



Performance Evaluation of an Optimally Designed Substation Grounding Grids

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ABSTRACT

The inadequacy of proper grounding or the lack of it leads to disruption of services, damages to equipment under fault conditions and personnel injury or death. This paper applied the Harmony Search Algorithm (HSA) and Genetic Algorithm (GA) to determine an optimal design of Substation grounding grids. Sets of data were collected from the proposed substation site. The area of land for the proposed substation is 70m x 70m. For ease of the design, the site is divided into grids of 10m intervals along the longitudinal and transverse plane. The apparent resistivity data obtained from the testing equipment serves as inputs to sets of equations used in determining the Performance metrics for an optimal design of a Substation grounding grid design in line with IEEE STD80-2000 standard. A comparison of the results obtained using the two algorithms give the information on the best technique in terms of Step and Touch voltages, Ground Potential Rise (GPR) and Ground Resistance R_g for the proposed siting of the substation. The simulation was done in MATLAB R2015b. A design evaluation obtained by applying HSA and GA shows performances that are superior to those of IEEE STD80-2000. The maximum touch voltages are 814.70V and 812.77V for HSA and GA respectively. These values are superior to a maximum touch voltage of 758.21V obtained by applying the IEEE STD 80-2000. The maximum step voltages obtained are 283.77V and 308.48V for HSA and GA respectively against the IEEE STD80-2000 value of 392.91V. The step voltage reduced by 8.7% when its value obtained by applying HSA is compared to that obtained by applying GA. These results show that HSA outperformed GA as it reduces the maximum step voltage thus increasing the safety level. Furthermore, the GPR and the grid resistance values obtained using HSA showed remarkable reduction of 3.44%.

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INTRODUCTION

Today, more and more substations are created and reconstructed to satisfy the growing electricity demands for both industry and households (Wu et al., 2016). As a result, an adequate grounding system is needed to protect people from dangerous touch and step potentials. Therefore, step and touch voltage at any point of the installation should not exceed the maximum allowable values (Wu et al., 2016). The purpose of grounding circuit is to provide a path for the fault currents enabling protection circuit to take necessary action (Kara et al., 2016). Performance of a grounding grid depends on the soil structure and grid configuration. Ground grid can have equally or

unequally spaced conductors with or without ground rods. Soil may be uniform, two layer or multilayer (Peng & Kuo, 2018). Various optimization techniques have been used in literature to design the grounding grid of substation. (Id et al., 2021) designed a digital application for grounding grid calculations of substations aimed at reducing the complexity and time of design. (Alik et al., 2015) minimized the problem of a cost function depending on the large number of parameters when designing grounding grid of substation using PSO, GA and a hybrid of PSO and GA. (Bonda & Mishra, 2018) presented an optimized design of earthing system for a substation located in high soil resistivity with limited plot using computer



design program. (Id et al., 2021) worked on features and cost optimizations of grounding grids in various soil conditions (i.e. uniform soil, two-layer horizontal soil, and two-layer vertical soil) using Simulated annealing and Current Distribution, Electromagnetic Fields, Grounding And Soil Structure Analysis(CDEGS). (Kara et al., 2016) designed an optimum grounding grid using GA. (Lei et al., 2012) designed an Optimal Substation Grounding Grid based on Genetic Algorithm Technique. (Wu et al., 2016) developed a software for an optimal substation ground grid design based on Genetic Algorithm and Pattern Search. This paper seeks to evaluate an optimal design of substation grounding grids by minimizing the step and touch voltages, the length of grounding grids and number of grounding rods using Harmony Search Algorithm, with a view to reducing the overall cost of procurement and installation of the grounding grids.

Grounding Grid

Grounding grid is an arrangement in an electrical substation, plant or system which is related to the protection of people and equipment and/or the optimal operation of the system involved (Zhang, 2014). The term "Grounding" is a method of providing a good electrical connection between metallic structures or electrical circuits and a metallic system buried in the earth. This is done with the aim of maintaining such structures at the general electrical potential of the earth (i.e. zero potential) or at the same potential with the earth, thus preventing undesirable and dangerous potential differences (Smestad et al., 2020)

Ground Potential Rise (GPR)

$$HM = \begin{bmatrix} x_1^1, x_2^1, \dots, x_n^1 \\ x_1^2, x_2^2, \dots, x_n^2 \\ \dots \\ x_1^{HMS}, x_2^{HMS}, \dots, x_n^{HMS} \end{bmatrix} \quad (2)$$

Where $[x_1^i, x_2^i, \dots, x_n^i]$, $(i=1, 2, \dots, HMS)$ is a solution candidate. HMS is typically set to be between 50 and 100.

The objective function is as stated in equation (3)

The performance and safety of any power substation is mainly dependent on the ability of the grounding grid to provide a robust

GPR occurs when a large current flow to earth through an earth grid impedance. It is caused by electrical faults that occur at electrical substations (Kapijan, 2017). Since the resistance of the earth is non-zero, a current injected into the ground produces a potential rise (El-Fergany, 2013). GPR therefore is the maximum electrical potential a grounding grid may attain relative to a distant grounding point assumed to be at the potential of remote earth (El-Fergany, 2013). GPR is proportional to both the current flowing in the ground grid and the equivalent grid impedance and is presented mathematically as (El-Fergany, 2013):

$$GPR = I_f \times R_{grid} \quad (1)$$

Where I_f is the current flowing in the ground grid

R_{grid} is the equivalent grid impedance.

Harmony Search Algorithm (HSA)

In the basic Harmony Search Algorithm, the music improvisation is a process of searching for a better harmony by trying various combinations of pitches that should follow any of the following three rules (Id et al., 2021). The rules are, choosing any value from the HS memory, choosing an adjacent value from the HS memory and choosing a random value from the possible value range. The three rules in the HSA are effectively directed using two essential parameters: harmony memory considering rate (HMCR) and pitch adjusting rate (PAR) (Uma et al., 2016).

For an n-dimension problem, an Harmony Memory (HM) of a particular Harmony Memory Size (HMS) can be represented as follows (Nasir et al., 2020):

path for the discharge of dangerous current that may arise from equipment fault or lightning such that both the equipment and personnel safety



are guaranteed in accordance to IEEE standard (Bhatia et al., 2020). The objective function is aimed at minimising such dangerous potentials vis a vis ground resistance R_g Ground potential rise, Step and touch voltages values that may arise during such fault. Minimization of the above parameters result in the reduction of the length and configuration of the conductor grids grounding and the grounding rods for the particular soil characteristics. This invariably

has a great significance on the cost of implementation when siting power substation in a particular location. Equation 3 depicts the cost optimisation in terms of the Area of the substation, the length of the grid in the X and Y axis and number of grounding rods needed to achieve the IEEE safety standard. Equation 4 to 6 are the constraints parameters to achieve the safety level desired.

$$\text{Optimal_cost} = C_{01} \cdot A(N_x \cdot L_y + N_y \cdot L_x) + C_{02} \cdot h \cdot (N_x \cdot L_y + N_y \cdot L_x) + C_{03} \cdot (N_x \cdot L_y + N_y) + C_{04} \cdot (N_r) \quad (3)$$

$$E_s = \frac{\rho_\alpha + K_i + K_s + I_g}{L_s} \quad (4)$$

$$E_m = \frac{\rho_\alpha + K_i + K_m + I_g}{L_m} \quad (5)$$

$$R_g = \rho_\alpha \left[\frac{1}{L_t} + \frac{1}{\sqrt{20A}} \left(1 + \frac{1}{1+h \left(\sqrt{\frac{20}{A}} \right)} \right) \right] \quad (6)$$

$$\text{Where } k = \frac{\rho_2 - \rho_1}{\rho_2 + \rho_1} \quad (7)$$

$$A = \left(\frac{2nh}{\alpha} \right)^2 \quad (8)$$

ρ	Soil resistivity, $\Omega \cdot m$
ρ_s	Surface layer resistivity, $\Omega \cdot m$
$3I_0$	Symmetrical fault current in substation for conductor sizing, A
C_s	Surface layer derating factor
d	Diameter of grid conductor, m
D	Spacing between parallel conductors, m
D_f	Decrement factor for determining I_G
D_m	Maximum distance between any two points on the grid, m
E_m	Mesh voltage at the center of the corner mesh for the simplified method, V
E_s	Step voltage between a point above the outer corner of the grid and a point 1 m diagonally outside the grid for the simplified method, V
$E_{ste\ p50}$	Tolerable step voltage for human with 50kg body weight, V
$E_{ste\ p70}$	Tolerable step voltage for human with 70kg body weight, V
$E_{tou\ ch50}$	Tolerable touch voltage for human with 50 kg body weight, V
$E_{tou\ ch70}$	Tolerable touch voltage for human with 70 kg body weight, V
h	Depth of ground grid conductors, m
h_s	Surface layer thickness, m
I_G	Maximum grid current that flows between ground grid and surrounding earth (including dc offset), A
I_g	Symmetrical grid current, A
K	Reflection factor between different
K_h	Corrective weighting factor that emphasizes the effects of grid depth, simplified method
K_i	Correction factor for grid geometry, simplified method
L_c	Total length of grid conductor, m
L_M	Effective length of $L_c + LR$ for mesh voltage, m



L_R	Total length of ground rods, m
L_r	Length of ground rod at each location, m
L_S	Effective length of $L_c + L_R$ for step voltage, m
L_T	Total effective length of grounding system conductor, including grid and ground rods, m
L_x	Maximum length of grid conductor in x direction, m
L_y	Maximum length of grid conductors in y direction, m
N	Geometric factor composed of factors $na, nb, nc,$ and nd
N_x	Number of grid conductors in horizontal axis
N_y	Number of grid conductors in vertical axis
N_r	Number of rods placed in area A
A	Total area enclosed for the grounding grid in m ² ;
R_g	Resistance of grounding system, Ω
S_f	Fault current division factor (split factor)
t_c	Duration of fault current for sizing ground conductor, s
K_{ii}	Corrective weighting factor that adjusts for the effects of inner conductors on the corner mesh, simplified method
K_m	Spacing factor for mesh voltage, simplified method
K_s	Spacing factor for step voltage, simplified method
C_{01}	Cost of one meter of conductor (N/m.mm ²)
C_{02}	Cost of burring in depth one meter of conductor in (N/m.m)
C_{03}	Cost of weld for one junction (N)
C_{04}	Cost of each rod (N)

Step voltage

Step voltage is the voltage between the feet of a person standing near an energized grounded object (Jambak et al., 2017). To evaluate the allowable step voltage, the equation relating to person weighing 50 kg/70kg is provided as:

$$E_{step} = (1000 + 6C_s \rho_s) \frac{C_w}{\sqrt{t_s}} \quad (9)$$

From (9), the correction factor is dependent on the depth and resistivity of the surface material and the resistivity of the soil layer underneath the surface material.

Touch voltage

Touch voltage is the voltage between an energized object and the feet of a person in contact with the energized object (Jambak et al., 2017). This is also stated that the allowable touch voltage for a person weighing 50 kg/ 70kg respectively is given as (Kapijan, 2017):

$$E_{touch} = (1000 + 1.5C_s \rho_s) \frac{C_w}{\sqrt{t_s}} \quad (10)$$

From (9) and (10), if the fault duration is made constant and the resistivity of the surface material is increased, a greater GPR may be present in substation without causing any hazardous effects (Ackerman, A., Sen, P. K., and Oertli, 2013)

METHODOLOGY

Measurement and collection of data for soil resistivity was carried out on Kubwa expressway in Abuja. The measurement was carried out on every grid of 10m x 10m spacing. Also, 4 sets of apparent resistivity readings were obtained for the probe spacing of 1.5m, 2.0m, 3.0m and 4.5m corresponding to the depth of measurement. The readings obtained gave different values of apparent resistivity at each depth. The thickness of each depth has corresponding resistivity value from one layer to the other. This test was repeated throughout the entire grid of 70m x 70m on site. Plate 1 shows the apparent resistivity reading in progress, while Plate 2 shows the test measurement on site as well.



Plate 1: Resistivity measurement at Site



Plate 2: Display of readings of soil resistivity on Megger DET2/2 Auto Earth Tester

Table 1: Measured apparent soil resistivity data

SAMPLE	LOCATION	TEST POINT	SPIKE DISTANCE[M]	APPARENT RESISTIVITY VALUE[ΩM]	APPARENT RESISTIVITY VALUE[ΩM]	APPARENT RESISTIVITY VALUE[ΩM]	APPARENT RESISTIVITY VALUE[ΩM]	APPARENT RESISTIVITY VALUE[ΩM]	APPARENT RESISTIVITY VALUE[ΩM]	APPARENT RESISTIVITY VALUE[ΩM]
				G0.0-10.0M	G10.0-20.0M	G20.0-30.0M	G30.0-40.0M	G40.0-50.0M	G50.0-60.0M	G60.0-70.0M
STEP 1 SITE	0.0M - 10.0M	1	1.5	170.61	155.53	146.10	157.41	164.96	193.23	170.61
		2	2	131.96	125.68	90.49	106.83	136.99	164.64	131.96
		3	3	135.73	126.31	103.69	131.96	131.96	169.67	135.73
		4	4.5	186.63	147.05	186.63	152.70	175.32	223.40	186.63
	10.0M - 20.0M	1	1.5	189.46	178.15	151.76	174.38	162.13	234.71	208.31
		2	2	145.79	136.99	119.40	131.96	136.99	167.15	145.79
		3	3	154.59	147.05	131.96	135.73	165.90	173.44	154.59
		4	4.5	183.81	172.50	183.81	178.15	169.67	223.40	183.81
	20.0M - 30.0M	1	1.5	146.10	155.53	142.33	152.70	153.64	146.10	183.81
		2	2	124.42	115.63	111.86	115.63	116.88	124.42	149.56
		3	3	131.96	128.19	126.31	124.42	128.19	131.96	164.01
		4	4.5	172.50	186.63	166.84	172.50	178.15	172.50	200.77
	30.0M - 40.0M	1	1.5	172.50	171.55	159.30	161.18	159.30	227.17	238.48
		2	2	116.88	126.94	116.88	113.11	125.68	154.59	179.72
		3	3	126.31	133.85	135.73	130.08	133.85	154.59	201.72
		4	4.5	172.50	178.15	161.18	166.84	186.63	212.09	229.05
40.0M - 50.0M	1	1.5	164.96	174.38	168.73	158.36	169.67	212.09	259.22	
	2	2	131.96	133.22	121.91	114.37	138.25	159.61	169.67	
	3	3	128.19	133.85	133.85	128.19	126.31	184.75	203.60	
	4	4.5	175.32	189.46	169.67	166.84	172.50	231.88	195.12	
50.0M - 60.0M	1	1.5	180.04	197.95	161.18	160.24	169.67	236.59	180.04	
	2	2	148.30	136.99	131.96	140.76	133.22	173.44	186.01	
	3	3	141.39	137.62	139.50	124.42	135.73	179.09	179.09	
	4	4.5	175.32	180.98	155.53	161.18	161.18	175.32	203.60	
60.0M - 70.0M	1	1.5	164.96	164.96	164.96	162.13	150.82	193.23	212.09	
	2	2	114.37	114.37	108.08	120.65	113.11	139.50	189.78	
	3	3	137.62	137.62	130.08	131.96	128.19	156.47	156.47	
	4	4.5	178.15	178.15	161.18	172.50	149.87	178.15	234.71	

Based on the measurement and characteristics of the soil, the apparent resistivity measurement was carried out at a distance of 0.5m and 1.5m to 4.5m between the Megger DET2/2 Testing equipment probes. This corresponded to the apparent resistivity values read off by the equipment at such depth.

Table 1 shows the measured apparent resistivity data. The measured values of the apparent ground resistivity from the selected site were used as data input to calculate for standard metrics for the design, using (11) – (14) according to IEEE STD80-2000 manuals for substation grounding design.

$$R_g = \frac{R_1 R_2 - R_m^2}{R_1 + R_2 - 2R_m} \quad (11)$$

The ground grid current I_G and ground potential rise GPR is obtained from (11) and (14).

$$S_f = \frac{I_g}{3.I_0} \quad (12)$$

$$I_G = I_f S_f D_f C_p \quad (13)$$

$$\text{GPR} = I_G \times R_{grid} \quad (14)$$

3.1 Estimation of maximum allowable (rate) touch voltage, step voltage, and ground potential rise suggested by the ANSI/IEEE STD80-2000

In order to find the ground grid resistance, maximum grid current and ground potential rise to make an estimation, (11) - (14) were used. They were determined so that the step and touch voltages could be computed from equations (9) - (10). The mesh voltage is dependent on the length of the copper conductor, grid arrangement in horizontal-vertical axis and the number of grounding rods on the site. The mesh voltage is determined as follows;

$$E_m = \frac{\rho_a \cdot I_G \cdot k_m \cdot k_i}{L_C + L_M} \quad (15)$$

The estimated step voltage for maximum allowable rate was determined as follows;

$$E_s = \frac{\rho_a \cdot I_G \cdot k_s \cdot k_i}{0.75L_C + 0.85L_R} \quad (16)$$

The equations presented in (15) to (17) were used to determine the tolerable touch and step voltages.

$$E_{step-70} = (1000 + 1.5C_s \rho_s) \frac{0.157}{\sqrt{t_s}} \quad (17)$$

$$E_{step-70} = (1000 + 6C_s \rho_s) \frac{0.157}{\sqrt{t_s}} \quad (18)$$

$$C_s = 1 - \frac{0.09 \left(1 - \frac{\rho}{\rho_s}\right)}{2h_s + 0.09} \quad (19)$$

Based on Equations (17) to (19), preliminary estimation of the conductor loop, number of rods and locations was performed. The initial estimates of conductor spacing based on the current I_G was also specified. The preliminary resistance of the grounding system in uniform soil was determined as follows;

$$R_1 = \frac{\rho}{\pi L_C} \left[\ln \left(\frac{2L_C}{a} \right) + \frac{k_1 L_C}{\sqrt{A}} - k_2 \right] \quad (20)$$

Where R_1 is the preliminary ground resistance in uniform soil model and is dependent on the average apparent soil resistivity from the site.

Performance evaluation

Certain metrics are used to evaluate the performance of the proposed design. These metrics include GPR, step voltage and touch voltage. The optimal results obtained by applying HSA and GA were compared to those obtained using IEEE STD80 2000 measurement.

RESULT AND DISCUSSION

The result in Figure 3 is a graphical representation of Grid Layout including the grounding rod points for IEEE80-2000 standard guide. The result was generated from the set of codes including equations (11)-(19) ran on MATLAB R2015b using GA and HSA with a view to meeting the touch potential criterion for safety.

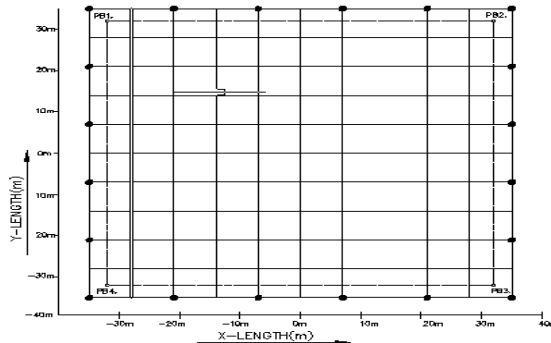


Figure 1: Grid Layout – IEEE STD80-2000

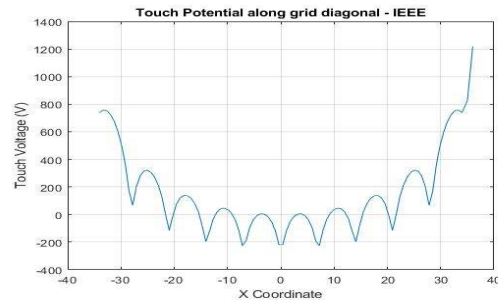


Figure 2: IEEE Touch potential

In the grid spacing, the touch voltage profile is more even for the IEEE generating 10 x 10 meshes with 20 grounding rods at the outer grids line as depicted in Figure 1, while Figure 2 depicts the touch voltage profile on the earth's surface computed along the main diagonal. Table 2 shows the Touch (E_{touch}) and Maximum touch voltages as 840.548V and 758.208V

respectively while the maximum step voltage is 392.9076V. Figure 3 shows the generated grid/grounding rods layouts as obtained from the output of the Genetic Algorithm. The grid layout is an uneven grid with meshes of 3 x 4 along vertical and horizontal axis with 2 grounding rods each at the upper and lower outer grids.

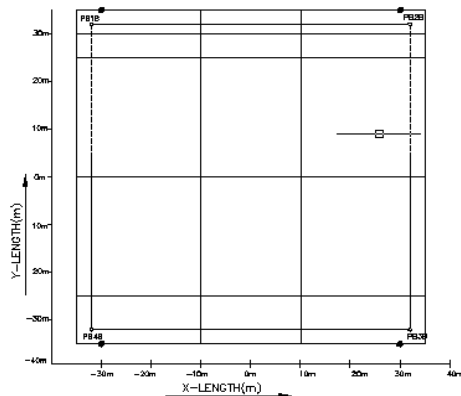


Figure 3: G. A. Grid Layout

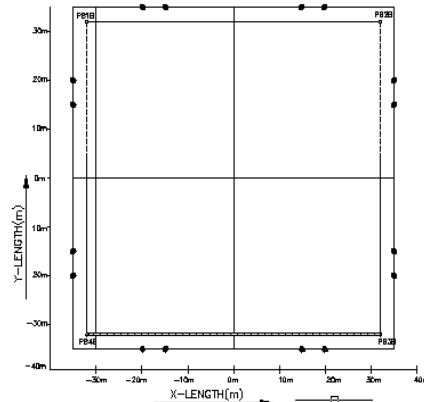


Figure 4: HSA Grid Layout.

It also showed a tremendous reduction in the length of the grid and number of grounding rods compared to IEEE std 80-2000. The dot point on the grid layout indicates the grounding rods positions. HSA also returned 2 x 2 meshes of an even and equally spaced grids with 4 grounding rods on the outermost grids as shown in Figure 4. A 3-dimensional view of the grid arrangement and their associated

grounding rods is as shown in Figure 5 and Figure 6 for GA and HSA. It can be seen that the total length of grounding grids is longer for the GA with fewer grounding rods (i.e. 4) while the grid length is shorter for HSA with an increase in the grounding rods (i.e. 16). Figure 7 and 8 depicts the Touch potential waveform along the diagonal of the grids as generated by GA and HSA.

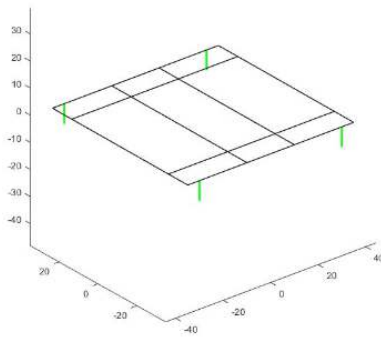


Figure 5: 3-Dimensional Grid/Grounding rod Layout for GA

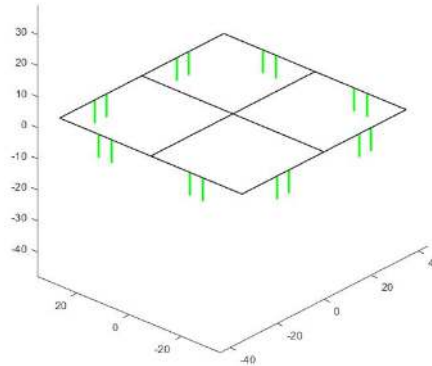


Figure 6: 3-Dimensional Grid/Grounding rod Layout for HSA

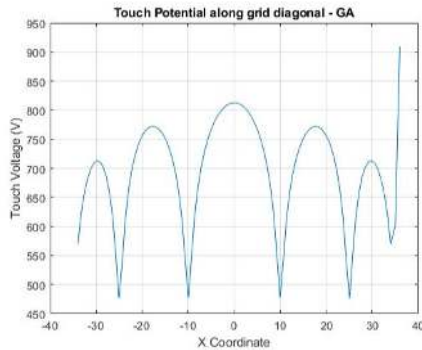


Figure 7: Touch Potentials waveform for Genetic Algorithm

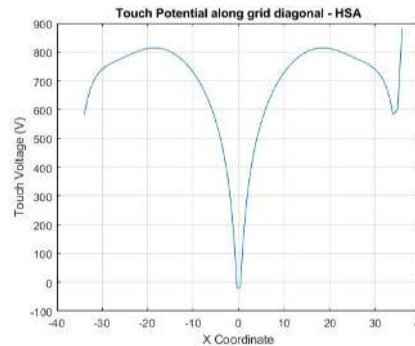


Figure 8: Touch Potential waveform for Harmony Search Algorithm

Table 2 gives the performance evaluation of the two algorithms compared with IEEE80-2000 for the selected site. The maximum E_{touch} voltages waveform along the

grid diagonals are 812.77V for GA and 814.70V for HSA respectively. HSA outperforms GA in this case by 0.236%.

Table 2: Summary of performance of GA and HSA compared with IEEE80-2000

Performance Metrics	IEEE	GA	HSA	IEEE TO GA% REDUCTION	IEEE TO HSA% REDUCTION	HSA TO GA% REDUCTION
Estep70 (V)	2696.1	2597.676	2597.68	3.65	3.65	0.000
Etouch70 (V)	840.548	815.94	815.94	2.93	2.93	0.000
GPR (V)	4871.8	3072.50	2970.30	36.93	39.03	3.441
Rg (Ω)	2.5534	1.61	1.56	36.93	39.03	3.441
Max Touch Voltage(V)	758.2076	812.77	814.70	7.20	7.45	0.236
Step Voltage (V)	392.9076	308.48	283.77	21.49	27.78	8.708

The maximum touch for IEEE was 758.21V against GA value of 812.77V and HSA value of 814.70V representing 0.236 %

improvement in maximum Touch voltage over GA. The step voltage for IEEE was 392.91V. GA gave a value of 308.48V while HSA returned a



reduced value of 283.77V representing 8.71% reduction when compared with the value from GA. Also, both the GPR and the Grid resistance computed using HSA are lower than the values computed using IEEE STD 80-2000. Both GA and HSA returned values that give better performance when compared with IEEE STD 80-2000 base case values. Table 3 gives the performance evaluation of HSA over GA in terms of Step voltages, Ground potential rise, the grid resistance and maximum touch potential. The performances shown by both GA and HSA arose from the reduction in the overall

grid resistances obtained due to the configurations returned by the two optimisation techniques. Since the dangerous fault current flows out to the earth through the least resistive path created by grid conductors/grounding rods positions, the GPR, step and touch voltages are also reduced through a lower grid resistance. Of significant importance is the reduction in the length of the grid conductors from the HSA that brought about 8.708% reduction in the step voltage and the GPR reduced by 3.441% from the GA values.

Table 3: GA and HSA Performance metrics evaluation for the selected site

Performance Metrics	GA	HSA	HSA TO GA %
			Improvement
Estep70 (V)	2597.676	2597.68	0.000
Etouch70 (V)	815.94	815.94	0.000
GPR (V)	3072.50	2970.30	3.441
Rg (Ω)	1.61	1.56	3.441
Max Touch Voltage (V)	812.77	814.70	0.236
Step Voltage (V)	308.48	283.77	8.708

CONCLUSION

An optimal design of substation grounding grids with two soil layer method has been evaluated in this paper. The touch and step voltages, ground potential rise and ground resistance of a site located in Kubwa expressway, Abuja have been determined by applying three different methods which are the IEEE STD80-2000, GA and HSA with a view to minimizing the GPR, step and touch voltages. The performance of HSA was compared with those of GA and IEEE STD80-2000 standard. The algorithms were implemented in MATLAB R2015b. From the analysis and evaluation, it was observed that the selected site was suitable for the construction/siting of the proposed substation and that a cost-effective installation is achievable for this location.

REFERENCE

- Ackerman, A., Sen, P. K., and Oertli, C. (2013). *Designing Safe and Reliable Grounding in AC Substations With Poor Soil Resistivity: An.* 49(4), 1883–1889.
- Alik, B., Kemari, Y., Bendekliche, N., Tegar, M., & Mekhaldi, A. (2015). *Optimization of Grounding System of*

60 / 30 kV Substation of Ain El-Melh using GAO. December. <https://doi.org/10.1109/INTEE.2015.7416675>

- Bhatia, K., Darji, P. B., & Jariwala, H. R. (2020). Evaluation of sustainability of microgrid grounding grid design under varying soil conditions through estimation of touch, step voltages and novel methods of earthing. *IET Science, Measurement and Technology*, 14(5), 621–632. <https://doi.org/10.1049/iet-smt.2019.0168>
- Bonda, P. R., & Mishra, M. K. (2018). Optimized Design of Earthing System for Substations with High Soil Resistivity and Limited Plot Area. *2018 20th National Power Systems Conference, NPSC 2018*, 1–6. <https://doi.org/10.1109/NPSC.2018.8771780>
- El-Fergany, A. (2013). Accelerated Particle Swarm Optimization-based approach to the optimal design of substation grounding grid. *Przeglad Elektrotechniczny*, 89(7), 30–34.
- Id, N. P., Osman, M., Ariffin, A. M., Boopalan,



- N., Zainal, M., & Ab, A. (2021). *PLOS ONE Optimization of substation grounding grid design for horizontal and vertical multilayer and uniform soil condition using Simulated Annealing method*. 1–16.
<https://doi.org/10.1371/journal.pone.0256298>
- Jambak, M. I., Ahmad, H., & Jumaat, S. A. (2017). *Evaluation of Grounding System for AC Substation Using Sub-Ground (SG) Software for Novice Professionals : Interpretation Based on*. 321–327.
- Kapijan, P. (2017). *Grounding System Design of Substation Using Matlab Program*. 3(March), 8–10.
- Kara, S., Kalenderli, O., & Altay, O. (2016). *Optimum grounding grid design by using genetic algorithms*. *ELECO 2015 - 9th International Conference on Electrical and Electronics Engineering*, 1117–1121.
<https://doi.org/10.1109/ELECO.2015.7394602>
- Lei, J., Peng, M., Shen, M., & Yang, T. (2012). *Optimal design of grounding grid based on cloud genetic algorithm*. *Dianli Zidonghua Shebei/Electric Power Automation Equipment*, 32(7), 119–123.
- Nasir, M., Sadollah, A., Yoon, J. H., & Geem, Z. W. (2020). *Comparative study of harmony search algorithm and its applications in China, Japan and Korea*. *Applied Sciences* (Switzerland), 10(11).
<https://doi.org/10.3390/app10113970>
- Peng, J., & Kuo, Y. (2018). *Grounding System Cost Analysis Using Optimization Algorithms*. 1–19.
<https://doi.org/10.3390/en11123484>
- Smestad, G. P., Germer, T. A., Alrashidi, H., Fernández, E. F., Dey, S., Brahma, H., Sarmah, N., Ghosh, A., Sellami, N., Hassan, I. A. I., Desouky, M., Kasry, A., Pesala, B., Sundaram, S., Almonacid, F., Reddy, K. S., Mallick, T. K., & Micheli, L. (2020). *Modelling photovoltaic soiling losses through optical characterization*. *Scientific Reports*, 10(1), 1–14.
<https://doi.org/10.1038/s41598-019-56868-z>
- Uma, U., Uzoechi, L., & Robert, B. (2016). *Optimization Design of Ground Grid Mesh of 132/33Kv Substation Using Etap*. *Nigerian Journal of Technology*, 35(4), 926.
<https://doi.org/10.4314/njt.v35i4.30>
- Wu, X., Power, A. E., & Zhang, Q. (2016). *Substation Grounding System Optimization with Utilizing a Novel MATLAB Application*. January 2018.
<https://doi.org/10.1109/APPEEC.2016.7779580>
- Zhang, Q. (2014). *Software Development of Optimal Substation Ground Grid Design Based on Genetic Algorithm and Pattern Search*. 0–5.