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Optimal Design of Substation Grounding Grid Based on Genetic Algorithm Technique

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Abstract**—**With the incessant increase of power systems capacity and voltage grade, the safety of grounding grid becomes more and more prominent. In this paper, the designing substation grounding grid is presented by means of genetic algorithm (GA). This approach purposes to control the grounding cost of the power system with the aid of controlling grounding rod number and conductor lengths under the same safety limitations. The proposed technique is used for the design of the substation grounding grid in Khalda Petroleum Company "El-Qasr" power plant and the design was simulated by using CYMGRD software for results verification. The result of the design is highly complying with IEEE 80-2000 standard requirements.

Keywords**—**Genetic algorithm, optimum grounding grid design, power system analysis, power system protection, single layer model, substation.

I. INTRODUCTION

IN every electrical installation, one of the most important aspects is the adequate grounding; more specifically the grounding of high voltage substation [1]. Grounding, generally mean an electrical connection to the general mass of earth, the latter being a volume of soil, rock etc. whose dimensions are very large in comparison to the electricity system being considered. It is worth noting that, in Europe they tend to use the term "Earthing" whilst in North America, the term "Grounding" is more common [2]. A power plant with a reasonable grounding system is the key to the safe operation of a power system. The working grounding is designed for different operation modes of the power system. Grounding has a lot of purposes like, reducing the insulation level of electrical equipment, ensuring safe operation of power system, ensuring personnel safety, eliminating electrostatic accidents, detecting ground faults, and ensures that externally exposed conductive bodies of a device have the same potential by means of equipotential bonding, reducing the electromagnetic interference. Finally, some equipment needs to be grounded functionally like cathodic protection [3]. It is very important to design the grounding system correctly so that there is no danger for human life. After high-voltage substations are constructed, solving the problems related to grounding system can be expensive and difficult. Hence, grounding grid design must be carried out consistently [4]. The grounding system includes all of the interconnected grounding facilities in the substation area, including the ground grid, overhead ground wires, neutral conductors, underground cables, foundations, deep well, and so on. The ground grid consists of horizontal interconnected bare conductors (mat) and ground rods. The design of the ground grid to control voltage levels to safe values should consider the total grounding system to provide a safe system at an economical cost [5]. At the event of short circuit or any ground fault occurrence at any substation, the current may flow across many paths. All these paths are depending on its impedance. So, the ground fault current may flow through the overhead transmission lines or through the substation and surrounding earth or across all these paths together. The first guide for the substation grounding design was introduced on 1961: the ANSI/IEEE 80-2000 standard, and it was based on a lot of experience and models. This document and other three revisions on 1976, 1986, and 2000 are the main helping tools for engineers in designing a substation grounding mat systems [6]-[8]. The IEEE definition of grounding is: a conducting connection, whether international or accidental by which an electric circuit or equipment is connected to the earth or some conducting body of relatively large extent that serves in place of the earth [2]. A lot of studies were made to describe and analyze the substation grounding grid design criteria. In 2011, Hellany et al. made a study to view the safety restrictions of substation grounding grid design [9]. In 2014, Lantharthong presented the electrical effect of two neighboring distribution substation during the construction phase and they found that the size of auxiliaries grounding grid have an effect on the entire grounding system [10]. CYMGRD is a software program specialized in the substation grounding mat design. It may be used to make a new design for new grids or to optimize and enhance an existing one of any shape. This module can evaluate the estimate places for the danger voltage points in the grid and its adopting with IEEE 80-2000 STD. The CYMGRD software enables choosing the most economical way for any installation through a lot of design alternatives [11]. CYMGRD has been used to investigate the effect of increasing in grounding grid resistance on transient overvoltage which is caused by short circuit, switching, and lightening on the interior equipment and safety in a grounding grid at substation. The indices for ground grid safety are expressed and grounding grid analysis had done with the CYMGRD software. In 2009, Uzunlar and Kalenderli used CYMGRD software to make a computer model for analysis of grounding systems conforming to IEEE standards. Their method and computer software were supported with a real case measurement [12].

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GA is a commonly used technique to solve the optimization problems even if these problems were constrained or unconstrained. At each iteration, it generates a lot of points called population. The best point in this population is the nearest one to the optimum solution [13]. In 1998, Otero et al. used the GA method to minimize the total cost of the grounding grid design [14]. In 2004, Neri used the GA method to control the touch voltage in the grounding grid design [15]. In 2009, Yi-min et al. used the GA method to make an optimal design for grounding grids [16]. In 2009, Yang et al. used the GA method to make analysis on soil structure for the grounding projects [17]. In 2009, Gursu and Ince used the GA method to limit the GPR in a two-layer soil model [18]. In 2011, Zhiqiang and Bin used the GA method to make the soil model inversion calculations [19].

In this paper, a method for constructing a grounding grid substation is proposed by using an approach based on hand calculations, CYMGRD software, and GA technique. The aim is to minimize the cost of the grounding system by minimizing the total length of conductors and the quantity of grounding rods while the safety restrictions required by the IEEE Std.80-2000 regulations are met. Although, here, only rectangular grids are considered for simplicity, the method is totally applicable to systems with any other shape.

II. SUBSTATION GROUNDING GRID DESIGN, SAFETY CHECK AND OPTIMIZATION

The main objective of this research is not only to develop a method to design a grounding grid mat but also to optimize the construction and material costs of a grounding grid mat while still satisfying the maximum GPR, and step and touch voltages, and GA is the technique which had been used for this optimization.

A. Hand Calculations Design

It is important to use the hand calculations method in the substation grounding grid design because it allows us to get the appropriate distance between conductors. Total length of conductors and the appropriate number of rods will be used.

In this paper, a real case study from Khalda Petroleum Company “El-QASR” power plant substation had been designed. This power plant lies on the western desert South Matrouh, Egypt, with Latitude: 300 38’ 46.82’’ N, Longitude: 260 44’ 18.13’’ E, and Altitude: 800 ft. The preliminary layout of 92 m × 134 m grid with equally spaced conductors, with spacing D= 10 m, grid burial depth h= 0.5 m, grid with 20 ground rods. Each rod is 2 m long, and it is placed around the perimeter of the grid. The Decrement factor D_f= 1, the current division factor S_f= 0.6. Fault duration t_f=0.5 sec. An average soil resistivity of 100 Ω.m is assumed, based on soil resistivity measurements with asphalt surface layer with 0.5 m thickness. The total fault current is 40 kA and the X/R ratio is 10. Using copper annealed hard drawn and an ambient temperature of 45 °C, the person’s weight can be expected to be at least 70 kg, consequently the area occupied by such a grid is A= 12328 m^2.

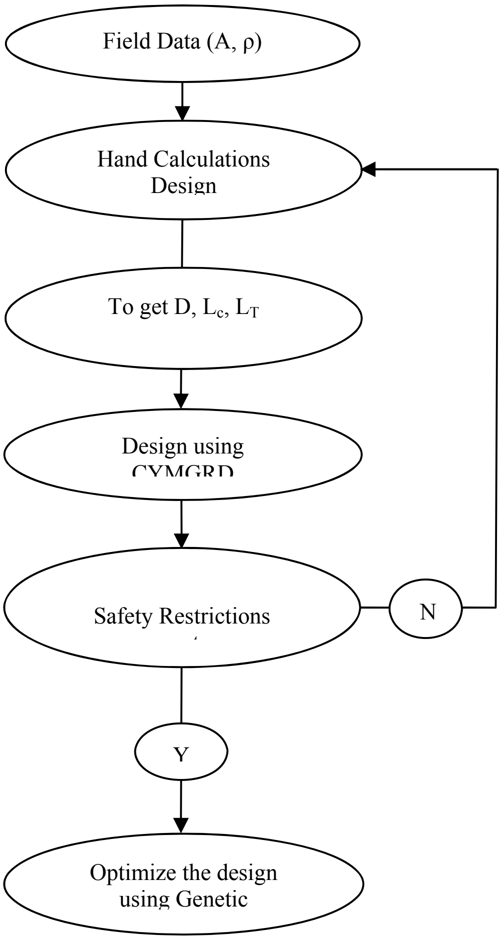

Fig. 1 Substation Grounding Grid Design and Optimization Block Diagram

1. Calculating the Ground Resistance

$$R_g = \rho\left[\frac{1}{L_T} + \frac{1}{\sqrt{20A}}\left(1 + \frac{1}{h\sqrt{20/A}}\right)\right] \tag{1}$$

$$L_T = L_c + L_R \tag{2}$$

$$L_c = \left(\left(\frac{L_x}{D} + 1\right) \times L_y\right) + \left(\left(\frac{L_y}{D} + 1\right) \times L_x\right) \tag{3}$$

$$L_R = L_r \times N_R \tag{4}$$

$$R_g = 100\left[\frac{1}{2731} + \frac{1}{\sqrt{20*12328}}\left(1 + \frac{1}{0.5\sqrt{\frac{20}{12328}}}\right)\right] = 0.435\Omega$$

2. Calculating the Maximum Grid Current

$$I_G = I_f \times D_f \times S_f \tag{5}$$

I_G=40×1.069×0.6=24000 A

3. Calculating the GPR

$$GPR = I_G \times R_g \tag{6}$$

The revised ground potential rise GPR is (24000) × (0.435) = 10464 V.

4. Calculating the Touch and Step Voltage

$$C_s = 1 - \frac{0.09\left(1-\frac{\rho}{\rho_s}\right)}{2h_s+0.09} \tag{7}$$

$$C_s = 1 - \frac{0.09\left(1-\frac{100}{10000}\right)}{(2\times0.5)+0.09} = 0.919$$

$$E_{step\ 70} = \frac{(1000+6C_s\rho_s)0.157}{\sqrt{t_s}} \tag{8}$$

$$E_{step\ 70} = \frac{(1000+6\times0.919\times10000)0.157}{\sqrt{0.5}} = 12344.95\ V$$

$$E_{touch\ 70} = \frac{(1000+1.5C_s\rho_s)0.157}{\sqrt{t_s}} \tag{9}$$

$$E_{touch\ 70} = \frac{(1000+1.5\times0.919\times10000)0.157}{\sqrt{0.5}} = 3252.23\ V$$

5. Calculating the Mesh Voltage

$$E_m = \frac{\rho K_m K_i I_G}{L_M} \tag{10}$$

$$K_m = \frac{1}{2\pi}\left(\ln\left(\frac{D^2}{16\times h\times d} + \frac{(D+2h)^2}{8\times D\times d} - \frac{h}{4\times d}\right) + \frac{K_{ii}}{K_h}\ln\frac{8}{\pi(2n-1)}\right) \tag{11}$$

$$K_{ii}=1,\ K_h = \sqrt{1+\frac{h}{h_0}} \tag{12}$$

h_0=1m “grid reference depth”

$n=n_a \times n_b \times n_c \times n_d$

$$n_a = \frac{2L_c}{L_p} \tag{13}$$

$$n_b = \sqrt{\frac{L_p}{4\sqrt{A}}} \tag{14}$$

n_c & n_d=1 “rectangle grid”

n_a=11.909 & n_b=1.008

n=12.014

$K_m = 0.844$

$$K_i=0.644+0.148n \tag{15}$$

K_i=2.422

$$L_M = L_c + \left[1.55 + 1.22\left(\frac{L_r}{\sqrt{L_x^2+L_y^2}}\right)\right]L_R \tag{16}$$

L_M=2754.2 m

$$\therefore E_m = \frac{100\times0.828\times2.212\times24\times1000}{2464.60} = 1782.9\ \mathrm{V}$$

6. Calculating the Step Voltage

$$E_s = \frac{\rho K_s K_i I_G}{L_s} \tag{17}$$

$$K_s = \frac{1}{2\pi}\left(\frac{1}{2h} + \frac{1}{D+h} + \frac{1}{D}(1-0.5^{n-2})\right) \tag{18}$$

K_s=0.190

$$L_s=0.75L_c+0.85L_R \tag{19}$$

“For usual buried length 0.25<h<2.5 m”

L_s= (0.75×2402) + (0.85×40) =2052.7 m

$$\therefore E_s = \frac{100\times0.190\times2.212\times24\times1000}{1835.5} = 538.68\ \mathrm{V}$$

The calculated corner mesh voltage is lower than the tolerable touch voltage (1782.9 V versus 3252.23 V) and the computed E_s is well below the tolerable step voltage (538.68 V versus 12344.95 V). A safe design has been established. Note that all these results had been calculated by using IEEE Std. 80-2000 [2] as shown in Fig 2.

B. CYMGRD Implementation for “El-Qasr” Substation Design

Although, the hand calculations were very important for the design to get D, L_c, and L_t, but this way has many disadvantages as:

1. It cannot determine the potential at each point inside the grid along x-axis or y-axis.
2. It cannot determine the potential at the boundaries of the grid which have the most critical values.
3. It cannot determine the appropriate distribution of the rods along the grid perimeter.

All these values can be determined, and safety is checked by using the CYMGRD software. The CYMGRD software is a substation grounding grid design and analysis program specially designed to help engineers to optimize the design of new grids and reinforce existing grids, of any shape, by virtue of easy to use, built-in danger point evaluation facilities. The main features of this software are: computation of R_g and GPR (Ground Potential Rise), touch and surface potential analysis, inside and outside the grid perimeter, with color display in 2D or 3D representation.

TABLE I
COMPARATIVE RESULTS FOR RECTANGLE GRID WITH GROUND RODS

Properties	Hand Calculations	CYMGRD Software	% Difference
Max allowable touch voltage	3252.23 V	3280.26 V	0.8%
Max allowable step voltage	12344.95 V	12455 V	0.8 %
Reduction factor Cs	0.919	0.918	0.1 %
Ground Resistance	0.435 Ω	0.419 Ω	3.8 %
Ground Potential Rise	10464 V	10372.4 V	0.8 %

The data entered to the CYMGRD software is listed in Appendices (see Table III). The results obtained from the

CYMGRD program are shown in Figs. 3-5, while the comparative results for rectangle grid with ground rods are shown in Table I.

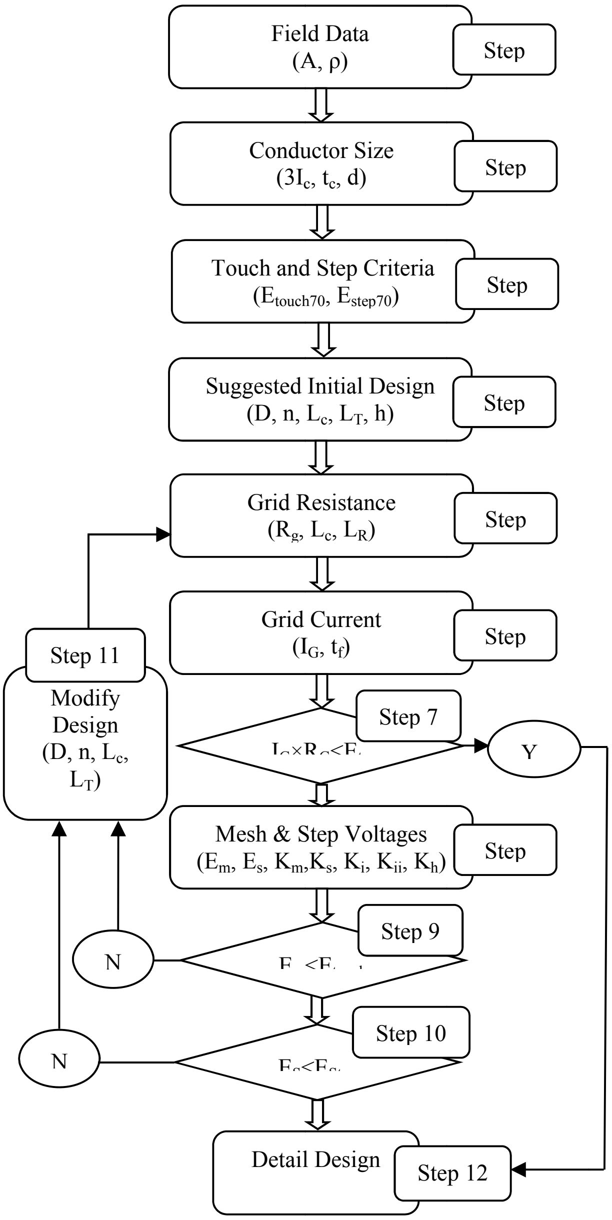

Fig. 2 Substation Grounding Grid Design Procedure Block Diagram

C. Design Optimization Using GA

The objective of the grounding grid design is to find a structure of buried conductors that ensures the safety of people and equipment, using the smallest possible number of rods and smallest possible length of conductors. Both objectives are in conflict, and compromise solution must be found. So, the problem can be expressed as the search for an arrangement of buried conductors observed the following objectives:

1. Step and touch voltage at any point of the installation must be lower than the maximum value required by the regulations.
2. The ground resistance R_g must be lower than 0.5 Ω.
3. The total length of conductors and total number of rods (the cost) should be as low as possible.

Despite the CYMGRD software was very useful in the design safety check but it cannot get an optimal solution for the number of rods and the total length of conductors to minimize the installation cost, so we used the GA technique to optimize the solution that we get from both hand calculations and the CYMGRD software.

Mathematically, the problem may be expressed as the minimization of the cost function:

$$C = (C_{cond} \times L_c) + (C_{rod} \times N_r) + (C_{operator} \times no.operators) + C_{install} \qquad (20)$$

The optimization of the function C must satisfy the constraints:

$$E_m < E_{touch\ 70}, E_s < E_{step\ 70} \text{ and } R_g < 0.5\Omega$$

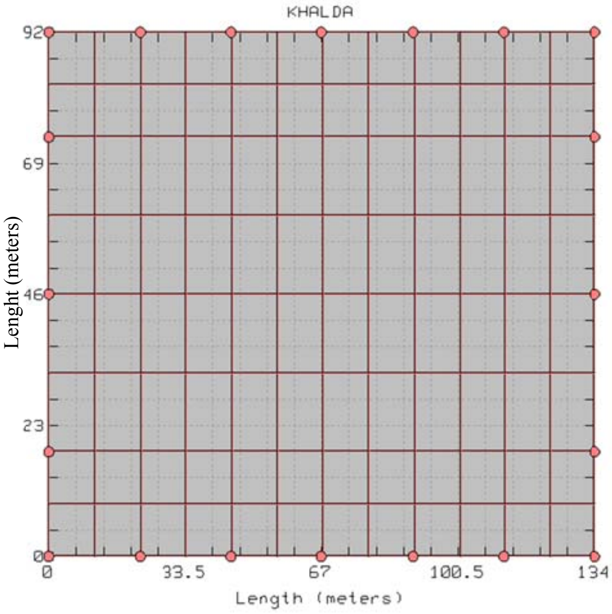

Fig. 3 El-Qasr Grid layout using the software

Besides these objectives, the following conditions are introduced in the design with the aim of simplifying the problem:

1. A continuous conductor loop surrounding the perimeter of the substation is assumed. This loop enclosed the total area of the installation.
2. The spacing between the conductors is equally spaced "D". That makes the total length of the conductors L_c as (3).

A MATLAB function using the GA technique was developed that allowed the number of rods and spacing between conductors to vary as part of the optimization routine. This technique makes the calculations of the grounding resistance faster. At each iteration of grounding grid resistance calculation, it should be ensured that the safety parameters and constraints "step and touch voltages" are still in the safety region values. The fitness function was to minimize the total cost of designing the substation grid as shown in equation (20). There were two variables, the first was X(1) (the spacing between conductors) and the second was X(2) (total number of rods). X(1) must be an integer number according to the distribution constraints, and X(2) is constrained to be an even number. There were three nonlinear constraints to keep the optimized design in a safe region. Also, the design has a lower bounds and upper bounds for the variables. The population type was double vector to keep the output in an integer form, then chose the population size. The default of the population size is (10×no. variables), then run the solver to get the results. This research used “El-Qasr” power plant as a case study. The actual parameters used in the objective function are listed in Appendices (see Table IV).

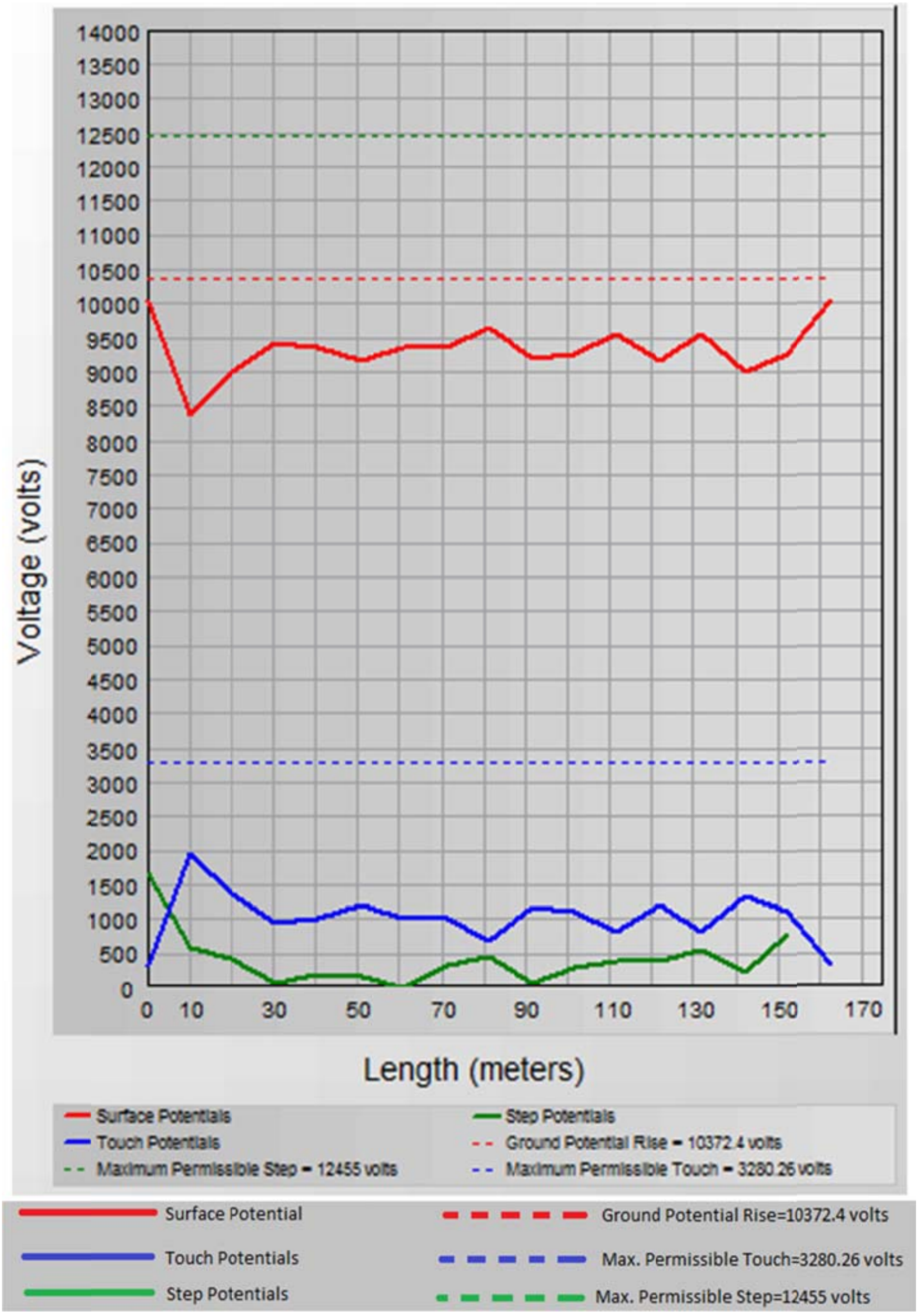

Fig. 4 El-Qasr profile plot in 2D form

The permissible values for the touch and step voltage were calculated depending on the soil parameters of the power plant as previous. After completion of the optimization, the results were 24 m spacing between conductors and 23 placed rods. X(1) = 24 m and X(2) = 23 rods. So, the total length of the installed conductor will be 1253 m. Referring to Eq. (3). A comparison between the original design of Khalda “El-Qasr” power plant and the optimized one had been established as shown in Table II.

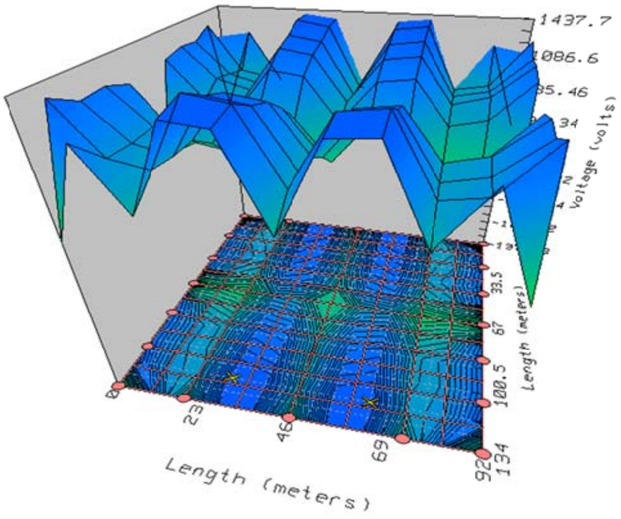

Fig. 5 El-Qasr contour plot in 3D form

As it is clear in Table II, the optimization technique saved about 403,290 L.E. (Egyptian Pound)

TABLE II
COMPARISON BETWEEN ORIGINAL DESIGNS AND OPTIMIZED ONE

Properties	Original Design	Optimized Design	Critical Values
Spacing between conductors D	10 m	24 m	
Number of Rods n_R	20	23	
Total length of conductors L_c	2691	1253	
Step potential E_{step}	538.68 V	619.65 V	12344.95 V
Touch potential E_{touch}	1782.9 V	3250.5 V	3252.23 V
R_g	0.435 Ω	0.47 Ω	0.5 Ω
Design Cost (L.E)	767,850	364,560	

III. CONCLUSION

In every electrical installation, one of the most important aspects is adequate grounding, not only the proper design but also an optimized one to get the minimum cost of design. We used the hand calculations method in the substation grounding grid design because it allows to get the appropriate distance between conductors, total length of conductors, and the appropriate number of rods. Hand calculations cannot determine the potential at each point inside the grid along x-axis or y-axis, it cannot determine the potential at the boundaries of the grid which have the most critical values and It cannot determine the appropriate distribution of the rods along the grid perimeter, so a CYMGRD software had been used to meet all these requirements. Although the CYMGRD software was very useful in the design safety check but it was unable to get an optimal solution for the number of rods and total length of conductors to minimize the installation cost, so we utilized the GA technique to optimize the solution obtained from both hand calculations and the CYMGRD software. El-Qasr power plant was designed and finally a 403,290 L.E had been saved by using the GA optimization technique.

APPENDICES

TABLE III
INPUT DATA TO CYMGRD PROGRAM

Properties	I/P Data	Unit
Surface layer resistivity	10000	Ω.m
Surface layer thickness	0.5 m	m
Top layer resistivity	100	Ω
Top layer depth	10 m	m
Lower layer resistivity	0.001 Ω	Ω
Body weight	70 Kg	Kg
Fault duration	0.5 Sec	Sec
Ground fault current	40 KA	KA
X/R ratio	10	
Current split factor S_f	60 %	
Grid size	92 * 134	m^2
No. of conductors in X direction	9	
No. of conductors in Y direction	13	
Conductors burial depth	0.5 m	m
Conductors diameter	14.020 m	m
Conductor type	Copper annealed hard drawn	
No. of rods	20	
Rod diameter	20 mm	mm
Rod length	2 m	m
Rods arrangement	Along the grid perimeter	
Rod type	Copper annealed hard drawn	

TABLE IV
EL-QASR POWER PLANT OPTIMIZATION PARAMETERS

Properties	Value	Unit
C_{cond}	281 L.E	L.E.
C_{rod}	143 L.E	L.E.
$C_{operator}$	150 L.E	L.E.
$C_{install}$	4292	
No.operators	10	
One rod length	2 m	m
N_r	X(2)	
L_c		
LY	92 m	m
LX	134 m	m
D	X(1)	
LB	[0,4]	
UB	[92,30]	

TABLE V
LIST OF USED SYMBOLS

Symbol	Nomenclature	Units
ρ	Soil resistivity	Ω.m
ρ_s	Surface Layer Resistivity	Ω.m
A	Total area enclosed by ground grid	m^2
C_s	Surface Layer Derating Factor	
C_{cond}	Cost of one meter of Conductor	L.E
C_{rod}	Cost of one rod	L.E
$C_{operator}$	Cost of one operator	L.E
$C_{install}$	Cost of installation	L.E
d	Diameter of grid conductor	M
D	Spacing between parallel conductors	m
D_f	Decrement Factor	
E_m	Mesh voltage at the center of the corner mesh for the simplified method	Volt
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	Volt
E_{step70}	Tolerable step voltage for human with 70 kg body weight	Volt
Et_{ouch70}	Tolerable touch voltage for human with 70 kg body weight	Volt
h_s	Surface layer thickness	m
I_f	Total fault current	Ampere
$\frac{I_G}{L_M}$	Average current per unit of effective buried length	
$\frac{I_G}{L_s}$	The average current per unit of buried length of grounding system conductor	
K_i	Correction factor for grid geometry	
K_{ii}	Corrective weighting factor that adjusts for the effects of inner conductors on the corner mesh	
K_m	Spacing factor for mesh voltage	
K_s	Spacing factor for step voltage	
LB	Lower Bonds	
L_c	Total length of grid conductor	m
L_p	Perimeter of the grid	m
L_m	Total length of grid conductor	m
L_R	Total length of ground rods	m
L_r	Length of ground rod at each location	m
L_s	Effective length of Lc+LR 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 conductor in y direction	m
NR	Number of rods placed in area A	
n	Geometric factor composed of factors na, nb, nc and nd	
n_a	Factor used to calculate “n”	
n_b	=1 for square grids	
n_c	=1 for square and rectangular grids	
n_d	=1 for square, rectangular and L-shaped grids	
R_g	Resistance of grounding system	Ω
S_f	Fault current division factor (Split factor)	
t_s	Duration of shock for determining allowable body current	Sec
UB	Upper Bonds	

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