Compensation and Cathodic Protection of Steel Grounding Grids Corrosion

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Abstract— Under normal conditions, electrical power systems will satisfactorily deliver power with the need of proper grounding. Grounding is very important for the generation, transmission and distribution systems of electrical power. Grounding creates stability for the electrical networks; the neutral grounding is useful in discharging over-voltages due to lightning to the earth, grounding is used in simplified design of earth fault protection, the grounded systems require relatively lower insulation levels as compared with underground and finally the most important reason is to protect people. Grounding system may be steel, copper or other materials, these materials prone to corrode. This study is specifically concerned with the effect of corrosion on steel grounding grid and methods to compensate the gird and surrounding metallic rods which are subjected to corrosion. Also this paper introduces the design of a cathodic protection of electrical substation grounding system in which a steel ground grid and rods are used instead of copper.

Index Terms— Grounding grid , Corrosion

1 Introduction

Reducing corrosion of electrical power network becomes not only an attractive option but now is necessary for the requirement of the National Electrical Safety Code (NESC) [1] The grounding grid is usually subjects to current discharge that might cause damage to the grid by time, with a conductor that has a sufficient current rating to carry the possible fault current and sufficiently low impedance to limit the voltage rise above the ground potential. As already proven by many researchers' two alternatives to protect the grounding grid from corrosion are investigated [2 -13]. The first alternative is achieved by compensation of the embedded conductors that qualifies the ageing of grounding system conductor due to current discharge in both steel and copper ground grid. The second is the cathodic protection system which uses additional current injection components to be installed in the ground system to protect the grid and surrounding metallic parts from corrosion [14 -26].The fundamental objective of the grounding system is to make a proper design for the grounding grid and provide suitable techniques to avoid corrosion for a long time such that the compensation for conductors. In order to design a safe grounding grid, the data of soil resistivity, conductor size of different materials, fault current, earth grid resistance, maximum grid current, grid potential rise (GPR), step and mesh voltage have to be collected [5]. Corrosion is a billion dollars thief; corrosion of metallic structures buried in soils or in contact with soils has long been a serious engineering and economic problem. There are all over the world millions of miles of gas, water, oil pipelines, power cable systems, as well as unknown numbers of grounding grid systems, and many other structures. Conversely, any product placed in the earth ultimately tends to revert by deterioration of non-metals or corrosion of metals, to their original form as found in nature and the grounding grid itself. Compensation of grounding grid conductors is an alternative to avoid corrosion in steel and copper grounding grid. There are many different causes for the corrosion types depending on the soil conditions, PH values, moisture and aeration. The rate of corrosion is also different according to the rate of the above mentioned causes. Cathodic protection is another alternative for grounding protection, [16-25] it has two methods using sacrificing anode or impressed current method. Determining of which method to be applied depends on some factors such as soil resistivity. The paper applies different applications of the grounding design using galvanized steel material in order to design a safe grounding grid by applying the compensation method to protect the grounding grid from corrosion or by applying cathodic protection system using its two available methods impressed current & sacrificing anode. In this paper a case study of designing grounding grid using steel conductors in different soil conditions is investigated. The compensation for avoiding grid corrosion is discussed.

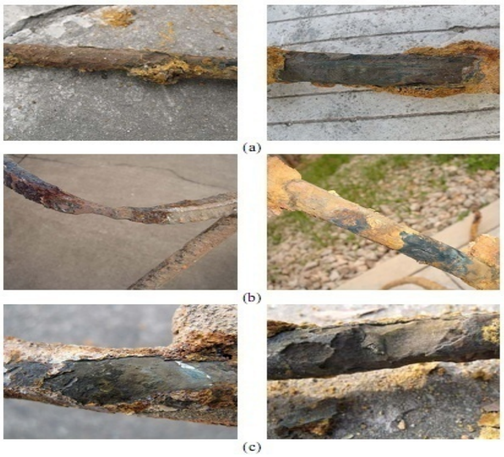

Fig 1 Example for corrosion of grounding grid of substation [3]. (Corrosion forms of (a) uniform corrosion, (b) pitting corrosion and (c) microbial influenced corrosion)

2 CORROSION RATE OF SUBSTATION GROUNDING GRID

An example of corrosion of grounding rod of grounding system is given in fig. 1[3]. Different ways are found to estimate the rate of corrosion in steel and other metallic materials. One important way for corrosion estimation is the experimental method. Experimental formula to calculate the corrosion rate of Bessemer steel is obtained by using actual experiments in 44 different soils conducted over a period of 12 years [5]. These tests used 1.5-inch and 3-inch diameter samples. The 3-inch samples corroded 13% more than the 1.5-inch samples with an error of 10 %. It is found that

$$Y = F(\rho, x_1, x_2, x_3) \qquad (1)$$

Y= Corrosion rate (mils/year), ρ =soil resistivity in ohm.cm, x_1= pH value, x_2= Moisture (%) in soil, and x_3=Aeration (%)

Finally the following equation is obtained [5]:

$$Y = 3.36 - 9.63(10^{-5})(\rho) + 0.29(x_1) + 0.034(x_2) + 0.012(x_3) \qquad (2)$$

Equation (2) is experimentally obtained and it is limited by extreme corrosion conditions such as, high resistivity (> 10,000 ohm.cm) or extremely low aeration quantities (< 3%) [5]. It is concluded experimentally also that the average corrosion rate decreases with time until stopping after 12 years. The corrosion rate can be estimated for several material corrosion rate based on Eqn. (2) [5].

In grounding grid design for AC substation, copper is used as the primary grid material. Steel-grounding system is widely used and readily accepted in many countries worldwide, where copper is very expensive. However, it is still common in this kind of grounding system for grounding faults problems to occur due to corrosion, which might result in plenty of economic loss [8].

Reliable performance of steel grounding systems can be insured by selecting a conductor cross-section area. Table 1 gives average corrosion rate of several materials [5].

TABLE 1.
Average corrosion rate of several materials [5]

Materials	**Corrosion rate (mils/years)**
Open earth steel	5.90
Wrought iron	5.00
Bessemer steel	5.30
Copper	1.25
Lead	3.00

3 Design Procedure of a Grounding System ACCORDING TO IEEE STANDARDS

The grounding system material is important factor in designing the electrical substations. IEEE [26-27] method is used to design the grounding grid including, conductor size, fault current, earth grid resistance, maximum grid current, grid potential rise (GPR), step and mesh voltage in order to design a safe grounding grid.

According to IEEE standards the grid conductor cross area simplified equation (3) can be used [27]

$$A_{Kcmil} = I . K_f . \sqrt{t_C} \qquad (3)$$

Where, K_f is constant found in Table 2 which is based on the fusing temperature of the grid material, t_C is the duration of fault current (s) and I is the rms current (kA),

TABLE 2
Constant for different materials [27]

Material	K_f
Copper, annealed soft-drawn	7.00
Copper, commercial hard-drawn	7.06
Copper, commercial hard-drawn	11.78
Copper-clad steel wire	10.45
Copper-clad steel wire	12.06
Copper-clad steel rod	14.64
Steel 1020	15.95
Stainless clad steel rod	14.72
Zing-coated steel rod	28.96
Stainless steel 304	30.05

To convert the conductor size from kcmil to mm^2 equation (4) is used [27]:

$$A_{mm^2} = \frac{A_{kcmil} \cdot 1000}{1973.52} \qquad (4)$$

The initial estimation of conductor spacing and ground rod locations should be based on the current, I_G and the area being grounded. Total resistance of a system consisting of a combination of horizontal grid and vertical rods electrodes can be obtained by equation (5) [27]

$$R_g = \frac{R_i R_j - R_{ij}^2}{R_i + R_j - 2R_{ij}} \qquad (5)$$

Where: R_g is the substation grounding resistance with respect to remote earth in ohms, R_i is the earth resistance of the grid conductors in ohms, R_{ij} is the earth resistance of the grounding electrodes in ohms, and R_{12} is the mutual earth resistance between the grid conductors and grounding electrodes in ohms. Schwarz used a method contains series of equations that are more accurate in calculating the earthing system resistance as follows [27]:

$$R_i = \frac{\rho}{\pi . L_c}\left[ln\left(\frac{2L_c}{a}\right) + \frac{K_1 L_c}{\sqrt{A}} - K_2\right] \qquad (6)$$

$$R_j = \frac{\rho_a}{2\pi n_r L_r}\left[ln\left(\frac{8L_r}{d_r}\right) - 1 + \frac{2K_1 L_r}{\sqrt{A}}(\sqrt{n_r} - 1)^2\right] \qquad (7)$$

$$R_{ij} = \frac{\rho_a}{\pi L_c}\left[ln\left(\frac{2L_c}{L_r}\right) + \frac{K_1 L_c}{\sqrt{A}} - K_2 + 1\right] \qquad (8)$$

Where: $a = \sqrt{hd_c}$ for grid conductors buried at depth h, in meters , ρ is the soil resistivity (Ω .m), L_c is the total length of buried grid conductors (m), A is the area occupied by grounding grid (m^2), L_r is the length of each grounding rod (m), n_r is the number of grounding rods in area A, K_1 and $K_2$are constant coefficients depending on the geometry of the grid, d_c is the diameter of grid conductor in (m) and d_r is the diameter of ground rods in (m) and ρ_a is the apparent soil resistivity (Ω .m) for double layer soil that can be calculated according to IEEE 80 using equation (9) [27-28].

$$\rho_a = L_r(\rho_1 \rho_2)/(\rho_2(H - h) + \rho_1(L_r + h - H)) \qquad (9)$$

ρ_2 *and* $\rho_1$are the resistivities of the lower and upper layers of the soil (Ω.m) respectively, H is the thickness of the upper layer soil (m) and h is the grid laying depth (m). The grid current can be expressed as [27-28].

$$I_g = I_f . S_f \qquad (10)$$

Where: I_f is the rms symmetrical fault current (A), I_g is the rms symmetrical grid current (A), and S_f is the fault current division factor.

To achieve the safety by using the grounding grids, the maximum tolerable limits for touch and step voltages that do not lead to lethal shocks can be calculated according to IEEE [27, 28]. The preliminary design should include a conductor loop surrounding the entire grounded area, plus adequate cross conductors to provide convenient access for equipment grounds, etc. The calculation of the mesh and step voltages for the grid as designed can be done by the approximate analysis techniques for uniform soil, or by the more accurate computer analysis techniques in non-uniform soil. Mesh voltage is the basis for designing a safe grounding system, both inside the substation and immediately outside. In order to the grounding system to be safe, the mesh voltage has to be less than the tolerable touch voltage. The mesh voltage can be calculated as [27-28].

$$E_m = \frac{\rho_s K_m K_i I_G}{L_M} \qquad (11)$$

Where: L_M is the effective burial length (m), K_m is the geometric spacing factor and K_i is the irregularity factor as given in IEEE 80 [27-32].

For the ground system to be safe, the step voltage has to be less than the tolerable step voltage. The step voltage can be calculated as:

$$E_s = \frac{\rho_s K_s K_i I_G}{L_s} \qquad (12)$$

Where: L_s is the buried conductor length (m) and K_s is the geometric spacing factor

If either the step or touch tolerable limits are exceeded, revision of the grid design is required. These revisions may include smaller conductor spacing and or additional ground rods.

After satisfying the step and touch voltage requirements, the final design should also be reviewed to eliminate hazards due to transferred potential and hazards associated with special areas of concern.

4 APPLICATIONS ON GROUNDING GRIDS

IEEE 80 standard [27-28] square 70m×70m and rectangular 144m × 120 m galvanized steel conductor grids are considered to be investigated, grid laying depth, h=0.5 m, 20 grounding rods each one 3.05 m long, are installed on the corners and perimeter of the grid, crushed rock surfacing layer of 0.1 m (4 inches) with resistivity of 2500 Ω.m, non-uniform soil is considered, thickness of the upper layer soil is taken as 2 m. The pH values versus the soil characteristics are given in table 3 [6] Aeration quantities are considered < 3% and the moisture content of the soil in the range of 10 % at high resistivity and 30% at low resistivity. The grid current is taken 11.946 kA at X/R ratio=10. Safety/growth factor of 20% and the decrement factor = 1.2026 are considered.

TABLE 3
pH values and **corrosion [6]**

Soil Characteristics	pH Values	Corrosion Rate
Extremely Acid	Below 4.5	Highest corrosion
Very Strongly Acid	4.5 - 5.0	
Strongly Acid	5.1 – 5.5	
Medium Acid	5.6 – 6.0	
Slightly Acid	6.1 – 6.5	
Mildly Alkaline	7.4 – 7.8	
Moderately Alkaline	7.9 – 8.4	

Strongly Alkaline	8.5 – 9.0	
Very Strongly Alkaline	9.1-higher	Higher Corrosion
Neutral	6.6 – 7.3	Least Corrosion

4.1 Step Voltage, Mesh Voltage and GPR

Design parameters of galvanized steel grounding system at different values of upper and lower resistivities ρ_1 and ρ_2 as given in table 4. In this table the design parameters of square galvanized steel conductor's grid are presented. Similar parameters in case of rectangular grid galvanized steel conductors are given in table 5, ρ_a is the apparent soil resistivity (Ω .m) for double layer soil **[27-32]** , d_c is the diameter of grid conductor in mm and D_r is the diameter of each ground rod =30 mm , n, is the number of conductors of each side in square grid , n_1 and n_2 are the number of conductors in length and width of rectangular grid galvanized steel, the total number of rods in all cases are 20 rods. The Ground Potential Rise (GPR) can be calculated by relation (14)

$$(\text{GPR}) = I_g \, . R_g \qquad (14)$$

Samples of three dimensions step and mesh voltages of the square and rectangular grids are given in figures 2-a, b, c and d. Figures 3, 4, 5 and 6 show the relations between apparent soils resistivity verses GPR, mesh voltage, E_m and step voltage, E_s.

TABLE 4

Design parameters of square grid galvanized steel conductors, 70m × 70m

ρ_1 (Ω .m)	ρ_2 (Ω .m)	ρ_a (Ω .m)	R_g Ω	d_c mm	n	D_r mm
400	377	370	1.6	12.6	19	30
290	250	239	1.4	12.6	13	30
200	190	187	1.3	12.6	10	30
150	120	113	0.9	12.6	5	30

TABLE 5

Design parameters of rectangular grid galvanized steel conductors, 144m ×120m

ρ_1 (Ω .m)	ρ_2 (Ω . m)	ρ_a (Ω .m)	R_g Ω	d_c mm	n_1	n_2	D_r mm
400	377	370	1.3	12.6	14	12	30
290	250	239	0.9	12.6	8	7	30
200	190	187	0.7	12.6	7	6	30
150	120	113	0.5	12.6	4	3	30

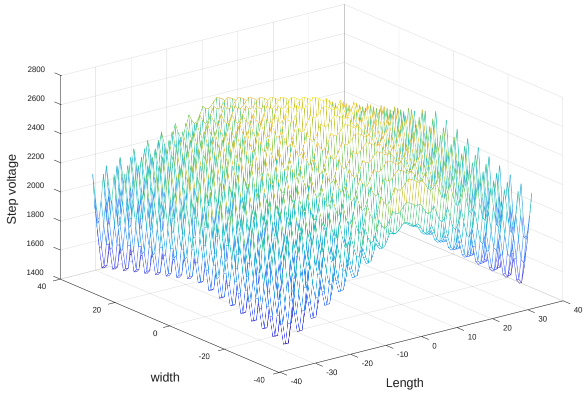

Fig. 2-a Step potential of Square galvanized steel grid, 70m × 70m, ρ_1 (Ω .m) = 400 , ρ_2= 377m (Ω .m) , Laying depth=0.5 m and each grid side grid conductors =19

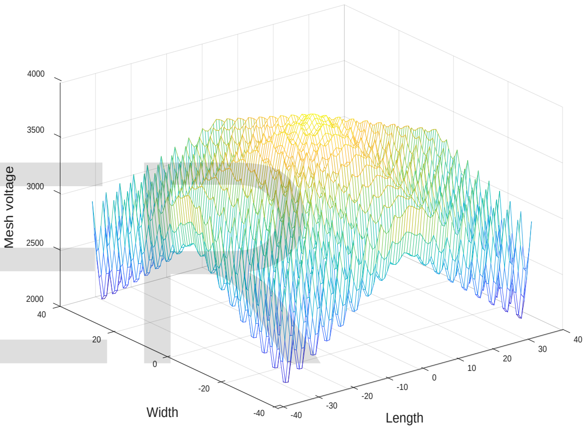

Fig. 2-b mesh potential of Square galvanized steel grid, 70m × 70m, ρ_1 (Ω .m) = 400 , ρ_2= 377 (Ω .m) , Laying depth=0.5 m and each grid side grid conductors =19 conductors

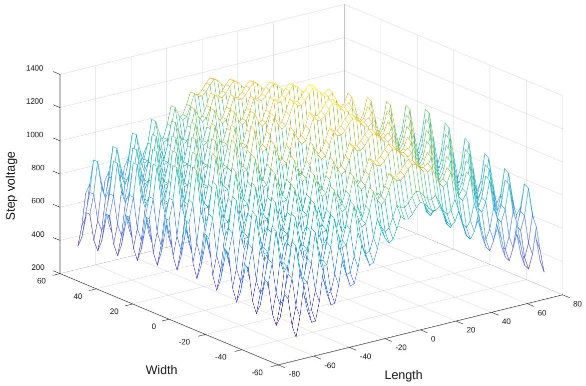

Fig. 2-c Step potential of rectangular galvanized steel grid, 140m × 120m, ρ_1 (Ω .m) = 400 , ρ_2 = 377 (Ω .m), Laying depth=0.5 m , one of the grid sides has 14 conductors and the other has 12 conductors

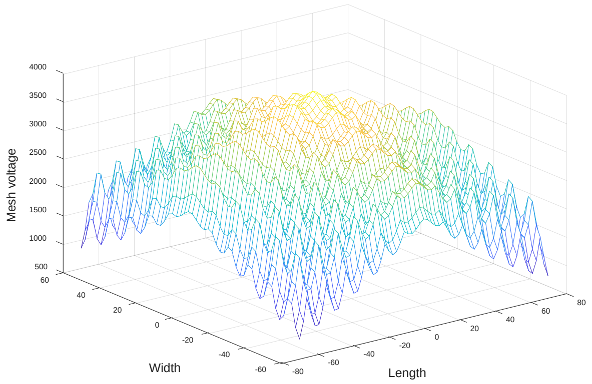

Fig.2-d mesh potential of rectangular galvanized steel grid, 140 m × 120 m, ρ_1 (Ω .m) = 400 , ρ_2 = 377 (Ω .m) , Laying depth=0.5 m , one of the grid sides has 14 conductors and the other has 12 conductors

Therefore, the associated grid conductor diameter as calculated and each rod diameter are increased to equalize the corrosion of conductors in future as shown in tables 6 and 7 for square grid galvanized steel conductor 70m × 70m and rectangular grid galvanized steel conductor 144m × 120m, d_n is grid galvanized steel conductor after compensation and D_r is the galvanized steel rod diameter after compensation. Figure 7shows the relation between the measured soil resistivity and corrosion rate during 12 years for galvanized steel grid

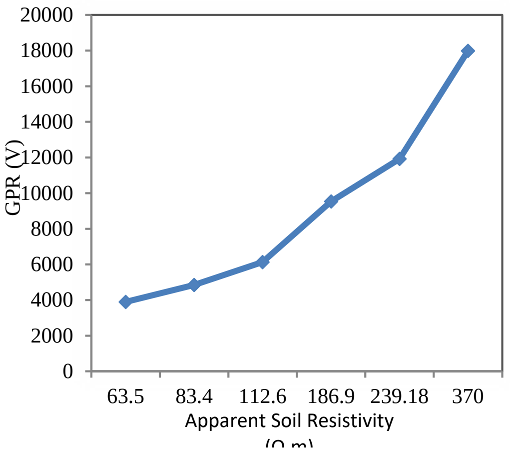

Fig. 3 Relation between apparent soil resistivity and GPR for Square galvanized steel grid, 70m × 70m

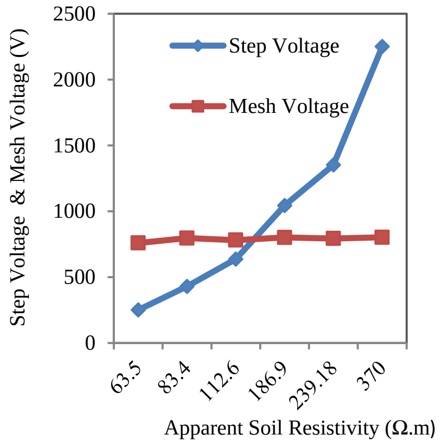

Fig. 4 Relation between apparent soil resistivity, E_m and E_s for Square galvanized steel grid, 70 m × 70 m

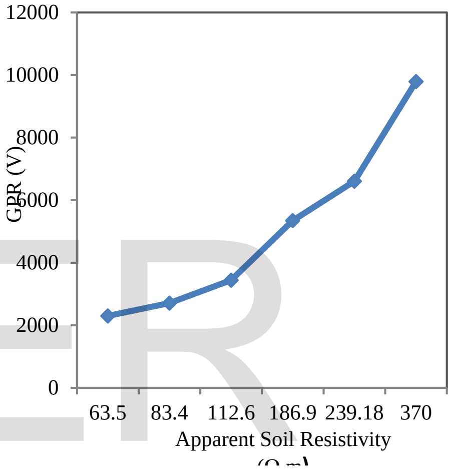

Fig. 5 Relation between apparent soil resistivity and GPR for rectangular galvanized steel grid, 144 m ×120 m.

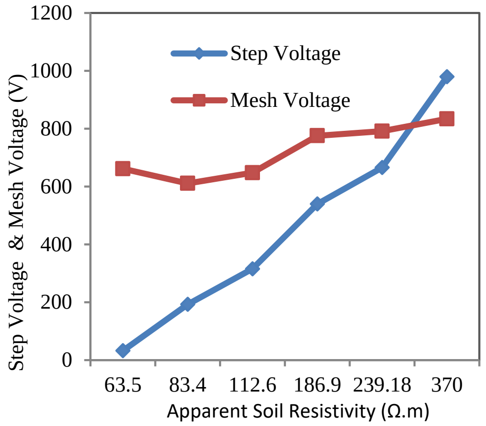

Fig. 6 Relation between apparent soil resistivity, E_m and E_s for rectangular galvanized steel grid, 144 m ×120 m.

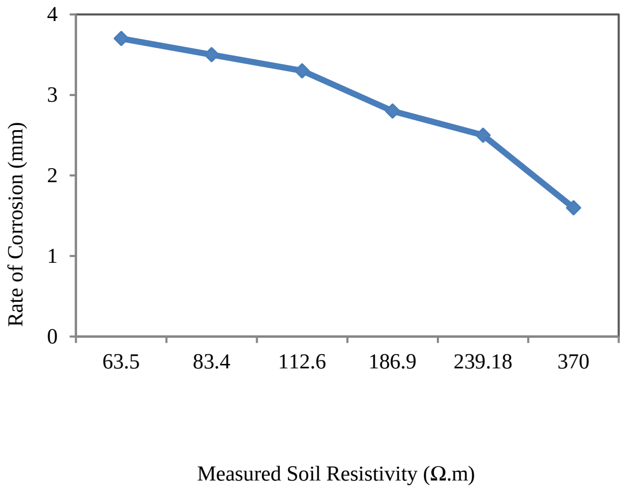

Fig. 7 Relation between measured soil resistivity and corrosion rate during 12 years for galvanized steel grid

TABLE 6

Compensation for square grid galvanized steel conductor 70m × 70m

ρ_1 (Ω.m)	ρ_2 (Ω.m)	ρ_a (Ω.m)	R_g Ω	dc mm	dn mm	n	Dr mm
400	377	370	1.6	12.6	15.4	19	32.8
290	250	239	1.4	12.6	16.2	13	33.6
200	190	187	1.3	12.6	17.6	10	35
150	120	113	0.9	12.6	18.47	5	35.87

TABLE 7

Compensation for rectangular grid galvanized steel conductor 144m × 120m

ρ_1 (Ω.m)	ρ_2 (Ω.m)	ρ_a (Ω.m)	R_g Ω	dc mm	dn mm	n1	n2	Dr mm
400	377	370	1.3	12.6	15.4	14	12	32.8
290	250	239	0.9	12.6	16.2	8	7	33.6
200	190	187	0.7	12.6	17.6	7	6	35
150	120	113	0.5	12.6	18.47	4	3	35.87

4.2 Galvanized Steel Grounding Grid Cost

The cost of Galvanized Steel Grounding Grid (GSGG) depends mainly on the amount of the steel used in construction of the grid .The amounts of galvanized steel required for the design of galvanized steel square and rectangular before and after taking the compensation into account are calculated. The total weight is estimated by Kg using Newton's law as given in equations (15) and (16).

$$M = \rho_a . V \qquad (15)$$

$$V = \frac{\pi}{4} . d_c^2 . L \qquad (16)$$

Where: M is the mass of material (Kg), ρ_d is the density of material (Kg/ m^3), V is the volume of material (m^3), d_c is the conductor rod diameter (m) and L is the conductor rod length (m). By the same way the rods weight can be calculated. The density for the steel is considered 8950(Kg/ m^3). The total estimated weight of square and rectangular galvanized steel grids are given in tables 8 and 9

TABLE 8

Total estimated weight for compensation of square grid galvanized steel conductor 70 m × 70 m

ρ_a (ohm .m)	Grounding grid + ground rods weight before compensation (Kg)	Grounding grid + ground rods weight after compensation (Kg)	% *increase*	R_g Ω
370	3346.37	4885.67	45.9 %	1.6
239	2409.42	3831.67	59.02 %	1.4
187	1940.95	3563.19	83.57 %	1.3
113	1160.17	2218.75	91.25%	0.9

TABLE 9

Total estimated weight for compensation of rectangular grid galvanized steel conductor 144 m × 120 m

ρ_a (ohm .m)	Grounding grid + ground rods weight before compensation (Kg)	Grounding grid + ground rods weight after compensation (Kg)	% *increase*	R_g Ω
370	4234.23	6211.994	46.7 %	1.3
239	2600.81	4148.81	59.52 %	0.9
187	2306.4	4277.09	85.4%	0.7
113	1422.795	2934.3047	100.6 %	0.5

As it is noticed from figure 6 and tables 6,7,8 and 9 the rate of corrosion increses with the decrease of the soil resistivy.To solve this problem an increase in the diameter of grounding steel conductors, as well as grounding rods to compensate the steel volume loss as given in tables 8and 9 is required. As it is observed in these tables the persentage compansated amount of galvanized steel to keep fixed value of grounding resistance and safe grounding system design at 370 ohm .m measured soil resistivity is between 45.9 % and 46.7 % and reached 91.25% to 100.6 % in case of measured soil resistivity 113ohm.m when using square grid galvanized steel conductor 70 m × 70 m and rectangular grid galvanized steel conductor 144m × 120 m respectively .The value of ground grid resistance depends on the amount of steel used in grid construction.

4.3 - Cathodic Protection of Steel Grounding Grids

Cathodic protection may be achieved in either of two ways, sacrificial (or galvanic) anode cathode protection (SACP) and impressed current cathodic protection (ICCP). The main difference between the two methods is that ICCP uses an external power source with inert anodes and SACP uses the naturally occurring electrochemical potential difference between different metallic elements to provide protection.

1 - Sacrificial anode (galvanic) cathodic (SACP) protection system

Anodes are one of four components of the (SACP) system, the others are the cathode, the grid to be protected, the connecting conductor between the anode and cathode and finally the earth electrolyte. The sacrificial anode has negative electrical metal which corrodes and provides current flow to the cathode, producing negative potential to the soil. To design the SACP system the soil resistivity ρ in Ω. m has to be measured and depending on soil resistivity value the anode material will be selected (if $\rho < 200$, Zinc anode is selected and if $\rho > 200$, Magnesium anode is selected). Each anode specification includes anode weight, anode dimensions, and package dimensions (anode plus backfill).In next step net driving potential for anodes (E) volt will be calculated. The number of required anodes needed to meet ground bed resistance limitations is calculated according to the relation **[22]**

$$N = \frac{0.0052.\rho}{R_A.L_b}\left[Ln\frac{8L_b}{d_b}-1\right] \quad (17)$$

R_A is the anode-to-electrolyte resistance, N is the number of anodes, d_b is the diameter of the backfill column in feet (specified by supplier), and L_b is the length of the backfill column in feet (specified by supplier). The number of anodes depending on the anode life time can be calculated using the relation

$$N = \frac{L_f.I}{49.3\times W_a} \quad (18)$$

W_a is the weight of one anode (in pound) and L_f is the expected anode lifetime in years. In the analysis carried out in this paper the expected life of each anode is 39 years.

Usually the selected number of anodes to be used is the greater value calculated by the above two equations. The area to be protected by one anode in square feet can be calculated by the following equation [**22]:**

$$A_a = \frac{A_s}{N} \quad (19)$$

The life-cycle cost for proposed design according to NACE Standard RP-02 can be determined **[12]**. The design process should be done for several different anode choices to find the one with minimal life-cycle cost.

2. Impressed current cathodic protection (ICCP) system

The required current can be obtained according to standard given in table 10. In this method the used anodes are most often made of high silicon chromium-bearing cast-iron (HSCBCI). Table 11 gives (HSCBCI) anode sizes and specifications.

The number of anodes needed to satisfy manufacture's current density limitations can be calculated according to equation.30. Impressed current anodes are supplied with a recommended maximum current density [23].

$$N = \frac{I}{A_1.I_1} \quad (20)$$

A_1 is the anode surface area per square feet per anode; I_1 is the recommended maximum current density output in mA. **The** number of anodes needed to meet design life requirement can be calculated using equation (20) [23].

TABLE 10

Typical current density requirements for cathodic protection of uncoated steel [23-24]

Environment	**Current density (mA/sq.ft)**	
	AFM 88 – 9[23]	**J.S Gerrard[24]**
Neutral soil	0.4 to 1.5	0.4 to 1.5
Well aerated neutral soil	2 to 3	2 to 3
Wet soil	1 t 6	2.5 t 6
Highly acidic soil	3 to 15	5 to 15
Soil supporting active sulfate reducing bacteria	6 to 42	Up to 42
Head soil	3 to 25	5 to 25
Stationary freshwater	1 to 6	5
Moving freshwater	5 to 15	5 to 15
Sea water	3 to 10	5 to 25

TABLE 11
Weights and dimensions of selected circular high silicon chromium bearing cast iron [22].

Anode weight (lb)	Anode dimensions (in.)	Anodes Surface size (in.)
12	1 × 60	1.4
44	2 × 60	2.6
60	2 × 60	2.8
110	3 × 60	4.0

$$N = \frac{L_f . I}{1000\ W_a} \quad (21)$$

W_a is the weight of one anode (in pound), L_f is the expected lifetime in years. The required number of anodes needed to meet maximum anode ground bed resistance requirements can be calculated according to the relation 22 [23].

$$R_a = \frac{\rho . K}{N . L_b} \frac{\rho . P}{S_b} \quad (22)$$

K is the anode shape factor it can be obtained from Table 12,

S_b is the center-to-center spacing between anode backfill columns in feet, L_b is the length of the anode backfill column in feet, (P) is the paralleling factor that can be obtained from Table 13

TABLE 12
Shape function (K) for impressed current cathodic protection anodes where is effective anode length and is anode / backfill diameter [25]

The highest number calculated by equations 20, 21 and 22 will be the number of anodes used.

The rectifier output voltage can be calculated by the relation. [22].

$$V_{rec} = IR_T 150\% \quad (23)$$

Where V_{rec} is the voltage output of rectifier, I is the total protection current in amperes, and R_T is the total circuit resistance. .As with the galvanic cathodic protection system, the choice of anode for the design calculation is arbitrary. When several anodes have been used in the design calculations, an economic analysis should be done as recommended by NACE Standard RP-02.

TABLE 13
Anode paralleling factor (P) of various numbers of anodes (N) installed in parallel [26]

N	P	N	P
2	0.00261	14	0.00168
3	0.00289	16	0.00155
4	0.00283	18	0.00145
5	0.00268	20	0.00135
6	0.00252	22	0.00128
7	0.00237	24	0.00121
8	0.00224	26	0.00168
9	0.00212	28	0.00155
10	0.00201	30	0.00145
12	0.00182	----	0.00135

L/d	K	L/d	K
5	0.0140	20	0.0213
6	0.0150	25	0.0224
7	0.0158	30	0.0234
8	0.0165	35	0.0242
9	0.0171	40	0.0249
10	0.0177	45	0.0255
12	0.0186	50	0.0261
14	0.0194	55	0.0266
16	0.0201	60	0.0270
28	0.0207	20	0.0213

Where, N3 is the number of anodes needed to satisfy manufacture's current density limitations that calculated according to Eqn. (20).

N_4 is the number of required anodes according to proposed life time that calculated according to Eqn. (21).

Measured soil resistivity (Ω.m)	**Grounding resistance Ω**	**Ratio between galvanized steel with compensation and copper (%)**	**Ratio between galvanized steel with compensation and cathodic protection (%)**
370	2.5	43%	87%
239.18	1.6	37%	77%
186.9	1.3	33%	71%
112.6	0.8	26%	59%
83.4	0.6	20%	48%
63.5	0.5	17%	41%

N_5 is the number of required anodes to meet maximum anode ground bed resistance that calculated according to Eqn. (22), and then the largest number of calculated anodes is selected to be the number of used anodes. Tables 14, 15, 16 and 17 show the required number of anodes for cathodic protection per grounding grid. The achieved results of the two techniques of the cathodic protection; are given in Tables 14, 15, 16 and 17 according to the details previously discussed in using magnesium anode for sacrificial anode method and circular high silicone chromium-bearing cast iron for impressed current cathodic protection

Mesuredsoil resistivity (Ω.m)	**Grounding resistance Ω**	**Ratio between galvanized steel with compensation and copper (%)**	**Ratio between galvanized steel with compensation and cathodic protection (%)**
370	2.5	38%	72%
239.18	1.6	52%	98%
186.9	1.3	33%	67%
112.6	0.8	25%	51%
63.5	0.5	-----------	-----------

TABLE 14
Galvanized steel square grid 70m × 70m, (ICCP) results

TABLE 15
Galvanized steel square grid (SACP) result 70m × 70m

TABLE 16
Steel rectangular grid (ICCP) results 144m × 120m

TABLE 17
Steel rectangular grid (SACP) result 144 m × 120 m

TABLE 18
Cost comparison between copper grid and galvanized steel grid with its the two alternatives for square shape

TABLE19
Cost comparison between copper grid and galvanized steel grid with it's the two alternatives for rectangular shape

N_1 is the number of required anodes that calculated according to Eqn. (17).

N_2 is the number of required anodes according to the proposed life time that calculated according to Eqn. (18), and then the largest number of anodes calculated is selected to be the number of used anodes.

Measured soil resistivity, Ω.m	**Grid resistance, Ω**	**I_{req} (mA)**	**Area protected (mm²)**	**N_3**	**N_4**	**N_5**	**G.P.R volt**	**Vrec (V)**
370	2.5	185.9	76.62	9	1	5	17990	3.7
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	20	2.5
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	.7	2.04
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	.1	1.5
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	.3	1.2
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	.2	1.1

Measured soil resistivity	**Grid resistance ,**	**I_{req} (mA)**	**Area protected (mm²)**	**N_1**	**N_2**	**Life time of Mg L_m (year)**	**G.P.R**

Measured soil resistivity	**Grid resistance,**	**I_{req} (mA)**	**Area protected (mm²)**	**N_3**	**N_4**	**N_5**	**G.P.R volt**	**Vrec (V)**
112.6	0.4	63.5	39	4	1	2	3440.2	1.08
83.4	0.3	49.9	46.3	3	1	1	2710	0.9
63.5	0.3	36.3	33.71	2	1	1	2298.8	0.7

Measured soil resistivity, Ω.m	**Grid resistance, Ω**	**I_{req} (mA)**	**Area protected (mm²)**	**N_1**	**N_2**	**Life time of Mg L_m (year)**	**G.P.R volt**
43.5	0.2	108.8	33.7	24	3	18.4	1577
33.6	0.1	48.9	15.17	19	3	14.2	1216.9

The ratios between galvanized steel costs relative to the copper cost for grounding grids having the same grounding resistance and GPR are given in tables 18 and 19 for square and rectangular grids. The ratios between the compensation method and cathodic protection method costs are presented in the same tables. The economic analysis is done as recommended by NACE Standard RP-02 [12]. From these tables it is noticed that galvanized steel grids are more economical compared with copper grids and the use of compensation method in grounding system is also more economical than the use of cathodic protection technique.

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5 Conclusion

From the study carried out in this paper the following conclusions can be obtained:

1- The corrosion rate of the galvanized steel conductor for the grounding system during a period of time (12 years) is considered for the design of safe grounding system.

2- IEEE 2000 is used to carry out this study on galvanized steel conductors for both square and rectangular shape taking into consideration the effect of corrosion.

3- Galvanized steel grounding grid with compensation method is more economical compared to the galvanized steel grounding grid with cathodic protection

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