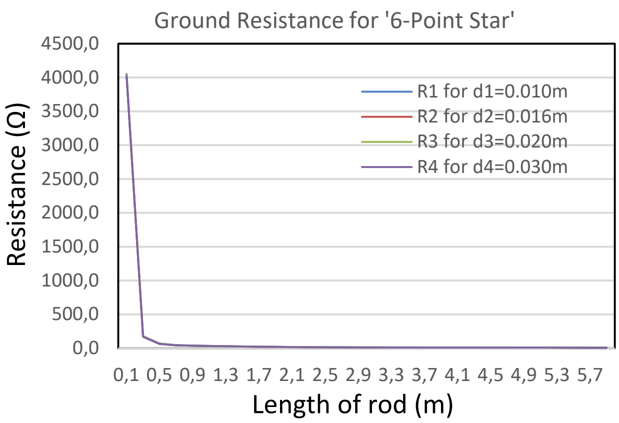

Fig. 6 The ground resistance of Six-Point Star for diameter electrode of 0.010 m, 0.016 m, 0.020 m, and 0.030 m with soil resistivity of 100 Ωm

From the results shown in Fig. 6, for a depth level of 0.5 m from the surface and with electrode length of 0.1 m embedded horizontally into the soil, the ground resistance for R1 (for diameter rod of 0.010 m) is 4048.6 Ω, R2 (for diameter rod of 0.016 m) is 4036.2 Ω, R3 (for diameter rod of 0.020 m) is 4030.2 Ω and R4 (for diameter rod of 0.030 m) is 4019.5 Ω. The differences of 0.3%, 0.2%, and 0.3% are seen between R1&R2, R2&R3, and R3&R4 respectively, observed a less reduction of ground resistance values.

As compared to the Four-Point Star configuration, the configuration recorded higher values of ground resistance at an initial length of 0.1 m. However, the grounding resistance values fall progressively when the length of the rod in horizontal is extended from 0.1 m to 0.9 m as observed in Fig. 6 (for a diameter of 0.010 m). It is shown that the ground resistance decreases by extending the length of the rod horizontally in soil. For the length of electrode embedded extended from 1.1 m to 1.7 m, there is a minimum difference in the ground resistance for the diameter of 0.016 m, 0.020 m, and 0.030 m respectively.

As compared to the Four-Point Star configuration, the Six Point Star obtained a lower value of ground resistance for the length of an electrode at initial 0.7 m and above.

Fig. 6 shows that for the length of the electrode at 1.9 m, the ground resistance is constant or saturated until the length of the rod is extended in horizontal up to 5.9 m. The results observed the realistic correlation or a good agreement for ground resistance and length of the electrode, where the ground resistance decreases with increases in length of the electrode. By comparing the resistance values for various diameter sizes, it is observed that there is a small difference in values of ground resistance

As compared to Four-Point Star configuration, at an initial length of electrode embedded (between 0.1-0.5 m), the result observed that ground resistance values of Six Point Star are higher than Four-Point Star, however for the length of the electrode is extended horizontally in the soil, the resistance value decreases effectively than the Four Point Star.

As compared to the Four-Point Star configuration, Six-Point Star is shown more effective in reducing the ground resistance with resistance reduction coefficient between 4-14.2% for all various diameters factor for length of rod at 0.7-5.9 m as shown in Fig. 7.

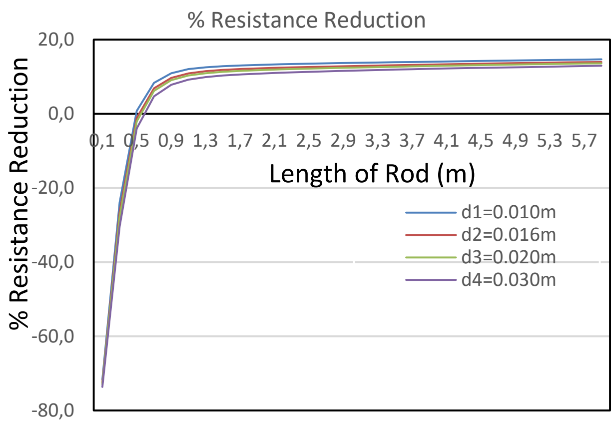

Fig. 7 Percentage reduction (Resistance coefficient) between Four-Point Star and Six Point Star

5. Case Study 5 – Ring of Wire

The Ring of Wire configuration is another alternative to the grounding system, which is embedded horizontally in a circle configuration as 'O' pattern.

Fig. 8 shows the ground resistance of Ring of Wire configuration for diameter rod of 0.010 m (d1), 0.016 m (d2), 0.020 m (d3), and 0.030 m (d3) respectively with soil resistivity of 100 Ωm.

From Fig. 8, for a depth level of 0.5 m from the surface and with an electrode length of 0.1 m diameter ring embedded horizontally into the soil, the ground resistance for R1 (for the diameter of the wire of 0.010 m) is 175.6 Ω, R2 (for the diameter of the wire of 0.016 m) is 151.8 Ω, R3 (for the diameter of the wire of 0.020 m) is 140.5 Ω and R4 (for the diameter of the wire of 0.030 m) is 119.9 Ω. The differences of 13.6%, 7.4%, and 14.7% are seen between R1&R2, R2&R3, and R3&R4 respectively.

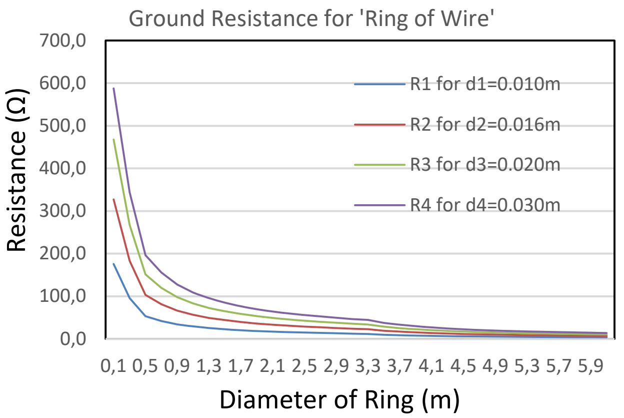

Fig. 8 The ground resistance of Ring of Wire for diameter rods of 0.010 m, 0.016 m, 0.020 m, and 0.030 m with soil resistivity of 100 Ωm

From the results in Fig. 8 (for the diameter of the wire of 0.010 m), it is shown that when the length of the rod in horizontal is extended from 0.1 m to 1.3 m, the resistance falls progressively. It is shown that the ground resistance decreases by extending the length of the rod horizontally in soil. When the length buried is increased from 1.5 m to 1.9 m, there is a minimum difference in the ground resistance. The ground resistance decreases for all diameter sizes as shown in Fig. 8 for the diameter of 0.016 m, 0.020 m, and 0.030 m respectively. Fig. 8 shows that when the diameter of the ring is increased to 2.1 m, the ground resistance becomes constant until the diameter ring is extended to 5.9 m.

IV. Conclusion

The effect of an extended electrode on vertical and horizontal positions shows an effect on decreasing the grounding resistance values. From the analytic case studies, the results have shown that the ground resistance falls very quickly by extending the length of electrode. The effect on multiple diameter sizes of electrodes observed minimal coefficient on reduction of ground resistance. The decrease of ground resistance reached a saturation point at a certain length due to the shielding effect increases with the decrease of the interval among rods.

From the case studies, the ground resistance depends significantly on the length of the electrode and the height/depth of buried electrode into the soil. Hence, the ground resistance decreases as the depth of the electrode are embedded into the ground. However, the ground resistance will reach a saturation level, whereby an increase in depth will not affect the ground resistance anymore.

The configurations on vertical and horizontal observed a certain advantage and degree of stability to the ground resistance but with different characteristics such as depth and length. It is observed from Figs. 4 and 7 (the case studies) that for electrode length of 0.1 to 6.0 m, the resistance reduction coefficients are 47.1-49.9% for vertical configurations (single ground rod and two-ground rod) and 4.0-14.2% for horizontal configurations (four-point star and six-point star) on diameter sizes of 0.010, 0.016, 0.020 and 0.030 m. These values indicate a good correlation and agreement between configuration and grounding resistance.

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