2018 Twentieth International Middle East Power Systems Conference (MEPCON), Cairo University, Egypt

Optimum Design of Substation Grounding Grid Based on Grid Balancing Parameters using Genetic Algorithm

Ahmed Taher
Departement of Electrical Engineering
Faculty of Engineering at Shoubra - Benha University
Cairo, Egypt
ahmed.taher@feng.bu.edu.eg

Abdelrahman Said
Departement of Electrical Engineering
Faculty of Engineering at Shoubra - Benha University
Cairo, Egypt
abdelrahman.ghoniem@feng.bu.edu.eg

Tamer Eliyan
Departement of Electrical Engineering
Faculty of Engineering at Shoubra - Benha University
Cairo, Egypt
tamer.alyan@feng.bu.edu.eg

Abdelsalam Hafez
Dean of HIET at Monoufia and Prof. at Departement of Electrical Engineering
Faculty of Engineering at Shoubra - Benha University
Cairo, Egypt
abdelsalam.hamza@feng.bu.edu.eg

***Abstract*—Substation is the most vital part of electrical power system that should be operated continually and safely. Ground grid is installed to help detecting ground faults and assure safety of persons. In this paper IEEE 80-2013 was utilized to make optimum design of substation ground grid. A new cost function was proposed which is based on the effective factors that affect grid performance. These factors include number of horizontal conductors, cross-sectional area of these conductors, grid burial depth, number of ground rods, length of each rod and surface material thickness. MATLAB software was used to design, study and analyze the whole parameters affecting the grid performance. The study of each of the mentioned parameters has been used to develop weight factors based on the effect of each parameter upon the grounding grid performance represented in grounding grid resistance, mesh voltage and step voltage. These weight factors were used in conjunction with the proposed cost function to aid the search for the optimum design of the grid. Genetic Algorithm (GA) utilized this function to minimize the cost of the grid and avoid over designing. This study was carried out on Future substation 220/22 kV located in Egypt. Results show that the use of cost function only is not sufficient to give a reasonable optimum design and the use of weight factors gives better and more realistic options for optimum design.**

Keywords*—*Grid design, Grid resistance, Mesh voltage, Step voltage, Genetic Algorithm, Weight Factors.

I. INTRODUCTION

The most important and vital part of any electrical power system is the substation, as it controls the level of voltage to be suitable for transmission process and distribution one. Also, it is the link between the generated energy and its usage. Substations generally have switching, protection and control equipment in addition to one or more transformer. In a large substation, circuit breakers are used to interrupt any short-circuits or overload currents that may occur on the network [1-2].

Substations might be subjected to abnormal conditions such as internal or external fault that could cause damage to property or hazardous electric shock to personnel and animals. Also, ground faults within a substation can cause a ground potential rise, currents flowing in the earth's surface during a fault can cause metal objects to have a significantly different potential than the earth under a person's feet which causes a hazard of electrocution [3].

Thus, the substation must be protected so as to be operated continually and safely to ensure reliability and continuity of service. This can be achieved by establishing a suitable grounding system which equip the substation with an alternative low impedance path to the earth to serve two main goals [4]. The first one to provide means to dissipate electric currents into the earth without exceeding any operating and equipment limits and the second one is to assure that a person in the vicinity of grounded facilities is not exposed to the danger of critical electric shock. Also, the alternative path provided by the grounding system helps in detecting and interrupting the ground faults.

All the parameters that govern the effectiveness of the grounding system -including number of horizontal conductors and vertical rods- have to be determined so as to meet the safety requirements of the grounding grid [5]. Not only the resistance of ground path to earth that can judge the effectiveness of ground grid but, there are also touch and step potentials that humans and animals are subjected to. These three parameters are with great importance in designing the ground grid [6].

The safety issue has to be resolved without constructing an over dimensioned, and more expensive than necessary, system [7]. Thus, an optimization technique is required to be adopted to minimize cost of construction of the grid within safety constrains [8].

In this paper new technique for optimum ground grid design is proposed. This technique was applied to the Egyptian future substation 220/22 kV. Also, the effective parameters were analyzed.

II. DESIGN CRITERIA

Ground grid can be designed and analyzed based on the procedures listed in IEEE80-2013. The grid resistance is

978-1-5386-6654-8/18/$31.00©2018 IEEE

calculated using Schwarz's equations [9]. Also, the touch and step voltages are calculated using Thaper equations [10].

According to the adopted method, the grid performance parameters (grid resistance, touch voltage and step voltage) must be lower than the safety limits so as to assure that fault currents dissipate mainly through the ground grid into the earth.

The aim of any ground grid design is to select type of the surface material ‘ρs’ and its thickness ‘hs’ then to determine, the number of horizontal conductors in both direction ‘Nx, Ny’, number of rods ‘Nr’, length of each rod ‘Lr’ and the diameter of both conductors and rods ‘dc, dr’.

From the technical data of the Future substation 220/22 kV, the area to be considered is 110 m x 110 m, the average soil resistivity is 40.8 Ω.m based on site measurement and the system fault current is 50 kA and its duration is 0.5 sec.

The accepted design was found based on soil parameters, grid parameters and substation parameters as listed in table I. The result show that the grid resistance, touch voltage and step voltage are within safety limit as listed in table II.

TABLE I. ALL DESIGN PARAMETERS AND THE ACCEPTED GROUND GRID DESIGN

Soil Parameters			
Surface material resistivity	ρ_s	10000	Ω.m
Thickness of surface material	h_s	0.15	m
Average soil resistivity	ρ	40.8	Ω.m
Grid burial depth	h	0.8	m
Grid parameters (Conductor and Rods)			
Length of grid	L_x	110	m
Width of grid	L_y	110	m
No. of conductors in X direction	N_x	12	
No. of conductors in Y direction	N_y	12	
No. of ground rods	N_r	16	
Length of each rod	L_r	3	m
Rod diameter	d_r	1.6	cm
Substation parameters			
Ground fault current	I_f	50	KA
Duration of shock current	t_s	0.5	Sec
Fault time	t_f	0.5	Sec
Clearing time	t_c	0.5	Sec
Current division factor	S_f	0.94	
Decrement factor	D_f	1	
X/R ratio	X/R	5	

TABLE II. ANALYSIS OF THE ACCEPTED GROUND GRID DESIGN

Tolerable touch voltage (70Kg)	2787	Volt
Tolerable step voltage (70Kg)	10482	Volt
Tolerable touch voltage (50Kg)	2059	Volt
Tolerable step voltage (50Kg)	7745	Volt
Mesh Voltage (Em)	1413	Volt
Step Voltage (Es)	887	Volt
Grounding Resistance (Rg)	0.1794	Ohm
Ground Potential Rise (GPR)	8565	Volt
Conductor X-sectional area	150	mm^2

III. EFFECT OF GRID DESIGN PARAMETERS

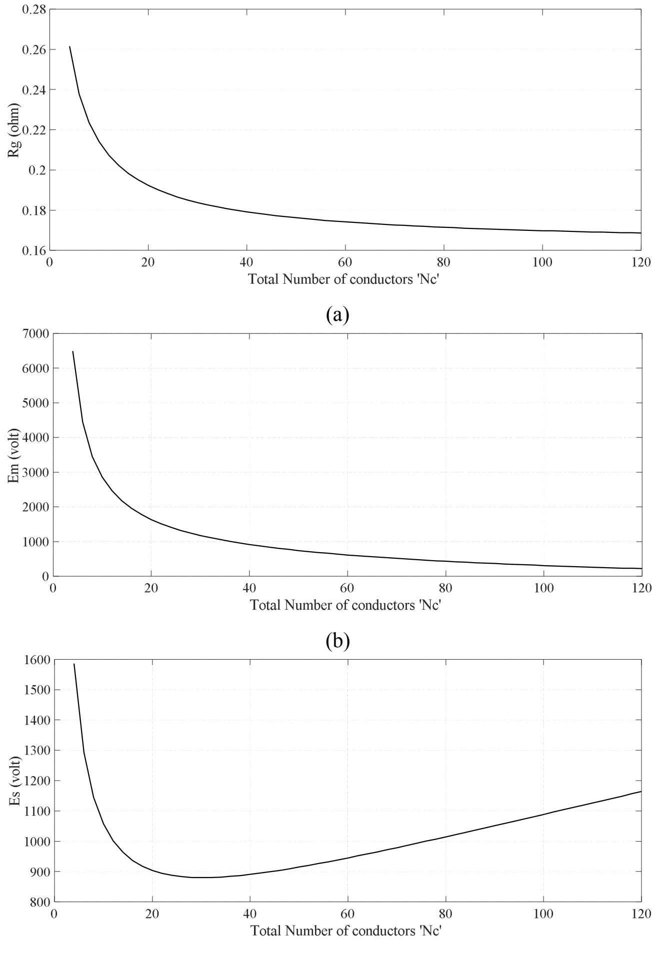
With The aid of the previously mentioned ground grid design based on IEEE80-2013, the effect of design parameters was studied. These parameters are number of conductors in x-direction (N_x), number of conductors in y-direction (N_y), diameter of grounding grid conductor (d_c), depth of the grounding grid (h), number of vertical rods (N_r), length of the vertical rod (L_r), diameter of vertical rods (d_r), surface layer thickness (h_s) and diameter of ground rod (d_r).

A. Effect of conductors' number "N_c"

The grid composes of horizontal conductors placed in two directions. The lower and upper limit of total number of conductors is set by the physical ability of installing these values.

The effect of total number of conductors placed in the grid is shown in fig. 1. This effect is represented as the percentage of the difference between initial and final values with respect to the initial one. But, for the effect of step voltage it is the percentage of the difference between initial and minimum values. Then the increase is the percentage difference between the minimum and final values w.r.t the minimum one. This is the same method adopted for all the following parameters.

The result show that, when "N_C" increase, the grid resistance will decrease by 35.51 % as shown in fig. 1.a. Also, the mesh voltage is decreased by 96.6 % as shown in fig. 1.b. But, the step voltage is decreased by 44.5% until ‘N_C’ reaches 30 conductors, then it will tend to increase by 32.2% as shown in fig. 1.c. This is due to the shielding effect among grounding conductors which is obvious when the conductors become closer [11].



(a)

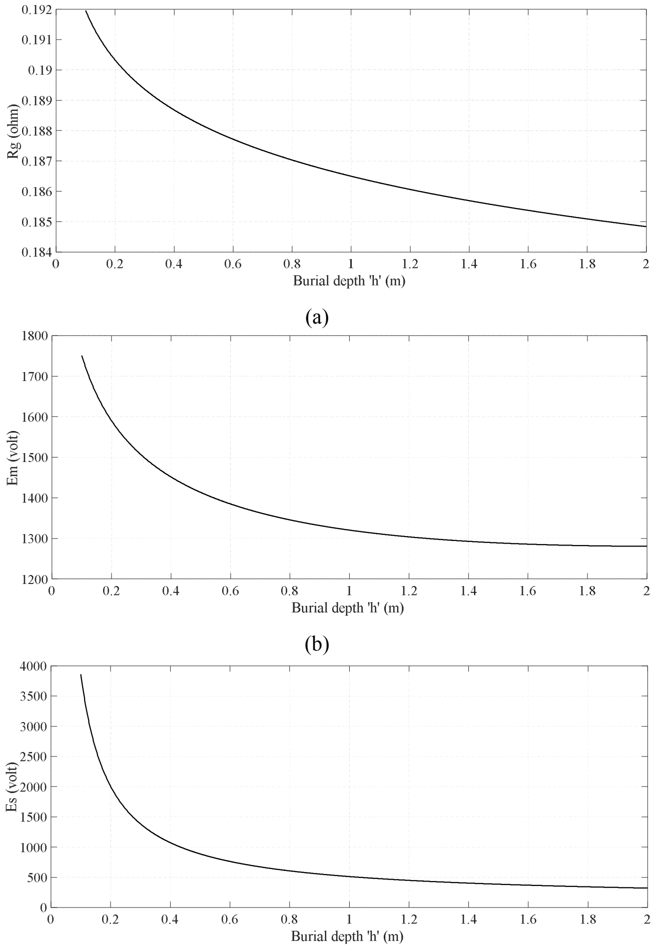
(b)

(c)

Fig. 1. Effect of total conductors' number on, a) grid resistance, b) mesh voltage, and c) step voltage.

B. *Effect of burial depth "h"*

The effect of the grid burial depth on R_g, E_m and E_s is shown in fig. 2. By increasing the depth of the grid, the grid resistance is decreased by 3.7% as shown in fig. 2.a. In fig. 2.b, the mesh voltage is decreased by 26.9% and the step voltage is decreased by 91.7% as shown in fig. 2.c.



(a)

(b)

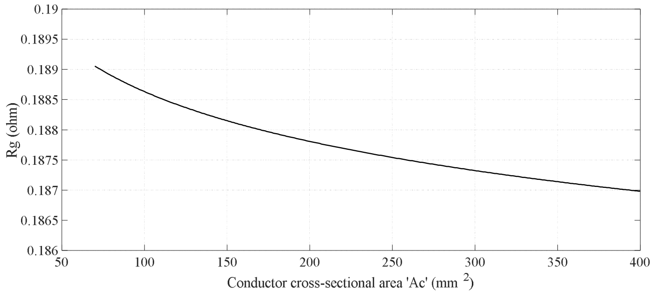
(c)

Fig. 2. Effect of grid burial depth on, a) grid resistance, b) mesh voltage, and c) step voltage

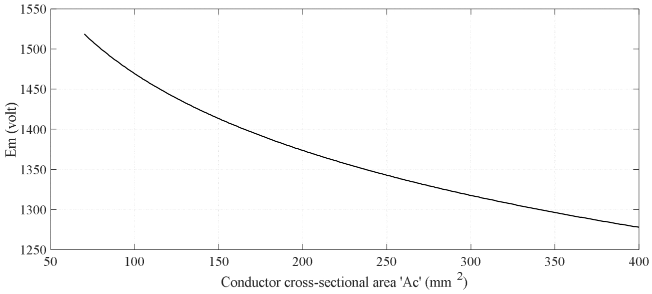
C. *Effect of conductor diameter "dc"*

The conductor diameter is represented by its cross-sectional area.

It is obvious that the effect of increasing the conductor cross-sectional area is to decrease the grid resistance by only a small value 1.1% as shown in fig. 3.a but, the mesh voltage is decreased by 15.9% as shown in fig. 3.b. And there is no effect on the step voltage.



(a)



(b)

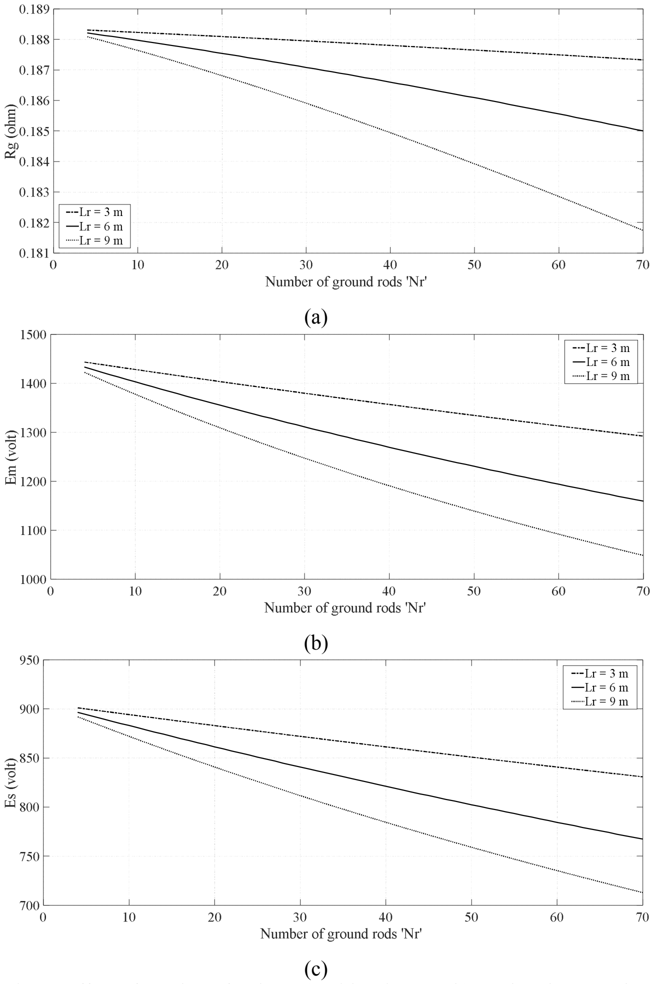
Fig. 3. Effect of conductor cross-sectional area on, a) grid resistance, and b) mesh voltage

D. *Effect of ground rods 'N_r' and length of each rod 'L_r'*

By increasing the number of ground rods all the three mentioned parameters will decrease as shown in fig. 4. The percentage decrease is listed in table III.

TABLE III. PERCENTAGE DECREASE OF GRID RESISTANCE, MESH VOLTAGE AND STEP VOLTAGE BY INCREASING THE NUMBER OF RODS AT DIFFERENT ROD LENGHTS

	% Rg	% Em	% Es
Lr = 3 m	0.52	10.49	7.8
Lr = 6 m	1.7	19.1	14.4
Lr = 9 m	3.37	26.29	20.07



(a)

(b)

(c)

Fig. 4. Effect of number of rod on, a) grid resistance, b) mesh voltage, and c) step voltage, at different rod lengths

Ground rods are used to increase the total buried length of conductors in the earth which will decrease the value of grid resistance also it causes lowering the value of mesh and step voltage [11]. The rods are an effective way for discharging the grid current especially when the lower layer of the soil is lower than upper on in two-layer soil model [13].

E. Effect of ground rod diameter "dr"

The rod diameter has a negligible effect on the grid resistance only as shown in fig. 5 with percentage decrease of 0.05% while it has no effect on the mesh and step voltages.

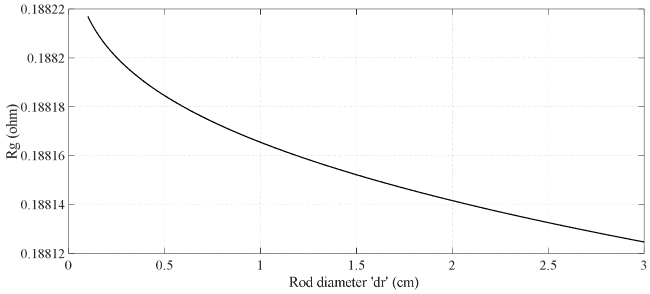
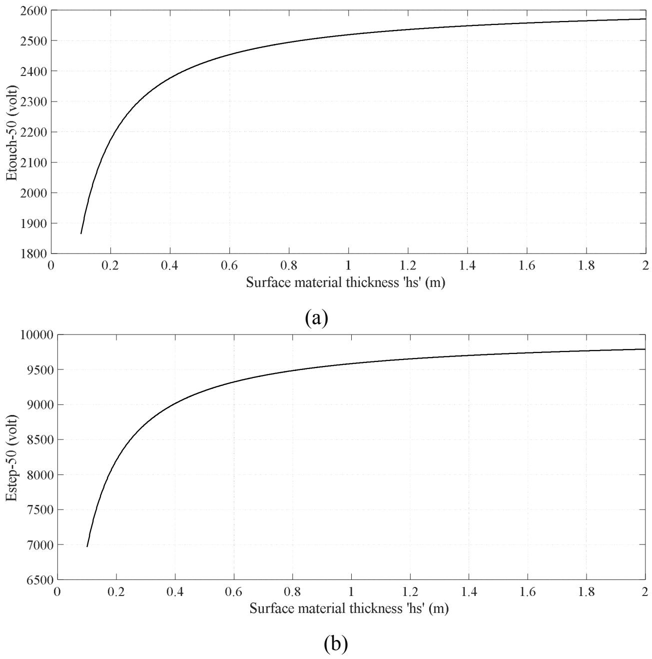


Fig. 5. Effect of rod diameter on grid resistance

F. Effect of surface material thickness "h_s"

The thickness of the surface material doesn't affect the grid resistance, mesh voltage or step voltage. However, it increases the tolerable touch and step voltages thus increasing the safety criteria as shown in fig. 6. The effect of increasing 'h_s' is to increase the tolerable touch voltage by 37.9% as shown in fig. 6.a and to increase the tolerable step voltage by 40.6 % as shown in fig. 6.b. But, a little variation in tolerable values is observed when the thickness is increased beyond 0.5 m.



(a)

(b)

Fig. 6. Effect of surface material thickness on, a) tolerable touch voltage, and b) tolerable step voltage

IV. OPTIMUM DESIGN OF GROUND GRID

Genetic Algorithm (GA) was introduced by John Holland in 1975 which is a search heuristic. This algorithm reflects the process of natural selection where the fittest individuals are selected for reproduction in order to produce offspring of the next generation [14]. Five steps are introduced in GA; initial population, fitness function, selection, crossover and mutation.

An individual is characterized by a set of parameters (variables) known as Genes. Genes are joined into a string to form a Chromosome (solution). The fitness function determines how fit an individual is, in this case the fitness function is the cost function.

The main objective of GA is to remove unsuitable individuals and replace them with more fit individuals [15]. Then, the optimum solution of the problem corresponds to the optimal individual [16-17].

Fitness function in this case is based mainly on the material cost of the grid, thus it will be known as cost function. Many mathematical cost functions have been developed to minimize the design cost as possible within the safety constrains. These functions are based on some or all of the effective controlled parameters.

The effective parameters adopted are number of conductors in x-direction (N_x), number of conductors in y-direction (N_y), diameter of grounding grid conductor (d_c), depth of the grounding grid (h), number of vertical rods (N_r), length of the vertical rod (L_r), diameter of vertical rods (d_r) and surface layer thickness (h_s). Different authors have used these parameters together to develop their objective function [18-20]. Beside these design control parameters, a lot of cost parameters are considered such as conductor and rod material cost, conductor and rod material cost, conductor and rod installation cost, trench excavation cost, surface material cost and bonding and welding cost.

Equation (1) give a very detailed cost function that has been developed by Alik, Tequar and Mekhaldi which includes cost of different materials related to conductors, rods, gravel, excavation and installation, using geometrical and construction parameters which are; number of conductors in both x and y directions, conductor diameter, grid burial depth, number of rods, size of rods, length of rod and the total area of excavation and revetment [21].

$$f(N_{mx}, N_{my}, d_c, h, N_r, L_r, d_r, h_s) = \left(C_{1\,cmat}\left(\frac{\pi d_c^2}{4}\right) + C_{1\,cinst} + C_{2\,exc}he_{trch}\right) * \left[(N_x+1)L_y + (N_y+1)L_x\right] + \left(C_{3\,rmat}\left(\frac{\pi d_r^2}{4}\right) + C_{3\,rinst}\right) * [N_r L_r] + (C_{4\,gmat} + C_{4\,ginst}) * [L_x L_y h_s] \quad (1)$$

where,
N_{mx}: number of unilateral mesh in x-direction
N_{my}: number of unilateral mesh in y-direction
C_{1cmat}: material cost of conductor
C_{1cinst}: installation cost of conductor
C_{2exc}: excavation cost
e_{trch} (=1m): width of excavation trench
C_{3rmat}: material cost of rod
C_{3rinst}: installation cost of rod
C_{4gmat}: material cost of gravel
C_{4ginst}: installation cost of gravel

In this paper new mathematical model is proposed based on a study on the effect of the design control parameters as in section III. More design details are added to the cost function such as number of exothermic welding and number of rod clamps in addition to their cost. Since the rod diameter has negligible effect it is excluded from the cost function also the installation cost isn't considered as it differs according to installation method and type of agreement.

$$f(N_x, N_y, d_c, h, N_r, L_r, h_s) = C_{1\,cmat} * \left(\frac{\pi d_c^2}{4}\right) * [N_x L_x + N_y L_y] + C_{2\,exo} * [N_x * N_y] + C_{3\,exc} * h * e_{trch} * [N_x L_x + N_y L_y] + C_{4\,rmat} * [N_r L_r] + C_{5\,rcon} * N_r + C_{6\,gmat} * [L_x * L_y * h_s] + K * [\Delta R_g + \Delta E_m + \Delta E_s] \tag{2}$$

where,
N_x: number of conductors in x-direction
N_y: number of conductors in y-direction
N_r: number of vertical ground rods
L_r: length of rod
d_c: conductor diameter
h: burial depth of grid
h_s: thickness of surface layer material
C_{1cmat}: material cost of conductor
C_{2exo}: material cost of exothermic welding
C_{3exc}: excavation cost
C_{4rmat}: material cost of rod
C_{5rcon}: material cos t rod connection
C_{6gmat}: material cost of gravel

$$R_g \le R_{gs} \tag{3}$$

$$E_m \le E_{touch} \tag{4}$$

$$E_s \le E_{step} \tag{5}$$

where,
R_g: ground grid resistance
E_m: actual mesh voltage
E_s: actual step voltage
R_{gs}: recommended acceptable value of grounding resistance
E_{step}: tolerable step voltage for body weights 50 or 70 Kg
E_{touch}: tolerable touch voltage for body weights 50 or 70 Kg

The acceptable value of grounding resistance differs according to the application of area which will be grounded; for large substations, transmission lines, or generating stations, a value of less than 1 ohm is required [3].

The tolerable touch and step voltages are not constants, but they vary from grid to another according to surface material resistivity "ρs" and its thickness "h_s", soil resistivity "ρ" and allowed duration of shock current "t_s" specified by Dalziel [22].

Instead of subjecting the cost function to safety constraint equations (3), (4) and (5), a penalty term is added. It is constituted by a multiplication of the difference between the real and the tolerable values of the mentioned constraints by a positive coefficient.

K is a positive weight coefficient (chosen equal to 10^6 [18]).

$$\Delta R_g = \begin{Bmatrix} R_g - R_{gs} & if\ R_g > R_{gs} \\ 0 & otherwise \end{Bmatrix} \tag{6}$$

$$\Delta E_{sm} = \begin{Bmatrix} E_m - E_{touch-50} & if\ E_m > E_{touch-50} \\ 0 & otherwise \end{Bmatrix} \tag{7}$$

$$\Delta E_s = \begin{Bmatrix} E_s - E_{step-50} & if\ E_s > E_{step-50} \\ 0 & otherwise \end{Bmatrix} \tag{8}$$

The material cost of the different ground grid components is gathered in table IV which are used to calculate the cost coefficients in (2) and their values are listed in table V.

Using (2), applying this fitness function to the data of Egyptian Future substation listed previously in table 1 so as to get an optimized design of ground grid.

The upper and lower limits of the cost function parameters (N_x, N_y, d_c, h, N_r, L_r, h_s) are selected based on the instructions of IEEE-80-2013 [4] in addition to the study of each effect previously shown in section 3.

$$N_x \in [2:25]\ ,\ N_y \in [2:25]\ ,\ d_c \in [0.0138:0.0226]\ ,\ h \in [0.1:1],\ N_r \in [4:30],\ L_r \in [1.5:9],\ h_s \in [0.05:0.5]$$

TABLE IV. Material cost for different grid components

<table>
<tr><td colspan="4">Bare stranded copper conductor [23]</td></tr>
<tr><td rowspan="9">C_{1cmat}</td><td colspan="2">C.S.A (mm2)</td><td>Price (£/m)</td></tr>
<tr><td colspan="2">70</td><td>12.55</td></tr>
<tr><td colspan="2">95</td><td>19.09</td></tr>
<tr><td colspan="2">120</td><td>24.27</td></tr>
<tr><td colspan="2">150</td><td>31.38</td></tr>
<tr><td colspan="2">185</td><td>39.04</td></tr>
<tr><td colspan="2">240</td><td>51.25</td></tr>
<tr><td colspan="2">300</td><td>59.98</td></tr>
<tr><td colspan="2">400</td><td>79.89</td></tr>
<tr><td colspan="4">CU-NNECT Exothermic welding [23]</td></tr>
<tr><td rowspan="3">C_{2exo}</td><td colspan="2">Connection type</td><td>Price (£) per piece</td></tr>
<tr><td colspan="2">Type 2 (T-connection)</td><td>11.57</td></tr>
<tr><td colspan="2">Type 4 (X-connection)</td><td>13.96</td></tr>
<tr><td colspan="4">Excavation cost for type of soil (£/m3) [24]</td></tr>
<tr><td rowspan="2">C_{3exe}</td><td colspan="2">Soil Resistivity <500</td><td>17</td></tr>
<tr><td colspan="2">Soil Resistivity >500</td><td>35</td></tr>
<tr><td colspan="4">Solid copper earth rod (dr = 1.6 cm) [23]</td></tr>
<tr><td rowspan="7">C_{4rmat}</td><td colspan="2">Length (m)</td><td>Price (£)</td></tr>
<tr><td colspan="2">1.5</td><td>56.26</td></tr>
<tr><td colspan="2">3</td><td>110.67</td></tr>
<tr><td colspan="2">4.5</td><td>165.08</td></tr>
<tr><td colspan="2">6</td><td>219.49</td></tr>
<tr><td colspan="2">7.5</td><td>273.9</td></tr>
<tr><td colspan="2">9</td><td>328.31</td></tr>
<tr><td colspan="4">Rod clamps [23]</td></tr>
<tr><td rowspan="3">C_{5rcon}</td><td>Max. rod diameter</td><td>Conductor range</td><td>Price (£) per piece</td></tr>
<tr><td>16 mm</td><td>16 - 150</td><td>16.71</td></tr>
<tr><td>16 mm</td><td>150 - 300</td><td>16.71</td></tr>
<tr><td colspan="4">Gravel cost (£/m3) [25]</td></tr>
<tr><td>C_{6gmat}</td><td colspan="2">Crushed gravel 8/16, 16/32</td><td>37</td></tr>
</table>

For calculating 'C_{1cmat}', It is required to calculate cost per meter long per millimetre-square (£/m/mm^2). But each cross-sectional area has a specific cost per meter long (£/m) so, there are multiple '£/m/mm^2'. Also, it isn't known which one will be chosen by the GA code. Thus, 'C_{1cmat}' is calculated as the average of all '£/m/mm^2' for different cross-sectional area of conductors.

In case of calculating 'C_{2exo}', type-2 is the T-connection and type-4 is the X-connection. It isn't known how many conductors that will be used so, the number of each type to be used is unknown. Thus, 'C_{2exo}' is calculated as the average of both prices of the two types.

Also, "C_{4rmat}" was calculated by calculating the average value of all cost per meter long (£/m) for different rod lengths.

TABLE V. COST COEFFICIENTS OF THE COST FUNCTION

C_{1cmat}	0.202	£/m/mm2
C_{2exo}	12.76	£/Nc
C_{3exe}	17	£/m
C_{4rmat}	36.78	£/m
C_{5rcon}	16.71	£/Nr
C_{6gmat}	37	£/m3

Conductor diameter limits are corresponding to cross-sectional area 150 to 400 mm^2, the minimum value is determined using (9) when bare stranded copper conductor is used. Also, the diameter of the rod is selected to be 1.6 cm for solid copper earth rod.

$$A_{mm^2} = 0.5066\, I_F . K_f \sqrt{t_c} \tag{9}$$

$$I_F = D_f I_f \tag{10}$$

where,
D_f: decrement factor
K_f: constant that depend on type of conductor material (Kf=7 [4])
t_c: duration of fault current

Using MATLAB software, a GA code was built to optimize the design of the ground grid [26,27]. A lot of solutions were obtained for many times of executions which reached 125 times, and the minimum value in all these times was corresponding to a cost of 111487 £. the result of the values of the optimizing parameter (N_x, N_y, d_c, h, N_r, L_r, h_s) for this minimum cost are listed in table VI. And, the grid performance corresponding to this solution is listed in table VII.

TABLE VI. RESULT OF GA FOR THE GRID PARAMETERS

GA Min. Result	
N_x	9
N_y	9
dc (m)	0.0138
h (m)	0.29
N_r	28
L_r	8.8
h_s (m)	0.07

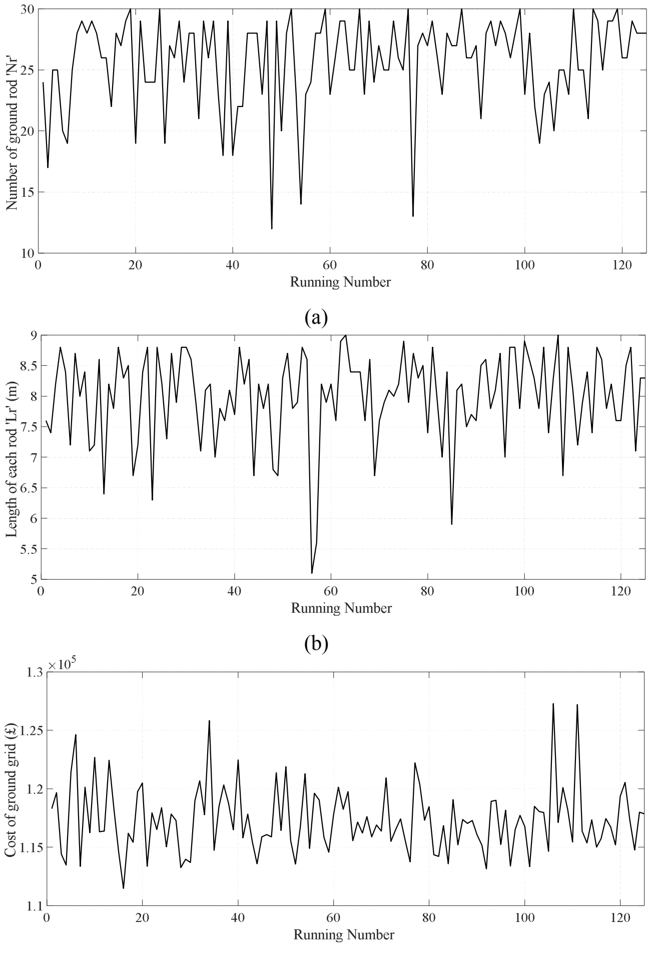
TABLE VII. ANALYSIS OF THE PROPOSED GROUND GRID

Tolerable touch voltage (70Kg)	2255	Volt
Tolerable step voltage (70Kg)	8352	Volt
Tolerable touch voltage (50Kg)	1666	Volt
Tolerable step voltage (50Kg)	6171	Volt
Mesh Voltage (Em)	1638	Volt
Step Voltage (Es)	1350	Volt
Grounding Resistance (Rg)	0.1832	Ohm
Ground Potential Rise (GPR)	8748	Volt
Conductor X-sectional area	150	mm^2

But, the result of the all executions show a main confusing issue; the GA code using the cost function in (2) always select values near the upper limit of the number of ground rod 'N_r' despite of the value of upper limit, also the length of each rod is subjected to the same issue. These two parameters values at all executions are shown in fig. 7.a and fig. 7.b. In these fig.s the minimum numbers of these two parameters are corresponding to maximum cost which can't be selected as a solution w.r.t all of these solutions. The variation of cost for all executions is shown in fig. 7.c.

The GA code always selects the available highest values of number of ground rods and length of each rod as the material cost of them is low w.r.t other material so as to increase the total length of buried rods 'L_R'.

It was clarified in section III that increasing the number of buried length of rods doesn't affect the effectiveness of the grid performance as compared to number of conductors.



(a)

(b)

(c)

Fig. 7. Result of, a) number of ground rods, b) length of each ground rod, and c) cost of ground grid, in all executions

It must be taken into consideration that installing long rods with such a large number is difficult and needs a lot of time which isn't possible because the ground grid installation is only the first step of the project which should be finished before proceeding to the next step.

So, the used cost function is not sufficient and need some modification.

V. COST FUNCTION SUBJECTED TO WEIGHT FACTORS

A new technique is used to combine both material cost of grid components and the effect of each one of them in one function and then the GA code is applied to this fitness function.

The effect of each parameter is added to (2) in the form of weight factors. The weight factor is a decimal number that represent the sharing of each parameter to the grid performance as discussed in section III.

Before proceeding to any step of the modified optimization method, the weight factors have to be calculated. The effect of each parameter based on the lower and upper limit used in GA code is the key to determine theses weight factors.

It should be mentioned that the weight factors calculated are restricted to this substation under consideration. For any other substation there will be a slight difference due to variation of upper and lower limit, soil resistivity, surface material resistivity, length and width of the grid, ground fault current, duration of this current, fault clearing current and current division factor.

$$f(N_x, N_y, d_c, h, N_r, L_r, h_s) = WF_{Ncdc} * C_{1\,cmat} * \left(\frac{\pi d_c^2}{4}\right) * [N_x L_x + N_y L_y] + WF_{Nc} * C_{2\,exo} * [N_x N_y] + WF_h * C_{3\,exc} * h * e_{trch} * [N_x L_x + N_y L_y] + WF_{NrLr} * C_{4\,rmat} * [N_r L_r] + WF_{Nr} * C_{5\,rcon} * N_r + WF_{hs} * C_{6\,gmat} * [L_x L_y h_s] + K * [\Delta R_g + \Delta E_m + \Delta E_s] \quad (11)$$

Where,
WF$N_c d_c$: Weight factor corresponding to the effect of both total number of conductors and diameter of them.
WF_N_c: Weight factor corresponding to the effect of total number of conductors alone.
WF_h: Weight factor corresponding to the effect of grid burial depth.
WF_N_r: Weight factor for representing the effect of number of ground rods alone.
WF_$N_r L_r$: Weight factor corresponding to the effect of both number of ground rods and length of each one of them.
WF_h_s: Weight factor corresponding to the degree of influence of surface material thickness.

When weight factors are combined with the cost function previously shown in (2), the cost function will be called fitness function which will give a solution based on cost of grid material in conjunction with the effectiveness of grid performance. The fitness function is shown in (11) and it will be subjected of course to the same lower and upper limit.

All of the weight factors are calculated based on the rate of decrease of grid resistance, mesh voltage and step voltage when that parameter is increased from lower to upper limit specified in GA code then. For some parameters there may be a rate of increase of grid resistance, mesh voltage and step voltage. These rates are shown in table VIII. For each parameter the average of these rates is taken as shown in table IX, then the reciprocal of each average rate is taken as the weight factor. These weight factors will be used in the fitness function.

When calculating 'WF_N_c' the effect of 'Nc' is to decrease the step voltage by 0.4002 up to a limit then any increase in 'N_c' beyond this limit will cause increase of the step voltage by 0.0453 thus, the rate of increase of the step voltage should be subtracted from the rate of decrease to get the overall effect. Thus, for calculating the weight factor 'WF_N_c', the overall effect will be the average of rate of decrease for R_g, E_m, Es and rate of increase of E_s but with negative sign. Also, for the weight factor 'WF_d_c', the overall effect will the average of rate of decrease for R_g and E_m only.

It should be mentioned that for the weight factor 'WF_$N_c d_c$', the overall effect is calculated by taking the average of the overall effects for both total number of conductors and conductor diameter.

For calculating 'WF_h', the overall effect will be the average of rate of decrease for R_g, E_m and E_s. Also, for 'WF_N_r'.

In case of calculating 'WF_$N_r L_r$' both parameters - number of rods and length of each rod - are considered by using total length of buried rods ($L_R = N_r L_r$), number of rods are increased from 4 to 30 and length of each rod is increased from 1.5 m to 9 m then, total length of buried rods is increased from 6 m to 270 m.

For the weight factor 'WF_h_s', the overall effect is the average of rate of increase for $E_{touch\text{-}50}$ and $E_{step\text{-}50}$.

TABLE VIII. CALCULATION OF WEIGHT FACTOR OF EACH PARAMETER

Parameter	R_g	E_m	E_s	$E_{touch\text{-}50}$	$E_{step\text{-}50}$
N_c	0.2914	0.8792	0.4002 / -0.0453	N/A	N/A
d_c	0.0056	0.1004	N/A	N/A	N/A
N_c & d_c	Average of N_c & d_c				
h	0.0257	0.2594	0.8644	N/A	N/A
N_r	0.0052	0.0786	0.0573	N/A	N/A
N_r & L_r	0.0104	0.127	0.0924	N/A	N/A
h_s	N/A	N/A	N/A	0.6547	0.7148

TABLE IX. CALCULATION OF WEIGHT

Parameter	**Overall effect**	**Weight factor**
N_c	0.3814	2.62
d_c	0.0530	18.87
N_c & d_c	0.2172	4.60
h	0.3832	2.61
N_r	0.0470	21.26
N_r & L_r	0.0766	13.05
h_s	0.6848	1.46

After calculating the weight factor, GA code can be applied again to search for optimum solution using (11). The GA code is excited many times and the cost in each time is calculated by substituting with solutions in (2), the optimum solution was corresponding to 124752 £ and the values of optimizing parameter (N_x, N_y, dc, h, N_r, L_r, h_s) at that minimum cost is listed in table X. And, the grid performance in case of applying these parameters is listed in table XI.

TABLE X. RESULT OF GA FOR THE GRID PARAMETER IN CASE OF USING WEIGHT FACTORS

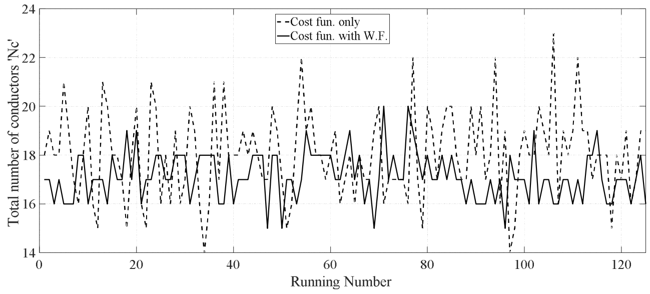
GA Min. Result	
N_x	8
N_y	9
dc (m)	0.0140
h (m)	0.6
N_r	8
L_r	5.8
h_s (m)	0.1

The issue mentioned in case of using cost function only without weight factor is eliminated and the result of the all executions is satisfied and can be adopted. All of these executions give optimal solutions which are differentiated by minimum cost. Fig. 8 shows a comparison of result of GA in two cases the first one without weight factors and the other one when weight factors are adopted.

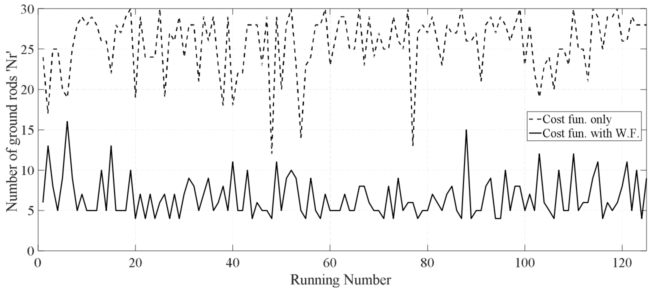
TABLE XI. ANALYSIS OF THE PROPOSED GROUND GRID

Tolerable touch voltage (70Kg)	2523	Volt
Tolerable step voltage (70Kg)	9426	Volt
Tolerable touch voltage (50Kg)	1864	Volt
Tolerable step voltage (50Kg)	6965	Volt
Mesh Voltage (Em)	1826	Volt
Step Voltage (Es)	790	Volt
Grounding Resistance (Rg)	0.1852	Ohm
Ground Potential Rise (GPR)	8841	Volt
Conductor X-sectional area	150	mm^2

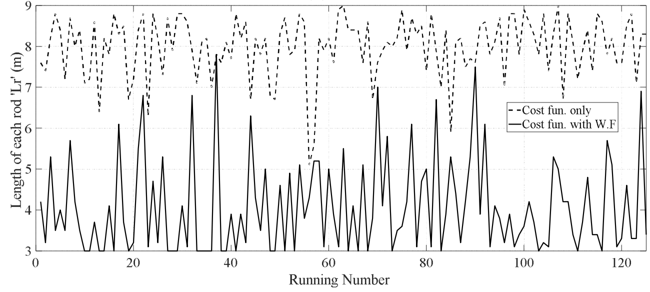
When optimization is carried out on cost function only, all the solutions to the grid design was based on the rods which is obvious from fig.s 8.b and 8.c as GA code always select the maximum allowable number of rods with maximum allowable length. Also, from fig.s 8.d and 8.e a relatively low value of grid burial depth and surface material thickness is selected. The grid design is mainly selected based on cost only despite of the effect of each one the grid performance.



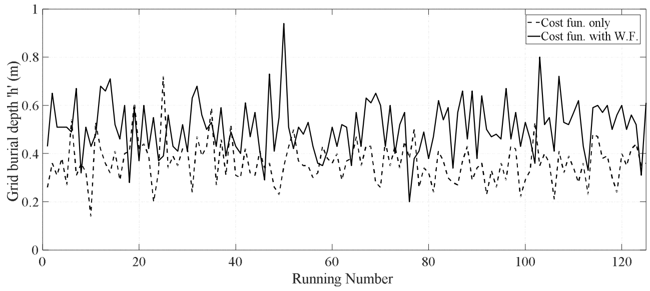
(a)



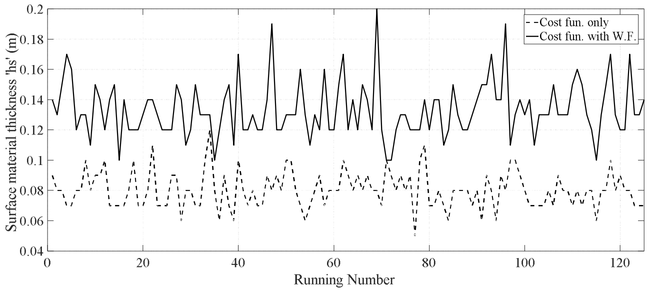
(b)



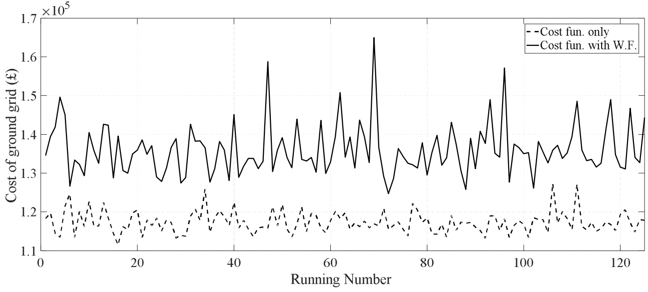
(c)



(d)



(e)



(f)

Fig. 8. Variation of, a) total number of conductors, b) number of ground rods, c) length of each rod, d) grid burial depth, e) surface material thickness and f) grid material cost, along executions in both cases

Of course, the cost of the grid is increased when using the weight factors by nearly 12 % as shown in fig. 8.f. But, this eliminates the difficulties in constructing and installing the grid itself and save time of the project.

In the second case when cost function is supported with the proposed weight factors, the optimization process is said to be directed. The whole optimizing parameters are selected according to their influence on the grid performance taking into consideration the material cost of each component.

VI. CONCLUSION

In this paper the factors affecting on grid performance was studied and analyzed. It is clear that the tolerable values of touch and step potentials was enhanced with increasing the thickness of surface material. The results show that the number of conductors is the most effective way to reduce the grid resistance, mesh and step voltages. The succession of parameters that affect grid performance was total number of conductors, grid burial depth, conductor diameter, number of rods and length of each rod respectively.

Two methods of optimum search for grid design were presented as follow;

1. the traditional is based on the material cost only discarding the impact of each parameter on the grid performance and the installation difficulties and needs.

2. the proposed method gives a solution based on the effectiveness of each parameter taking into account the material cost of each one.

The result show that both give an accepted solution to grid design. When traditional method is utilized the grid design and performance depend mainly on rods and their lengths. However, the effect of them on grid performance are relatively small as compared to other parameters.

While, in the proposed method the grid design and performance depend on the all parameters each one with its impact. The proposed method gives better and more realistic options for optimum design.

REFERENCES

[1] S. G. Shah and N. R. Bhasme," Design of Earthing System For HV/EHV Ac Substation", International Journal of Advances in Engineering and Technology, vol. 6, no. 6, pp. 2597-2605, 2014.

[2] N. M. Tabatabaei, and S. R. Mortezaeei, "Design of Grounding Systems in Substations by ETAP Intelligent Software", International Journal on Technical and Physical Problems of Engineering, vol. 2, no. 2, pp. 45-49, 2010.

[3] IEEE Recommended Practice for Grounding of Industrial and Commercial Power Systems, IEEE Std. 142, New York, 2007.

[4] IEEE Guide for Safety in AC Substation Grounding, IEEE Std. 80, New York, 2015.

[5] A. J. Datta, R. Taylor, and G. Ledwich, "Earth grid safety criteria determination with the standards IEEE-80 and IEC-60479 and optimization of installation depth", Australasian Universities Power Engineering Conference (AUPEC), Wollongong, NSW, Australia, 27-30 sept. 2015.

[6] J. L. D. Alamo, "A comparison among eight different techniques to achieve an optimum estimation of electrical grounding parameters in two-layered earth", IEEE Transactions on Power Delivery, vol. 8, no. 4, pp. 1890-1899, 1993.

[7] Y. Yang, M. Peng, H. Hong, and Y. Yuan, "Optimal Design of Grounding Grids Based on Genetic Algorithm", Third International Conference on Genetic and Evolutionary Computing, Guilin, China, 14-17 Oct. 2009.

[8] S. Kara, O. Kalenderli, and O. Altay, "Optimum grounding grid design by using genetic algorithms", International Conference on Electrical and Electronics Engineering , Bursa, Turkey, 26-28 Nov. 2015.

[9] S.J. Schwarz, "Analytical expression for resistance of grounding systems", Transactions of the American Institute of Electrical Engineers, Part 3: Power Apparatus and Systems, vol. 73, no. 2, pp. 1011-1016, 1954.

[10] B. Thapar, V. Gerez, A. Balakrishnan, and D.A. Blank, "Simplified equations for mesh and step voltages in an AC substation", IEEE Transactions on Power Delivery, vol. 6, no. 2, pp. 601-607, 1991.

[11] J. He, R. Zeng, and B. Zhang, Methodology and Technology for Power System Grounding, John Wiley and Sons Singapore Pte. Ltd., 2013.

[12] K. A. Vyas, and J.G. Jamnani,"Optimal Design and Development of Software for Design of Substation Grounding System", Nirma University International Conference on Engineering, Ahmedabad, Gujarat, India, 8-10 Dec. 2011.

[13] A. Puttarach, N. Chakpitak, T. Kasirawat, and C. Pongsriwat, "Substation Grounding Grid Analysis with the Variation of Soil layer depth Method", IEEE Lausanne Power Tech, Lausanne, Switzerland, 1-5 July 2007.

[14] J. H. Holland, Adaptation in natural artificial system, Univ. Michigan Press, 1975.

[15] M. Negnevitsky, Artificial intelligence: a guide to intelligent systems, Addison-Wesley Publishing Company, Massachusetts, 2005.

[16] A. F. Otero, J. Cidras, and C. Garrido, "Genetic algorithm based method for grounding grid design", IEEE International Conference on Evolutionary Computation Proceedings, Anchorage, AK, USA, 4-9 May 1998.

[17] C. C. Mauricio, "Optimization of grounding grids by response surfaces and genetic algorithms", IEEE Trans. Magn., vol. 39, no. 3, pp. 1301-1304, 2003.

[18] C. Lee, and Y. Shen, "Optimal Planning of Ground Grid Based on Particle Swam Algorithm", International Journal of Electrical and Computer Engineering, vol. 3, no. 12, 2009.

[19] K. Vyas, and J. Jamnani, "Development of IEEE Complaint Software 'Economical Substation Grounding System Designer' Using MATLAB GUI Development Environment", International Journal on Electrical Engineering and Informatics, vol. 4, no. 2, 2012.

[20] Q. Zhang, and X. Wu, "Software Development of Optimal Substation Ground Grid Design Based on Genetic Algorithm and Pattern Search", North American Power Symposium, Pullman, WA, USA, 7-9 sept. 2014.

[21] B. Alik, M. Teguar, and A. Mekhaldi, "Minimization of Grounding System Cost Using PSO, GAO, and HPSGAO Techniques", IEEE Transactions on Power Delivery, vol. 30, no. 6, pp. 2561-2569, 2015.

[22] C.F. Dalziel, and F.P Massogilia, "Let-go currents and voltages", Transactions of the American Institute of Electrical Engineers, Part 2: Applications and Industry, vol. 75, no. 2, pp. 49-56, 1956.

[23] A.N. Wallis, http://www.an-wallis.co.uk/

[24] A. El-Fergany, "Accelerated particle swarm optimization-based approach to the optimal design of substation grounding grid", Przegląd Elektrotechniczny, Poland, R. 89 no. 7, pp. 30-34, 2013.

[25] Genetti SA, gravel & concrete, http://www.genetti.ch

[26] Z. He, X. Wen, J. Wang, "Optimization Design of Substation Grounding Grid Based on Genetic Algorithm", Third International Conference on Natural Computation, Haikou, China, 24-27 Aug. 2007.

[27] B. Alik, Y. Kemari, N. Bendekkiche, M. Teguar, and A. Mekhaldi, "Optimization of grounding system of 60/30 kV substation of Ain El-Melh using GAO", International Conference on Electrical Engineering (ICEE), Boumerdes, Algeria, 13-15 Dec. 2015.