ISSN 2229-5518

Techniques Used for Unequally Spaced Grounding Grid Design

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Abstract— Grounding system (GS) represents one of the most essential items of the power plants and substation systems design. The main objective of power system substation grounding grids is to maintain reliable operation and protect personnel and equipment during fault conditions. For all substations planning, economical and effective GS plays an essential role since the absence of effective grounding grid can result in mal-operation of protective devices and hazardous for operators and substation equipment. Therefore, in this paper, the evolutional technique for unequally spaced grounding grid design is suggested. The design is based on hybridization of optimum compression ratio (OCR) and particle swarm optimization (PSO) techniques. This approach is purposed to control the grounding copper volume of the GS with the aid of controlling of unequally spaced grounding conductor lengths with reference to the safety measures. The proposed technique offers almost 20% of copper savings comparing with the optimum compression ratio method.

Index Terms— Ground Grid (GG); Optimum Compression Ratio (OCR); Particle Swarm Optimization (PSO); Ground Potential Rise (GPR); Step Voltage; Touch Voltage; Ground Resistance.

1 Introduction

The short-time large ground fault currents will make the power systems unstable and meantime be danger to persons and network equipment. Hence, the GG design should consider the limitations of the step voltage, touch voltage, ground potential rise (GPR), and GG resistance for safety. In modern substations, the GS is a necessary part for all electrical systems; its design has very much importance [1, 2].

According to IEEE 80 standard [2], the GG resistance must be low enough to guarantee that faults currents dissipate through the GG into the earth, while the GPR on the earth's surface must be remained under specific tolerances [2]. As it is known the person's safety which is one of the key goals of the GS is usually affecting by the GPR, step and touch voltages of GG structure during grounding faults of all electrical networks [3-9]. In order to limit the GPR to safe values, it is necessary to design a right GG that efficaciously connects with the metallic structure of the substation to ensure the safety criteria [10-12]. Some of the investigators and designers suggested unequally spaced grids as a method to save about 34% of GG material [13-15].

Some parameters of GG such as grounding resistance, step and touch voltages can be determined using simplified assumptions and some of these parameters are difficult to be determined by simplified method but they are determined by using experimental techniques [16-17]. Some investigators have proposed formulas to calculate the GPR, touch voltage, step voltage and grounding resistance. Others used the charge simulation method to carry out the same calculations [18-19]. Experimental models are used to obtain the same parameters by other investigators [20 -22].

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The optimal GS design for the substation is to suitably arrange the conductors of GS to equalize the leakage current distribution and the potential gradient of ground surface; while keeping the step and maximum touch voltages within the safe limits; this would assure making all grounding conductors sufficiently utilized so certified as a safe and economic design method. IEEE 80-2000 standard is used in the design of safe GG. Based on this standard software, programs are designed and used in choosing the economical design and installation of substations grounding system through a lot of alternatives [23-25]. Optimum GS design in uniform and non-uniform soils using ANN is presented by O. E. Gouda [26]. Optimized GS design of substation using newly developed IEEE compliant software is reported by Kaustubh A. Vyas. [27]. Optimal design of the GG by FEM considering different layered soil models is reported by Anton [28].

Recently, new techniques are used in the most economical GS design [29-36]. Designing of the GG system having safety and GG resistance requirements with the lowest cost is a nonlinear problem with relative minimum points. Some techniques have been suggested to achieve this goal. One of these techniques is the optimum compression ratio (OCR). Many studies of GG design have been planned on the trial-and-error approaches. These approaches make the mesh dimension of the GG satisfy with Limitations of the touch voltage, step voltage, GPR and GG resistance from standards. In this paper design of unequally spaced GG by hybridization of OCR and Particle Swarm Optimization (PSO) Techniques, is suggested. As it is known PSO is a powerful scheme for the solution of similar problems. The proposed technique proved that it is suitable for determining the best substation GS design. It offers almost 20% of copper savings comparing with the unequally spaced traditional methods.

2 METHODS USED IN THE DESIGN

2.1 Optimum Compression Ratio (OCR)

The conductor compression ratio (CR) is related to the grid dimensions and the maximum conductor separation dmax which occurs toward the grid center and is given by:

$$d_{max} = \frac{L(1-CR)}{1+CR-2CR^{(N/2+1)}} \qquad N \text{ is even} \qquad (1)$$

$$d_{max} = \frac{L(1-CR)}{2(1-CR^{(N-1)/2})} \qquad N \text{ is odd} \qquad (2)$$

Where N is the desired conductors' number perpendicular to axis of a given grid of length L. When the grounding conductors are arranged according to an exponent regularity, the conductors span decreases gradually from the center to the side of the GG. The i^{th} conductor span from the center is

$$d_i = d_{max} . CR^i \qquad (3)$$

For the optimal GG design, the OCR can be used, in which the touch voltage reaches its minimum value if the GG is designed under this CR [37]. Grid conductors of the unequally spaced grid having denser conductors at the edges proved the most safe and efficient design [38-40]. However, one merit of the use of unequally spaced grid produces more uniform current density in the grid conductors and therefore remarkable decrease in the voltage gradients of the earth's surface is reported [41- 44]. Then, the touch voltage for such grid reaches its lowest values and thus the conditions of safety for human above the earth surface of the substation will be ensured. It is concluded by [42] that the use of unequally spaced grid using OCR technique saves about 34% of GG material. Sequentially the installation cost of the GG will be reduced. An empirical expression is obtained to calculate OCR as follows [23].

$$OCR = a_0 + a_1 . e^{(0.0001h)} + a_2 . e^{(bh)} \qquad (4)$$

Where

$$b = -0.3503 - 9.6311e^{(-0.3666L)} \qquad (5)$$
$$a_0 = a_{01} + a_{02}k + a_{03}k^2 \qquad (6)$$
$$a_1 = a_{11} + a_{12}k + a_{13}k^2 \qquad (7)$$
$$a_2 = a_{21} + a_{22}k \qquad (8)$$

Where k is the conductor segments number in any direction; h is the laying depth of the grid. The relationship between a0, a1... and L is given in Table 1 [23].

TABLE 1
RELATIONSHIPS BETWEEN a_0,a_1, a_2 AND L

Coefficients	L≤100 m	100 m≤L≤175 m	175 m≤L≤250 m	L>250 m
a_{01}	0.44	0.38	-0.51	0.32
a_{02}	-77.43	-50.65	-33.18	-15.44
a_{03}	15.63	13.88	18.49	13.42
a_{11}	0.033	0.19	1.15	0.38
a_{12}	76.9	50.21	32.82	15.16
a_{13}	-15.56	-13.83	-18.44	-13.38
a_{21}	-0.067	-0.037	-0.029	-0.022
a_{22}	0.5	0.41	0.34	0.26

2.2 Particle Swarm Optimization (PSO) Algorithm

The PSO is defined as a multi-agent search technique that ensures a swarm of particles and each particle performs a prospect solution in the swarm. All the particles fly meanwhile multi-dimensional the search space. Each particle is regulating its position with respect to its own practice and the experience of neighbors [45]. Therefore, in a PSO technique, all particles are beginning randomly and estimated to compute fitness together with finding the personal best and global best. After that, a loop starts to find an optimum solution. In the loop, first the particles' velocity is updated by the personal and global bests, and then each particle's position is updated by the current velocity. The loop is ended with a stopping criterion predetermined in advance. Basically, two PSO algorithms, namely the Global Best (Gbest) and Local Best (Lbest) PSO, have been developed which differ in the size of their neighborhoods [45].

2.3 Voltage Profile Computation by Using Image Method

By using the Infinite Series Potential Method (I.S.M) [8, 9], the potential difference in volts can be determined in three dimensions (x, y, z) using the following equation.

$$v(x,y,z) = \frac{I\rho[ln f(x,y,z)]}{4\pi l} \qquad (9)$$

Where

$$f(x,y,z) = \frac{\sqrt{(x+0.5l)^2+y^2+z^2}+x+0.5l}{\sqrt{(x-0.5l)^2+y^2+z^2}+x-0.5l} \qquad (10)$$

Where I is the short circuit current in ampere, l is grid side length in meter and ρ is the soil resistivity in Ω.m [20, 21]. If there is a GG of total conductor length (L_C) buried in uniform soil, the total potential differences (V_{Total}) caused by this grid; means interference between any point and all conductors of the GG and its images, it will be the sum of the potential caused at this point by this grid conductors and all its images [44].

$$V_{Total} = \frac{I\rho \sum_{x,y}[\ln f(x,y,z) + \ln f(x,y,z+2h)]}{4\pi L_C} \qquad (11)$$

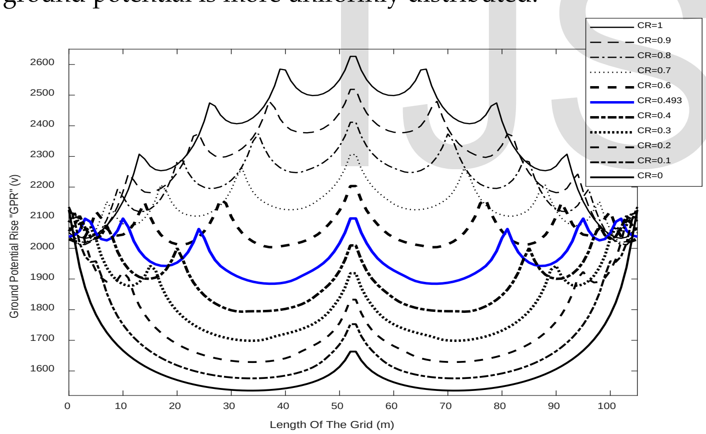
3 DESIGN OF UNEQUALLY SPACED GG USING OCR

The safe design of the unequally spaced GG system should limit the GPR, step and touch voltages of grounded structures during electric power faults to safe values, besides reaching to the predetermined value of the GG resistance. In this paper, the GPR, step voltage and touch voltage are calculated along the center conductor for unequally spaced grid area A=105×105 m² having 64 meshes. Figs.1(a) and (b) give the unequally spaced grid GPR and step potential of GG structure along the center conductor in case of unequally spaced grid having denser conductors at the edges under different values of compression ratios (CR) when the short circuit current is 10 kA and the soil resistivity is 100 Ω.m.

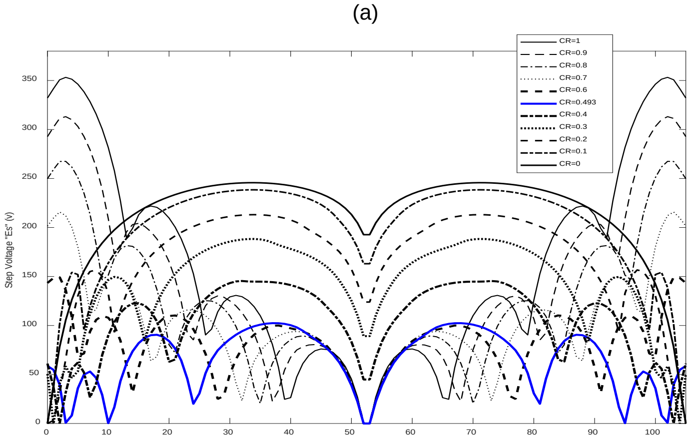
Summary of the relations between the GPR, step and touch voltages and GG resistance from one side and the compression ratios on the other side is given in Table 2. By the analysis of the achieved results given in Fig. 1 and Table 2, it is concluded that the GPR along the grid center conductor, the touch and step voltages along the center conductor and grid resistance reach their lowest value when the CR for this GG reaches 0.493 and the grid meshes number is 64. These results are in agreement with that obtained by O.E. Gouda [46].

To achieve the relation between the meshes number and optimum compressed ratios, calculations are done when the short circuit current is 10 kA and the soil resistivity is 100 Ω.m. Fig.2 gives the relation between the GPR along the center of the square GG for different values of compression ratios (CR).

Unfortunately, it is found that the OCR value is not constant for all the grounding grids. Each grid with different meshes number has its own value of OCR. Fig.2 illustrates the relationship between the GPR over the center conductor and the relation between OCR for the unequally spaced grid as a function of CR. Remarkable, these relationships usually have an obvious "U" shape. It is noticed also from Fig.2 that increasing in the grid meshes number increases it's OCR. As example OCR for 36 grid meshes is 0.31, it is 0.493 for N=64, 0.58 for N=100 and 0.65 for N=256. The voltage profile distribution samples in 3D for optimum compressed ratio value given in Fig. 3. It is observed that at CR=0.493 the ground potential is more uniformly distributed.



(a)



(b)

Fig. 1 The GRP and step potential versus the compression ratios (a) The GPR and (b) step potential along the center of the square grounding grids.

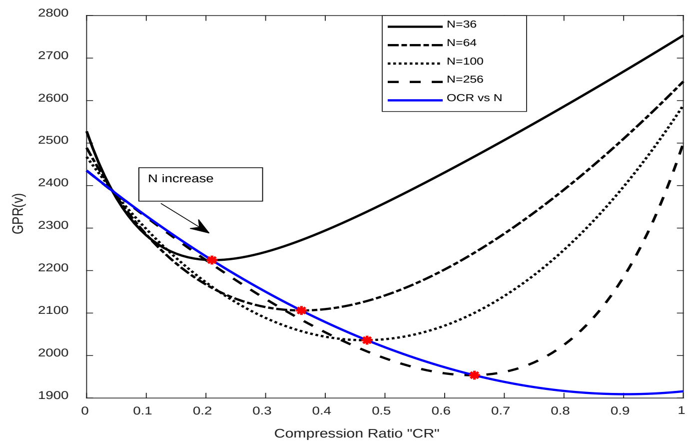


Fig. 2 The relation between the meshes number, GPR and the value of OCR

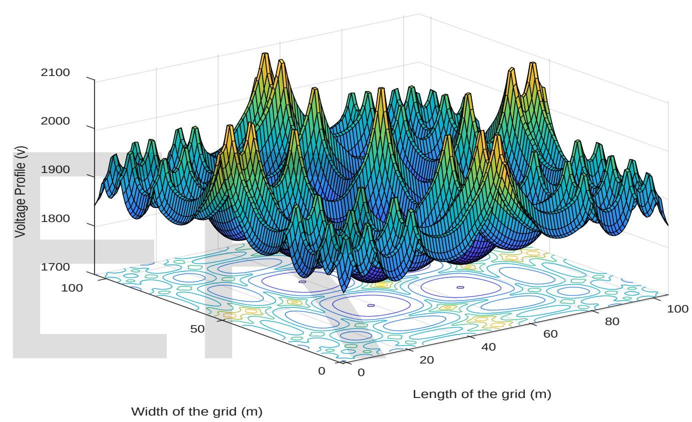


Fig. 3 The voltage profile along all conductors of the grid in case of the unequally spaced grid having denser conductors at the edges of (A=105×105 m2, N=64) in case of OCR=0.493.

TABLE 2
SUMMARY OF THE RELATION BETWEEN THE GPR, STEP AND TOUCH VOLTAGES AND GROUND RESISTANCE FROM ONE SIDE AND THE COMPRESSED RATIOS FROM THE OTHER SIDE, N= 64

Compression Ratio (CR)	GPR (Volt)	Emesh (Volt)	Estep (Volt)	Ground Resistance (Ω)
CR=0	2480.5	601.49	245.7	0.4134
CR=0.1	2295.3	559.26	238.45	0.3825
CR=0.2	2178.6	486.98	213.08	0.3631
CR=0.3	2116.6	417.96	188.28	0.3528
CR=0.4	2106	313.57	145.4	0.351
CR=0.493	2097.6	218.66	102.38	0.3496
CR=0.6	2203.2	266.56	149.34	0.3672
CR=0.7	2305.9	326.45	215.82	0.3843
CR=0.8	2411.5	401.7	267.5	0.4019
CR=0.9	2518.8	499.5	13.115	0.4198
CR=1	2626.4	593.7	353.2	0.4377

4 DESIGN OF THE GG USING PSO

In this part of the paper, the step voltage, touch voltage, GPR, and grounding resistance, based on ANSI/IEEE Std.80 and applying the PSO to achieve the optimal GG design, which includes meshes number, and is laying at a known depth. The GG design has to consider factors of safety and minimum used copper. The parameters of GG design and used copper volume are estimated based on ANSI/IEEE Std. 80 [2].

4.1 Total GG Conductors Volume

Attention has to be considered for the copper grid volume. To have the optimal GG design with minimum cost, the objective volume function has to be optimized while satisfying the safety considerations and predetermined value of GG resistance.
The copper volume of the conductors of the GG is evaluated as given in equation (13)

Objective Volume= $minimise\left\{(\pi \times \left(\frac{d}{2}\right)^2 \times (NL_c + Nw_c) \times Lc)+(\pi\times dr22\times Nr\times Lr)\right.$ (13)

Where
d the conductor diameter of GG (m)
NLc conductors number in the length direction
Nwc conductors number in the width direction
dr the ground rod diameter (m)

4.2 Safety Criteria Limitations and GG Resistance

The safety standard includes that the actual step and mesh potentials of the GG must be less than or even equal the corresponding acceptable potentials values which are borne by humans without being subjected to electric shocks.

$$E_{mesh-Actual} \leq E_{mesh-acceptable}$$
$$E_{step-Actual} \leq E_{step-acceptable} \quad (14)$$

The recommended limits of the GPR value is usually 5000V for the substations GG [2].

$$GPR_{-acceptaple} \leq GPR_{max} \quad (15)$$

The designed GG resistance has to be equal or less than the target GG resistance

$$R_g \leq R_{target} \quad (16)$$

For the most high-voltage and large substations, the GG resistance is usually less than 0.5 Ω. In smaller substations, the acceptable value usually depends on the local conditions [2]. The conductors' separation in x and y directions is proportional to the GG dimensions as follows [2]. In case of the unequally spaced grid, the space between the conductors depends on the designed compressed ratio.

$$D_{x,min} \leq D_x \leq D_{x,max}$$

$$D_{y,min} \leq D_y \leq D_{y,max} \quad (17)$$

The grid burial depth influences the GPR and the GG resistance. According to standards, the grid burial depth is recommended to be between 0.25-2.5 m.

$$h_{min} \leq h \leq h_{max} \quad (18)$$

Finally, a mathematical model is expressed in general constrained optimized problem.

$$minimise\{f(x,v) = Volume\}$$

$$S.t \begin{cases} g(x,v) = 0 \\ h(x,v) \leq 0 \end{cases} \quad (19)$$

$f(x,v)$ is defined as the objective function, $g(x,v)$ and $h(x,v)$ are defined as the set of inequality and equality limitations, respectively, x is known as state variables and v is the vector of variables. The control variables depend on the designer vision.

4.3 Applications of the PSO Algorithm in GG Design

The field data that are given in Table 3 is used for designing of GG by using PSO algorithm. The control variables considered in the design using PSO algorithm are the spacing between the grid adjacent conductors (continuous variable), the grid burial depth (continuous variable), rods number (integer number and continuous variable), and the grounding conductor cross-sectional area (discrete variable). The PSO algorithm and the GG optimization flowchart is given in [36].
The obtained designed parameters are given in Table 4 and it is compared with the GG parameters equally spaced between each conductor that is designed by using IEEE Std 80-2000. It is noticed that the GG design using PSO algorithm gives saving in copper volume and mass of the GG by about 24.9% and decreases the step potential by 12.3%, but unfortunately, an increase in GPR and mesh voltage by 5.5% and 4.9% respectively is noticed. It should be noted that nevertheless these values give a safe design for the GG and meets the design requirements.

TABLE 3
THE FIELD DATA OF THE GROUNDING SYSTEM

Grid parameter	Field data
A (Grid area, m^2)	105×105 m^2
ρ (Soil resistivity, Ω.m)	100 Ω.m
I_f (Fault current, A)	10000 Amp
D_f(Decrement factor)	1
S_f (Current division factor)	0.6
t_f (Duration of fault current)	1 sec
t_s (Duration of shock)	1 sec
ρ_s(Crushed Rock Resistivity)	2500 Ω.m
h_s (Thickness of Crushed Rock)	0.102 m
Diameter of the conductors	0.01 m
$E_{touch-tolerable}$	572.72 v
$E_{step-tolerable}$	1819.9 v

The voltage profile of the GG design using IEEE Std 80-2000 and using PSO in the 3-D and also the GPR in 2-D are given in Fig. 4.

TABLE 4
GROUNDING GRID PARAMETERS USING IEEE STD 80-2000 AND PSO WITHOUT USING RODS

Ground grid design without using rods	Using IEEE Std 80-2000	Using PSO
h (laying depth, m)	1	0.9
D (Spacing between each conductor and the other, m)	15	21
NLc (Conductors' number in each side)	8	6
Volume (m^3)	0.1319	0.0990
Mass (kg)	1179.18	885.06
GPR (v)	2553.9	2695.2
Estep (v)	303.35	266.01
Emesh (v)	538.92	565.51
Ground Resistance (Ω)	0.4257	0.4492

TABLE 5
GROUNDING GRID PARAMETERS USING IEEE STD 80-2000 AND PSO WITH USING RODS, EQUAL SPACE BETWEEN CONDUCTORS

Ground grid design with rods	Using IEEE Std 80-2000	Using PSO
h (laying depth, m)	1.5	1.1
D (Spacing between each conductor and the other, m)	26.25	35
NLc(Conductors' number in each side)	5	4
Nr (Number of rods)	17	16
Lr (Rod length, m)	3	3
Dr (Rod diameter, m)	0.03	0.03
Volume (m^3)	0.1185	0.0999
Mass (kg)	1059.39	893.106
GPR (v)	2566	2755.5
Estep (v)	215.53	185.03
Emesh(v)	476.87	559.11
Ground Resistance (Ω)	0.4277	0.4593

5 DESIGN OF THE GG USING HYBRIDIZATION BETWEEN CR AND PSO ALGORITHM

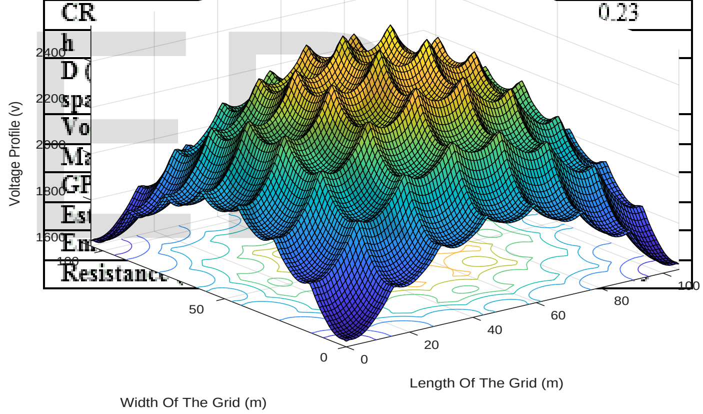
5.1 Uniform soil

Hybridization of the CR method and PSO algorithm is done to achieve the most economical and safe GG. It can be considered as an evolutionary technique for the unequally spaced GG design. In this technique, the compressed ratio CR is taken as one of the variables that are optimized by PSO. One advantage of the suggested method is to obtain unequally space, economical and safe grounding grid design.

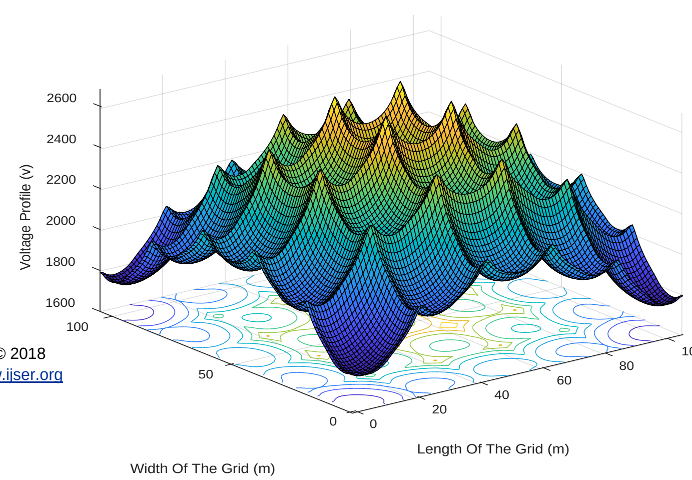
The considered control variables are the spacing between conductors, the required copper volume and the conductors' number in each side. It is found that the optimized value of CR is 0.23 in the case under study (A square grounding grids of 105×105 m² area, buried in 100 ohm.m uniform soil resistivity and the current emanating from this grid into the soil is 10 kA). Fig.4 (a) shows the voltage profile in 3-D of the GG designed by using IEEE Std 80-2000. Fig. 4 (b) gives the voltage profile by using PSO in 3-D. GPR of GG by using IEEE Std 80-2000 and PSO in 2-D is given in Fig. 4(c).Table VI gives the GG system design parameters by using OCR and PSO, the grid conductors are unequally spaced.

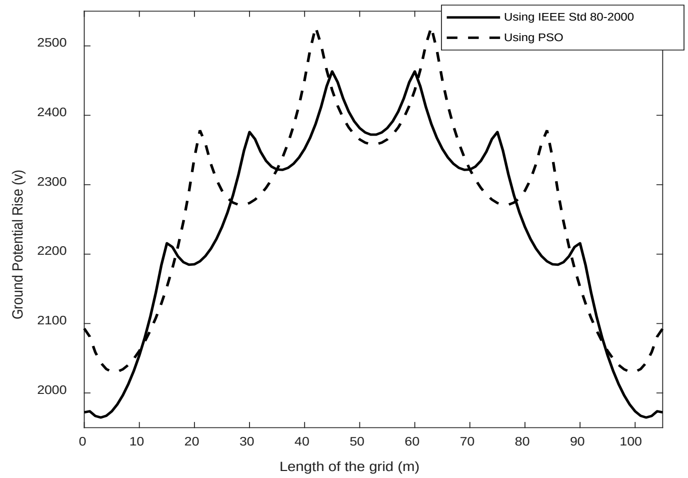
TABLE 6
DESIGN OF THE GG USING OCR AND PSO THE GRID CONDUCTORS ARE UNEQUALLY SPACED

Ground grid design	Using CR	Using	New technique
CR			0.23
h [illegible]	[illegible]	[illegible]	[illegible]
D (spa[illegible]	[illegible]	[illegible]	[illegible]
Vo[illegible]	[illegible]	[illegible]	[illegible]
Ma[illegible]	[illegible]	[illegible]	[illegible]
GP[illegible]	[illegible]	[illegible]	[illegible]
Est[illegible]	[illegible]	[illegible]	[illegible]
Em[illegible]	[illegible]	[illegible]	[illegible]
Resistance [illegible]	[illegible]	[illegible]	[illegible]



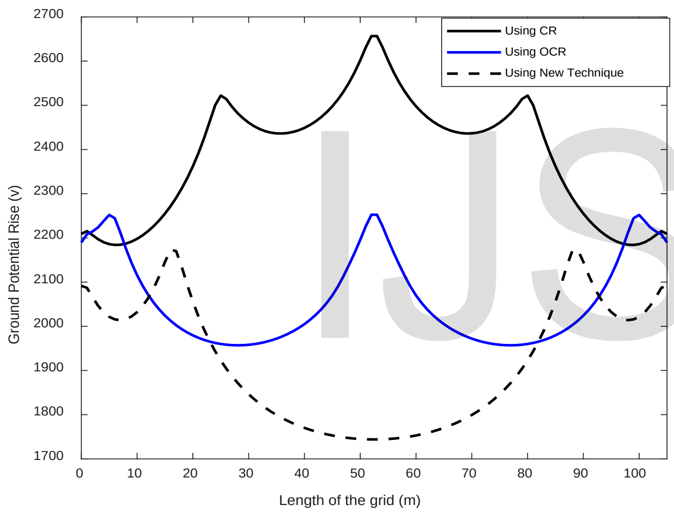
(a)
(b)





(c)

Fig. 4 Voltage profile of the GG system design, (a) using IEEE Std 80-2000 (b) using PSO in 3-D and (c) GPR of GG using IEEE Std 80-2000 and PSO in 2-D.



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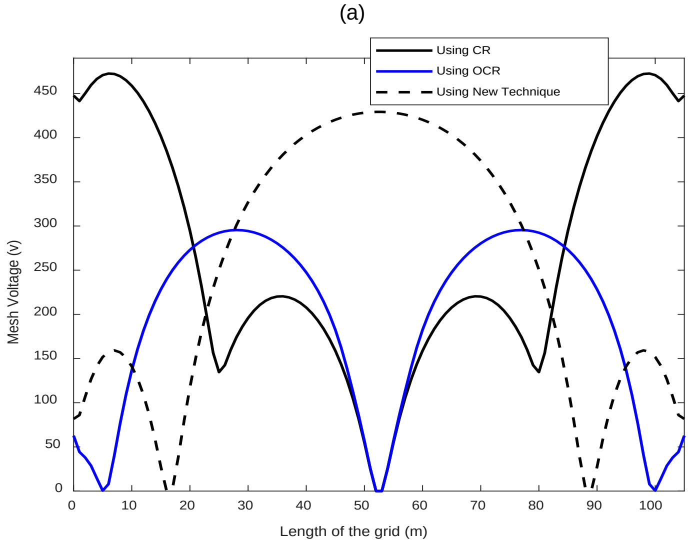

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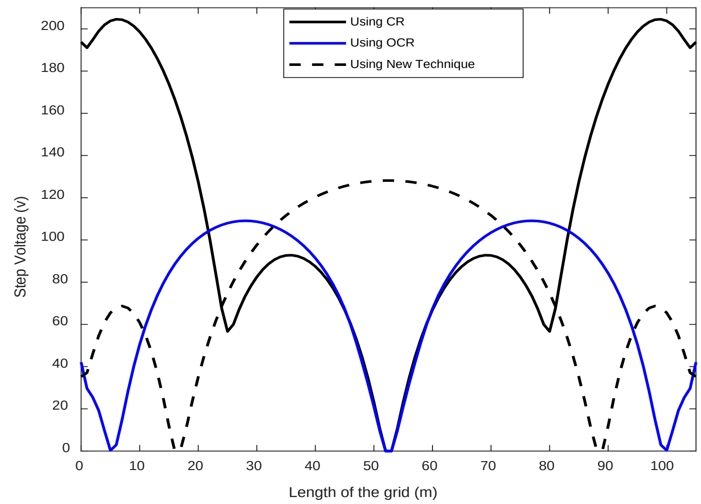


(c)

Fig. 5 Voltages of GG design, (a) GPR, (b) Mesh voltage and (c) Step voltage of the designed grids given in Table 6.

The comparison is done between grid designed by using the new technique, using the OCR method and also by using compressed ratio equals 0.9 as given in Table 6. Fig.5 (a) shows the GPR of the three grids, Fig.5 (b) shows the mesh voltage and Fig.5 (c) shows the step voltage of the designed grids. Using the new technique in the GG design indicates that 4 conductors only in each side of the grid gave economical and safe GG. From Table 6 it is noticed that 19.27% saving in copper GG volume is done by using the new technique and slight increase is observed in the GG resistance, GPR and mesh voltage comparing with using OCR and CR= 0.9 methods in the GG design, with acceptable safe design.

5.2 Non-uniform soil

The apparent soil resistivity of two-layer soil can be calculated using the following formulas that are developed by E. D. Sunde [47]:

$$\rho_{a0} = 2(\rho_2 - (\rho_2 - \rho_1).e^{-js}) - (\rho_2 - (\rho_2 - \rho_1).e^{-2js}) \quad (20)$$

Where

$\rho_{ao:}$ Apparent soil resistivity between first and second layer

$\rho_{1:}$ First layer soil resistivity

$\rho_{2:}$ Second layer soil resistivity

S: the spacing between probe electrodes of measuring soil resistivity.

d_1:First layer soil thickness

δ : Scaling factor

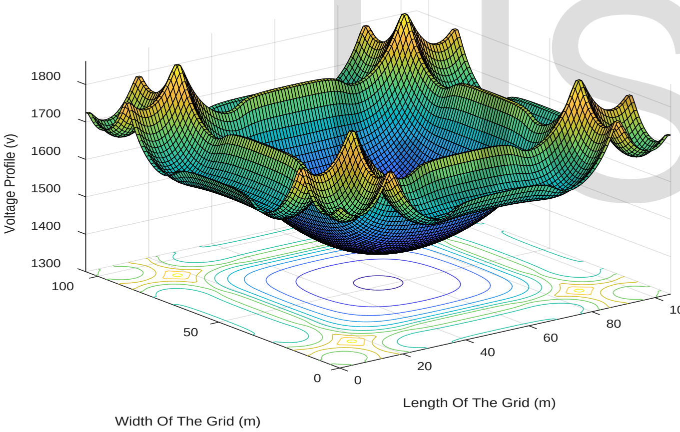
$$j = \delta / 2(d_1), \delta = \frac{ln\left(\frac{\rho_1}{\rho_2}\right) - ln\,(0.0176)}{3.5}$$

The apparent soil resistivity in the above example is taken 80 Ω.m. The designed GG parameters using the new technique is shown in Table 7. It is found that the optimized value of CR is 0.23 in the case under study, a square grounding grids of

105×105 m² area, buried in the first layer of the three layers and 80 Ω.m apparent soil resistivity of the three layers. The current emanating from this GG into the soil is 10 kA. Fig.6 (a) shows the voltage profile in 3-D of the GG designed by the suggested technique and Fig. 6 (b) shows the GPR.

TABLE 7
GROUNDING GRID PARAMETERS OF THREE LAYERS BY USING THE SUGGESTED TECHNIQUE

Ground grid design	Using the suggested technique
Soil resistivity	80 Ω.m
CR	0.23
H	1.5
D	[26.25 52.5 26.25] , 4
NLc	4
Volume (m^3)	0.0660
Mass (kg)	590
GPR (v)	1861.7
Estep (v)	102.51
Emesh(v)	343.32
Ground Resistance (Ω)	0.3103

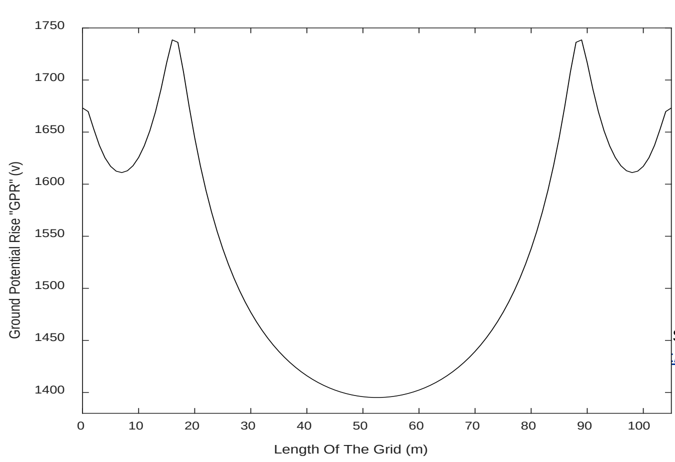


(a)
(b)

Fig.6 Voltages of GG design using the new technique of three layers example (apparent soil resistivity is 80 Ω.m) (a) Voltage profile (b) GPR.

6 Conclusion

In this paper, the design methods of GG using OCR method



and PSO technique are presented. It has been found that each grid has its own OCR depending on the grid meshes number. Hybridization of CR and PSO techniques is suggested. This approach is purposed to control the copper GG volume with the aid of controlling the grid conductors' length under the safety limitations. The proposed technique offers almost 20% of copper savings while respecting all design requirements and safety measures. Hence it is obvious that the suggested method is quite satisfactory for the GG design in uniform as well as multi-layered soils and meets IEEE safety criteria. Hence this technique proves to be an effective method and copper savings for preliminary design at least of the optimum grounding grid, rather than using the experience rules.

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