VOL. 11, NO. 7, APRIL 2016 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

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REDUCTION OF EARTH GRID RESISTANCE BY ADDITION OF EARTH RODS TO VARIOUS GRID CONFIGURATIONS

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ABSTRACT

Achieving low earth grid resistance is highly desirable in power distribution substations design. However, due to variation of soil resistivity from one location to another, it is not possible to obtain the same value of low earth resistance at all locations. Changing earth conductor dimensions such as cross sectional area and length may lower earth resistance. In this paper, six different earth grid configurations have been used to study the effect of adding vertical earth rods to the grid periphery and at all grid conductor intersections of each configuration with the aim of reducing the overall grid resistance. Three grids were designed with compression ratio of 1, while the other three had a compression ratio of 0.8. Results indicated that for grids with compression ratio of 0.8 and with earth rods at all conductor intersections, the grid resistance was lower than those with a compression ratio of 1. It was also found that, the resistance of all grids with a compression ratio of 0.8 were lower than those with a compression ratio of 1.

Keywords: grid resistance, grid configuration, earth rods, compression ratio.

INTRODUCTION

A distribution substation is basically an electric facility comprising of equipment such as transformers, circuit breakers, capacitor banks and other devices that are necessary for transformation, regulation and distribution of electrical energy. As a result of its functions, a substation is potentially a hazardous area that is prone to various kinds of power system faults which may have its origin within the substation or along the distribution lines emanating from or terminating at the substation. Therefore, it is mandatory to ensure that the safety of personnel and the general public is guaranteed against any potential hazard, such as electric shock resulting from direct or indirect contact with energised parts and that substation equipment are protected against overvoltage. Protection of personnel and equipment in substations and its vicinity is normally achieved by connecting and bonding all the metallic frames of equipment and other metallic structures such as fences and utility pipes to a common earthing system. An earthing system in this context refers to a connection of metallic conductors or wire(s) of different geometrical structures such as single horizontal earthing wire, vertical rods, ring conductors and earthing grid occupying a large area, or a suitable combination of above mentioned structures between an electrical circuit and the soil with the aim of achieving a permanent and continuous electrical conducting path to the ground, (Liu, 2004). MacDonald (2007) added that substation earthing system is an interconnection of all earthing facilities in the substation area, including the earth grid, overhead earth wires, neutral conductors, underground cables, foundations and deep wells.

The main function of substation earthing grid is to provide a means to dissipate fault currents into the ground in the shortest time possible without exceeding any operating and equipment limits under both normal as well as fault conditions. Also, to assure that a person in the vicinity of earthed facilities is not exposed to the danger of critical electric shock. Other functions performed by the earthing grids in a substation are to ensure the safe operation of the distribution system and to guarantee the safety of personnel and equipment by limiting the touch and step voltages and earth potential rise during earth fault conditions to tolerable limits, (IEEE Std. 80-2013), (Paulino et al. 2011). In order for a substation earthing system to perform its function effectively, the earth grid resistance Rg must be low enough to assure that fault currents dissipate mainly through the earthing grid into the soil (Ahmeda, 2012). According to (IEEE Std. 142-2007), the acceptable range of Rg for a small distribution substation is from 1 Ω to 5 Ω, depending on the local soil conditions. Popovic (2007), suggested that distribution substations are often located as near as possible to load locations they serve which may sometimes be within a city centre where there is very little land for installing large earthing grids and there are obstructions such as important public buildings that cannot be demolished in lieu of distribution substations. In some countries such as Malaysia, land for installation of electrical substations is allocated based on the voltage level to be handled by the substation. Typical land sizes for specific voltage levels are 30x30m for 33/11kV main switching station (SSU) and 13.6x14.8m for 11/0.415kV distribution substation (P/E) (ESAH, 2007). This situation poses great challenges during earth grid design if the soil resistivity is high and the recommended earth resistance values are to be maintained. Note that, the reference substation in this paper is the open terminal air insulated type.

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Several commercial softwares are available for the design and analysis of substation earthing grids. El-Fergany (2007) applied Particle Swarm Optimization (PSO) approach for the design and optimization of substation earth grid geometry. Khodr et al. (2009) proposed the use of Mixed-integer linear programming method considering both technical and security issues in the design of substation earth grids. EDSA, CYMGRD and ETAP were utilized for the design and analysis of substation earth grids by (EDSA, 2008), (Nithiyathan, 2011), (Potta and Balakrishnan, 2013). A graphical User Interface (GUI) coupled with an interactive computer program using MATLAB 7.10 was also developed by (Kaustubh and Jamnani, 2012) to accurately compute the safety parameters of an earth grid. However, there is no available literature showing the effect of earth rods on different grid arrangements with the aim of reducing earth grid resistance. Therefore, in this paper, the design of a distribution substation earth grid was conducted using CDEGS considering the effect of addition of vertical earth rods to the grids whose compression ratio was alternately changed from 1 to 0.8 in three different arrangements.

METHODOLOGY

The process of designing substation earth grid design involves many stages which have been outlined in [3]. However, when the earth grid design is done using computer program such as CDEGS, some of the steps detailed in [3] are truncated. Basically, there are two design stages, i.e. preliminary and actual. The preliminary stage involves field survey and data collection which is normally done by carrying out soil resistivity measurements at the allocated site for a substation to be built in order to determine the soil structure models of such location. The actual design on the other hand comprises of calculations of parameters such as maximum expected grid current, grid conductor size, grid resistance, tolerable touch and step voltages, and EPR which are automatically computed by the CDEGS. In this paper, an earth grid has been designed for a distribution substation proposed to serve a residential area supplied by 1000kVA,11/0.43-0.24kV transformer. Soil resistivity measurement was conducted at the proposed substation site located at College 12, Universiti Putra Malaysia, Serdang, Selangor, Malaysia based on Wenner method using a 4-Pole Earth Tester. The initial spacing between probes was 1m and increased in steps of 1m up to 6m. For accuracy purposes, the spacing between probes was equally maintained and all probes were arranged in a straight line. The RESAP module of CDEGS software was used to determine the soil model from measured soil resistivity field data. In order to determine the maximum expected grid current, the available short circuit capacity at the secondary terminals of the upstream transformer rated at 15MVA, 33/11kV, 10% Z was computed as 7,873A using (1) and (2). This current was assumed to flow in the event of a bolted three phase fault on the high voltage (HV) side of the downstream transformer rated at 11/0.43-0.24kV. The length of the cable line between the upstream and downstream substations was taken as 0.69km, where a split factor of 0.75 was assumed, implying that the grid energization current is 5,905A.

$$I_L = \frac{P}{\sqrt{3 \times V_L}} A \tag{1}$$

Where, I_L is the full load current in Amps; P is the power rating of the transformer in MVA, and V_L is the line voltage in *kV*.

$$I_{SC} = I_L \times \frac{100}{\%Z} A \tag{2}$$

Where, I_{SC} is the short circuit current in Amps; I_L is the transformer full load current in Amps, %Z is the percentage impedance of the transformer.

SESCAD DESIGN DATA

Earth grid was designed using SESCAD and executed using the MALT module of CDEGS to obtain the safety parameters such as the touch and step voltages and fibrillation current for fault durations of 0.3s. An initial estimate of the grid resistance was made using (3) where a grid dimension of 60m x 60m was assumed yielding an $R_g<5\Omega$. The earth grid comprised of 21 parallel horizontal rows and 21 parallel columns spaced 3m apart in both directions. The earth grids were designed in six different configurations. The configurations are earth grid with compression ratio (spacing between parallel conductors) of 1 without earth rods (A_1), grid with compression ratio 0.8 without rods (A_2), grid with compression ratio 1 with earth rods at the grid periphery (B_1), grid with compression ratio 0.8 with rods at the grid periphery (B_2), grid with compression ratio 1 with earth rods at all grid conductor intersections (C_1), grid with compression ratio 0.8 with rods at all conductor intersections (C_2). Note that, a compression ratio of 1 means equally spaced rows and columns of parallel grid conductors, while a compression ratio of 0.8 represent closely spaced rows and columns of parallel conductors around the grid periphery and widely spaced towards the grid centre. The earth rods were 3m long and spaced 3m apart around the grid periphery and at conductor intersections. The burial depth of the earth grid was 1.3m based on the soil model obtained. The grid conductors and the earth rods were both assumed to be made of hard dawn copper of radius 0.0067056m. All six configurations are illustrated in Figures 1 until 6 for A_1 to C_2 earth grid configurations, respectively.

$$R_g = \frac{\rho}{4}\sqrt{\frac{\pi}{A}}\Omega \tag{3}$$

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Where, R_g is the grid resistance in Ω, ρ is the soil resistivity in Ω-m, A is the area occupied by the grid in m^2.

RESULTS AND DISCUSSIONS

Table-1 depicts the soil resistivity field data indicating measured apparent resistance and computed resistivity values which are average values of six measurements conducted at alternate probe spacing. These data were used as input to RESAP module of CDEGS software in order to determine the soil model as indicated in Table-2. It indicates that the soil at the area is a two-layer soil. The first, i.e. top layer has a resistivity of 2231.9Ω-m and a thickness of 1.1m. The second, i.e. bottom layer has a resistivity of 752.4Ω-m and an infinite thickness. It could be observed that the bottom layer has lower resistivity than the top layer; therefore, the earth grid may be buried within this layer to take advantage of lower resistivity. In this paper, a burial depth of 1.3m was considered for the grid design.

Table-1. Average of measured soil resistivity field data.

Probe spacing (m)	**Average apparent resistance** (Ω)	**Average apparent resistivity** (Ω-m)
1.0	308.6	1,938
2.0	110.2	1,384
3.0	52.8	995
4.0	33.6	844
5.0	32.0	1,005
6.0	20.0	754

Table-2. Soil model computed by RESAP.

Soil layers	**Resistivity** (Ω-m)	**Thickness** (m)
1	2231.9	1.1
2	752.4	infinite

Table-3 lists the performance of earth grids designed using six different configurations comprising of three cases A_1, B_1 and C_1 with compression ratios of 1 and three cases A_2, B_2 and C_2 with compression ratios of 0.8, respectively. Figures 1 and 2 illustrate the grid configurations for A_1 and A_2 with compression ratios 1 and 0.8. It could be observed from Table-3 that although the total length of buried conductors for both A_1 and A_2 is similar, i.e. 2940m, the grid resistances R_g were slightly different with 4.7041Ω for A_1 and 4.6685Ω for A_2 grids, respectively. This indicates that compression ratio has a slight effect on earth grid resistance even in terms of 0.16Ω difference only. Considering the EPR with respect to the two grid configurations, with an energization current of magnitude 5.709kA, it is observed that the grid with A_1 configuration had an EPR of 27.778kV, while an EPR of 27.567kV was obtained from A_2 grid showing a difference of 211V which is sufficient to cause a shock hazard, especially to personnel who are directly or indirectly in contact with equipment in the substation.

Table-3. Performance of six earth grid with different configurations.

Earth grid configurations	**Length of conductors** (m)	R_g (Ω)	**EPR** (V)
A_1	2940	4.7041	27,778
A_2	2940	4.6685	27,567
B_1	3180	4.5557	26,901
B_2	3180	4.5454	26,841
C_1	4263	4.4815	26,463
C_2	4263	4.3744	25,831

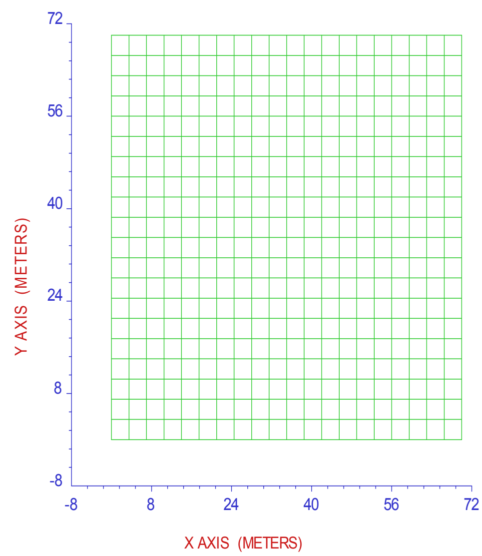

Figure-1. Top view of earth grid A_1.

Figures 3 and 4 shows the grid configurations B_1 and B_2 with 3m long earth rods installed along the grid periphery and separated 3m apart. As a result, the total length of buried conductor increased from 2940m to 3180m yielding a difference of 240m. However, addition of the earth rods had little impact on the value of R_g.

VOL. 11, NO. 7, APRIL 2016 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

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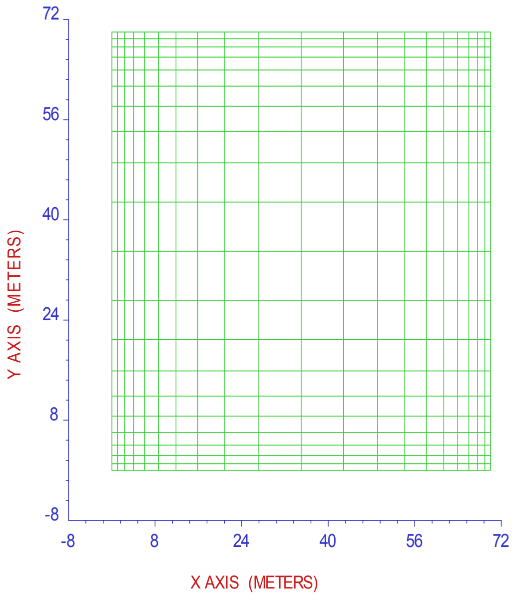

Figure-2. Top view of earth grid A_2.

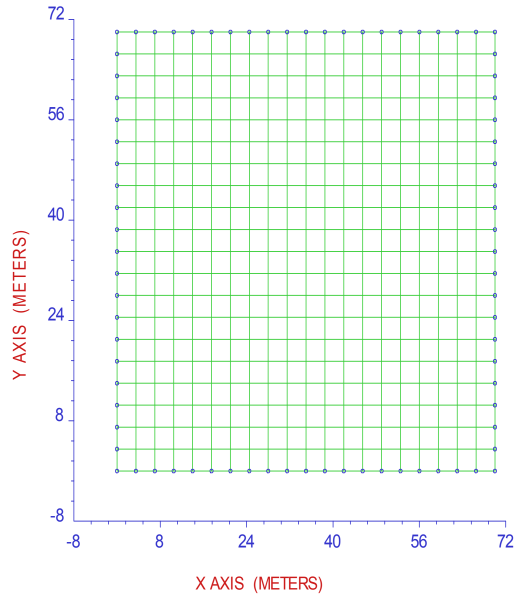

Figure-3. Top view of earth grid B_1.

For instance, comparing grids A_1 and B_1 in terms of the value of R_g, It could be seen that there is a difference of 0.1484Ω only. Similarly, comparing grids A_2 and B_2 it could be noted that there is a difference of only 0.1231Ω despite the increase in buried conductor length and change in compression ratio. In terms of EPR, when grids A_1 and B_1 are compared, it is observed that there is a difference of 877V with B_1 having a lower value than A_1. This implies that installation of earth rods at the grid periphery contributes in lowering the EPR. Similarly, when A_2 and B_2 are compared in terms of EPR, it could be seen that the EPR with respect to grid B_2 is lower than that of A_2 by 726V which further indicates the contribution of earth rods in reduction of EPR. It could therefore be deduced that installation of earth rods at the grid periphery is advantageous when reduction of EPR is desired but is insignificant for reduction of R_g irrespective of the compression ratio of 1.0 or 0.8. Therefore, for configurations with earth rods at the periphery, compression ratio of 1 is recommended for installation as there is no much difference of R_g as demonstrated using CDEGS.

Figures 5 and 6 show the configuration for grids C_1 and C_2 having earth rods at all grid conductor intersections and the periphery, thus, the total length of buried conductors swelled from 3180m to 4263m yielding a difference of 1084m. Comparing grid A_1 and C_1 in terms of R_g referring to Table 3, it could be noted that the value of R_g in C_1 grid is lower than A_1 grid by 0.2226Ω which may be considered insignificant for 1,084m increase in buried conductor length. In the same vein, comparing A_2 and C_2, it is obvious that the value of R_g in grid C_2 is lower than grid A_2 by 0.2941Ω showing little impact for the 1, 084m length of buried conductors installed at the grid intersections. In terms of EPR, the value recorded from grid C_1 is significantly lower than that from grid A_1 by 1,315V which is dangerously high. Also, comparing C_2 and A_2, it could be seen that the EPR obtained from grid C_2 is yet lower than grid A_2 by 1,736V which could be potentially hazardous to personnel and other living things in the vicinity of the substation. Comparing the values EPR for A_1, B_1 and C_1 with A_2, B_2 and C_2 grid configurations, it could be deduced that, earth grids designed with compression ratio of 0.8 have lower EPR than those with a compression ratio of 1. Impliedly, compression ratio has a significant effect on EPR especially when vertical earth rods are installed at all grid conductor intersections. Similarly, relating the values of R_g for A_1, B_1 and C_1 grids with A_2, B_2 and C_2 grids, it is clear that there is no significant change in the value of R_g despite the increase of buried conductor length in B_1, B_2 and C_1, C_2 grid configurations. It is also evident from Table 3 that, compression ratio has negligible or no effect on the value of R_g as it was changed from 1.0 to 0.8.

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ARPN Journal of Engineering and Applied Sciences

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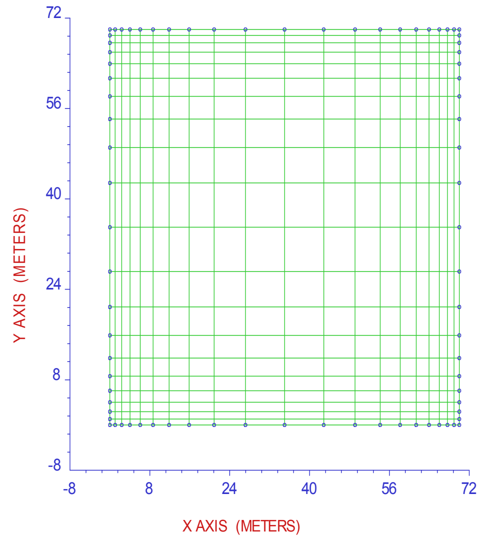

Figure-4. Top view of earth grid B_2.

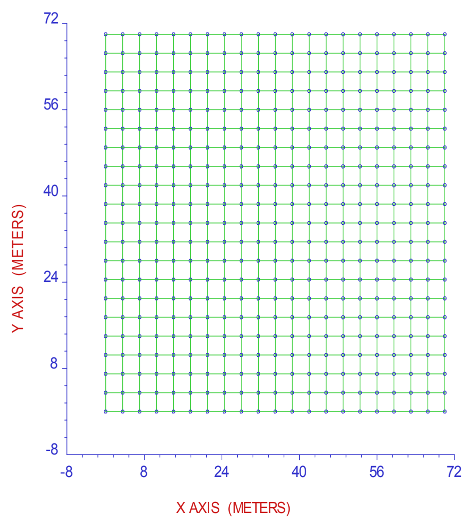

Figure-5. Top view of earth grid C_1.

Note that the buried conductor lengths for grid A_1 and A_2 are similar despite the different configurations. In the same vein, B_1 and B_2 are similar; C_1 and C_2 are also similar as indicated in Table-3. Comparing the grid configurations according to type A, B and C with regard to buried conductor length, it could be seen that grid C has the highest length of buried conductor comprising of stranded bare conductors and earth rods both made of copper at all grid intersections. Grid configuration B has the next higher length of buried conductor also including earth rods, while grid A had the least length of buried conductor without rods. Typical values of buried conductor lengths are 4263m, 3180m and 2940m, respectively.

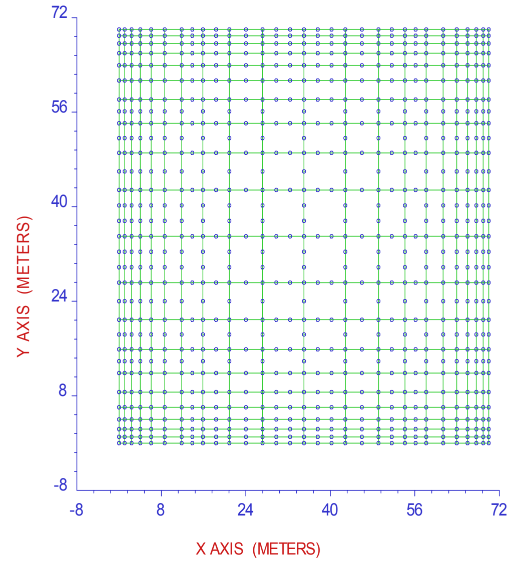

Figure-6. Top view of earth grid C_2.

Table-4 lists the cost of buried conductors for the each of the grid configurations. The cost of 1 metre length of 4/0 AWG (0.0134m diameter) stranded bare copper conductor from Southwire catalogue is MYR35.00, while the cost of one metre length of 0.013m diameter earth rod from Element 14 catalogue is MYR41.00. It could be observed that the cost of 2940m length of stranded bare copper conductor making grid configuration A is MYR102, 900.00. Similarly, the cost of 2940m of bare copper conductor plus 240m length of earth rods (3180m) grid configuration B is MYR 112,740.00. The cost difference between grid configurations A and B is MYR 9,840.00. In the same vein, the cost of 2940m of bare copper conductor and 1323m of earth rods (4263m) for grid C configuration is MYR157, 143.00. The cost difference between grid A and C is MYR54, 243.00 and between grid B and C is MYR44, 403.00. Based on cost comparison and the value of R_g obtained from grids A, B and C, it is obvious that grid C configuration is not economical to construct as the cost of buried conductor is very high compared to the cost of grid configurations A and B, also the change in the value of R_g is not significant.

Table-4. Cost of buried conductors.

Earth grid configuration	**Length of buried conductor** (m)	**Cost** (MYR)
A	2940	102,900.00
B	3180	112,740.00
C	4263	157,143.00

CONCLUSIONS

A study of the effect of earth rods on reduction of grid resistance using six different earth grid configurations was presented. Two parameters were considered, the

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spacing between grid conductors of compression ratio 1 and 0.8, and earth grid configuration in which one was installed without any vertical earth rods, while another was installed with vertical earth rods at the grid periphery and the last with vertical rods at all grid intersections. It was found that, grids designed with compression ratio of 0.8 yielded lower grid resistances than those with compression ratio 1. It was also revealed that the grid resistance obtained after installation of earth rods at all conductor intersections was negligible considering the increase in total buried conductor length. Furthermore, it was discovered that, the EPR produced by grids designed with compression ratio 0.8 were lower than those with compression ratio of 1. It could therefore be concluded that, installation of earth rods at all conductor intersections in a grid with the aim of reducing the grid resistance is not recommended as the reduction in resistance (0.11Ω) is not commensurate to the increase in buried conductor length (1084m).

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