Multi-Objective Optimization for Safety in the Grounding of AC Substations

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***Abstract*—This work proposes a multi-objective optimization problem for the optimal design of grounding systems, considering personnel safety limits and design guidelines defined in the IEEE Standard Std. 80 - IEEE Guide for Safety in AC Substation Grounding. The initial objective functions proposed include the amount of conductor and the number of ground rods in the grounding grid, ensuring that the mesh voltage (E_m) and step voltage (E_s) do not exceed the tolerable limits for the human body (E_{touch} and E_{step}). The multi-objective problem generates the Pareto front and Parallel Coordinates Plot, providing valuable insights for result analysis, sensitivity analysis, and informed decision-making for grounding system designers. The model is validated using the exercises in Annex B of IEEE Std. 80, demonstrating its ability to deliver a comprehensive analysis of results while considering the full range of feasible solutions for an optimal and safe design of AC substation grounding systems.**

Link to graphical and video abstracts, and to code: https://latamt.ieeer9.org/index.php/transactions/article/view/9549

***Index Terms*—Grounding, Multi-objective Optimization, Sensitivity Analysis, Pareto Front, IEEE80, Substation grounding system.**

I. INTRODUCTION

THE electrical infrastructure grows year by year to meet an ever-increasing electricity demand, which involves the construction of distribution and transmission substations, as well as generation plants, with designs that ensure safety for people under both normal and fault conditions. In this regard, optimal designs are necessary to regulate touch and step voltages, ensuring a safe environment for individuals in the substation area. The design engineer has limited options to modify the design in order to keep touch and step voltages, including Ground Potential Rise (GPR), within safe and acceptable limits in the substation.

Researchers have implemented optimization algorithms over the years to achieve the optimal design of grounding systems, taking into account the constraints posed by hazardous potentials that affect human safety. [1], [2].

A comprehensive bibliographic review was conducted to examine significant works on the design of grounding systems using optimization algorithms, spanning from their initial developments to the most recent advancements. The key contributions from this review are summarized in Table I.

In [1], Sverak (1976) proposes a uniformly spaced grounding grid, highlighting issues of overdesign at the center and underdesign at the perimeter. To improve accuracy, he refines the 1961 IEEE Std. 80 method [19], enabling recursive point-by-point integration of surface gradients, and uses a computer program to assess the influence of grid spacing.

Later, in [3], Sverak (1984) builds upon the 1976 edition of IEEE Std. 80 [20], analyzing simplified equations for touch and step voltages, especially at grid corners. He introduces an improved expression for the mesh spacing factor K_m, evaluates the effect of ground rods on K_i, and considers surface materials such as crushed stone. His studies include comparisons with models by other authors, contributing to updates in the IEEE guide.

In Part II [4], he formulates a dual optimization problem considering safety constraints. Subsequently, in [2], a computer-based tool is developed to optimize grid configurations using combinations of horizontal and vertical electrodes.

The third edition, IEEE Std. 80-1986, introduced significant revisions since the original 1961 version, including redefined simplified equations for touch and step voltage calculations and updated safety criteria [21]. In [22], the importance of considering internal impedance in large grounding systems was highlighted, showing that transferred network potentials can generate hazardous contact voltages elsewhere. The fourth edition, IEEE Std. 80-2000, further expanded the equations to accommodate "L"- and "T"-shaped grids, revised derating factor curves for surface materials, and updated conductor selection criteria. It also incorporated discussions on multi-layer soil models and included new equations for resistance calculation [23].

In [5], the authors apply electromagnetic field theory and circuit analysis, using genetic algorithms to optimize the grounding grid design under the touch voltage limit established in IEEE Std. 80-2000. The fifth and most recent edition of IEEE Std. 80, released in 2013, incorporates TCAP calculations for bimetallic electrodes and introduces benchmarks that compare IEEE equations with commercial software, highlighting both their strengths and limitations [24].

Subsequent works, such as [6], [25], employ genetic algorithms to optimize grounding systems considering both safety and cost, as applied to the Ain El-Melh substation. Their models include variables like the number and length of conductors and rods, and total mesh area, with results compared to CYMGrd software.

Similarly, in [7], three metaheuristic techniques—PSO,

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TABLE I
REVIEW OF WORKS ON OPTIMIZATION OF GROUNDING SYSTEM DESIGNS

Reviewed Aspects		Reviewed Works																	
		[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]	[10]	[11]	[12]	[13]	[14]	[15]	[16]	[17], [18]	P*
Variables considered in the optimization	Resistance (Rg)										✓				✓	✓	✓	✓	✓
	Touch and step potentials (Em and Es)				✓	✓						✓			✓	✓	✓	✓	✓
	Ground Potential Rise (GPR)											✓			✓	✓	✓		✓
	Cost minimization						✓	✓		✓		✓		✓	✓			✓	
	Mesh depth						✓	✓								✓	✓		
	Geometric spaces	✓		✓			✓	✓					✓		✓			✓	✓
	Vertical rods				✓		✓	✓					✓		✓	✓	✓	✓	✓
	Horizontal electrodes				✓		✓	✓					✓		✓	✓	✓	✓	✓
	Optimizes the overall design	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓
Algorithms	Particle swarm optimization (PSO)						✓	✓								✓			
	Genetic Algorithm					✓		✓	✓					✓		✓			✓
	Hybrid particle swarm genetic algorithm optimization							✓											
	Recognition and re-modeling patterns				✓														
	Pattern Search (PS)													✓					
	Evolutionary optimization																✓		
	Co-simulation																✓		
	Multi-objective optimization														✓	✓	✓	✓	✓
Relevant applied methodologies	Sverak's method	✓									✓	✓	✓			✓			✓
	Schwarz's equations															✓			
	IEEE Std. 80	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓			✓
	Finite elements (FEM)										✓	✓				✓			
	Maxwell imaging																	✓	
	Charge Simulation Method (CSM)											✓							
Software used	ETAP										✓	✓				✓			✓
	CYMGrd						✓	✓											
	MATLAB								✓	✓			✓	✓	✓			✓	✓
	WinIGS													✓					
	Python																✓		
	Others	✓	✓	✓	✓	✓	✓	✓	✓							✓	✓	✓	

P*: Proposed methodology.

GAO, and HPSGAO—are used to design an optimal and safe grounding system for the Labreg power plant, minimizing costs related to materials, excavation, and coating while satisfying IEEE Std. 80-2000 safety criteria. The HPSGAO approach outperforms the others, and results are benchmarked against CYMGrd [26].

In [8], the authors propose a three-step optimization method for designing grounding grids with regular geometries (square, rectangular, L-shaped) under a two-layer soil model. If the initial solution is not globally optimal, genetic algorithms and pattern search are applied. The objective is to minimize conductor and rod usage while meeting safety constraints.

In [9], a MATLAB-based graphical tool is developed to optimize grounding systems, focusing on cost minimization and compliance with IEEE Std. 80.

In [11], the Charge Simulation Method (CSM) is used to calculate surface potential, and an optimization problem is formulated to minimize grounding resistance and cost, ensuring limits for touch, step, and GPR voltages.

Filipe et al. [12] present a method that reduces conductor material while satisfying safety requirements, combining Sverak's variable spacing technique with optimized rod placement.

Zhang et al. [13] develop a MATLAB software package using a hybrid optimization method (genetic algorithm + pattern search) for grounding design. Results are benchmarked against WinIGS [27].

In [10], the authors use ETAP software to optimize the grounding system design, considering human safety.

Certain commercial software such as [28] allows for the optimization of conductors and/or rods in substation grounding system designs, but it does not provide the efficient Pareto front for the grounding system design.

In [14], the authors optimize the design of a grounding system using Multi-Objective Particle Swarm Optimization (MOPSO) and the IEEE Std. 80 standard. Feasible solutions are obtained based on the optimization problem, which includes four objective functions.

The authors in [15] optimize the grounding system by applying the IEEE Std. 80 methodology, a fuzzy algorithm on the genetic algorithm, the Bees algorithm, Schwarz's equation, and multi-objective optimization. The Pareto frontier is generated with two objective functions: grid depth and the number of rods, considering that the performance of the grounding system improves as these variables increase.

The authors in [17], [18] apply multi-objective techniques using NSGA-II and Elite algorithms. A comparison is performed between the results obtained using the NSGA-II algorithm and those obtained through semi-optimization. However, the authors do not present the Pareto frontier in their results.

In [16], the authors apply co-simulation, the Finite Element Method (FEM), and both single-objective and multi-objective optimization. They generate the Pareto frontier for the objective functions: Rg, LC and E_s.

There are few studies utilizing multi-objective techniques, and only one work that employs the Pareto frontier ([16]), which uses the Finite Element Method (FEM) and does not apply the IEEE Std. 80 methodology. Therefore, this work proposes a multi-objective problem to obtain the Pareto front with feasible optimal points in the design, based on the formulation of the fifth edition of the IEEE Std. 80-2013, IEEE Guide for Safety in AC Substation Grounding, and it is applied to the examples provided in Annex B of the mentioned standard. Additionally, considering that the design of a ground grid with rods and conductors may be oversized, leading to cost overruns due to excess material in the grounding system, it is necessary to apply robust algorithms that take design safety limits into account. To address these issues,

The structure of the article is as follows: Section II outlines the design principles of the IEEE Std. 80 grounding system, which are considered in the formulation of the multi-objective optimization problem. In Section III, the multi-objective problem for designing grounding systems is formulated. In Section IV, the case study and results analysis are presented, showing the performance of the multi-objective optimization problem based on simulations conducted on the example from Annex B of IEEE Std. 80-2013. In Section V, the limitations of the proposed methodology are detailed, and relevant topics are discussed. Finally, the conclusions are presented in Section Section VI.

The nomenclature used in the formulation of this article is detailed in Table II.

TABLE II
NOMENCLATURE

Symbol	Description
A	Total surface area of the ground grid, m^2
L_C	Overall length of the grid conductor, m
L_M	Effective length of $L_C + L_R$ for mesh voltage, m
L_R	Total length of the ground rods, m
L_r	Length of each individual ground rod, m
L_x	Maximum length of the grid conductor along the x axis, m
L_y	Maximum length of the grid conductors along the y axis, m
L_P	Perimeter length of the grid, m
D_x	Distance between parallel conductors in the x direction, m
D_y	Distance between parallel conductors in the y direction, m
I_G	Maximum current between the ground grid and surrounding soil (including DC offset), A
R_g	Grounding system resistance, Ω
GPR	Ground Potential Rise ($GPR = I_G R_g$)
E_m	Mesh voltage, V
E_s	Step voltage, V
K_i	Grid geometry correction factor, simplified method
K_{ii}	Weighting factor for the impact of inner conductors on the corner mesh, simplified method
K_h	Weighting factor that accounts for the effects of grid depth, simplified method
K_m	Mesh voltage spacing factor, simplified method
K_s	Step voltage spacing factor, simplified method
t_f	Duration of the fault, in seconds s
t_s	Duration of the shock current, in seconds s
$TCAP$	Thermal capacity per unit volume, in $J/(cm^3\ ^\circ C)$
ρ	Soil resistivity, $\Omega \cdot m$
ρ_s	Surface layer resistivity, $\Omega \cdot m$
h	Depth of the ground grid conductors, m
h_s	Thickness of the surface layer, m
d	Diameter of the grid conductor, m
C_s	Derating factor for the surface layer
E_{step}	Maximum tolerable step voltage for humans, V
E_{touch}	Maximum tolerable touch voltage for humans, V
n_R	Number of rods placed in the area

II. GROUND GRID DESIGN

There are several methodologies for the design of grounding systems. Among the most widely used approaches are the following [29]:

a) Calculation of grounding parameters using analytical equations (IEEE Std. 80),

b) Finite Element Method (FEM) for complex soil structures.

This article adopts the methodology based on the analytical equations of IEEE Std. 80. Accordingly, this section outlines the procedure and mathematical formulation used in the multi-objective optimization problem for the optimal design of grounding systems within the IEEE Std. 80 framework.

A. Methodology for Optimal Design of Grounding System

The IEEE Std. 80 standard outlines a 12-step process for the comprehensive design of a grounding grid in alternating current (AC) substations [24]. However, this study focuses specifically on the optimal grid design, addressing factors such as conductor length, the number of rods, grounding resistance, grid configuration, and design safety limits. Therefore, the steps considered in this research are summarized in Table III.

TABLE III
METHODOLOGY

Step	Description
Step 1	Field Data $t_f, \rho, \rho_s, h_s, h, L_x, L_y, L_r$ $A \leftarrow L_x L_y$
Step 2	Touch and Step Criteria $C_s \leftarrow (\rho, \rho_s, h_s)$ $E_{step}, E_{touch} \leftarrow (C_s, \rho_s, t_s)$
Step 3	Limits of Problem Variables $lb \leq x \leq ub$
Step 4	Initial conditions of the variables ($x0$)
Step 5	Set optimization problem constraints 1. Conductor length 2. Overall length in rods 3. Resistance Rg 4. Ground Potencial Rise (GPR) 5. Mesh Voltage (E_m) 6. Step Voltage (E_s)
Step 6	Multi-Objective optimization problem - Define number of variables of the Objective function - Define limits: lower and upper of the Pareto frontier - Problem Tuning
Step 7	Analyze results: feasible solutions on the Pareto frontier.

B. Formulation of Grounding System Design

The input data is defined in Step 1. Using L_x and L_y, the land area is calculated as shown in Eq. (1) [24]. The touch and step voltage criteria, corresponding to Step 2, are computed using Eqs. (2), (3), and (4). In these equations, ρ denotes the soil resistivity, ρ_s is the surface layer resistivity, h_s represents the thickness of the surface layer, C_s is the derating factor for the surface layer, and t_s is the duration of the shock current. These calculations consider $k = 0.116$ for a 50 kg person and $k = 0.157$ for a 70 kg person.

$$A = L_x \cdot L_y \tag{1}$$

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

$$E_{step} = (1000 + 6 \cdot C_s \cdot \rho_s)\,\frac{k}{\sqrt{t_s}} \tag{3}$$

$$E_{touch} = (1000 + 1.5 \cdot C_s \cdot \rho_s)\,\frac{k}{\sqrt{t_s}} \tag{4}$$

The Ground Potential Rise (GPR) is determined using Eq. (5), which depends on I_G (the maximum current flowing from the ground grid to the surrounding soil) and the resistance R_g [24].

$$GPR = I_G \cdot R_g \tag{5}$$

Eq. (7) determines the effective buried length, taking into account that the mesh incorporates rods distributed across the area, perimeter, and corners, along with the total rod length and the conductor length L_C [24]. The total length of the ground rods is calculated using Eq. (6), based on the number of rods n_R and the length of each rod L_r.

$$L_R = L_r \cdot n_R \tag{6}$$

$$L_M = L_C + \left[1.55 + 1.22\left(\frac{L_r}{\sqrt{L_x^2 + L_y^2}}\right)\right] L_R \tag{7}$$

For grids without ground rods, or with only a few rods randomly distributed and none located at the corners or along the perimeter, the effective buried length L_M is given by Eq. (8) [24].

$$L_M = L_C + L_R \tag{8}$$

The determination of the maximum step and mesh voltages is presented in Eq. (9) and Eq. (10) [24].

$$E_m = \frac{\rho \cdot I_G \cdot K_m \cdot K_i}{L_M} \tag{9}$$

$$E_s = \frac{\rho \cdot I_G \cdot K_S \cdot K_i}{0.75 \cdot L_C + 0.85 \cdot L_R} \tag{10}$$

The calculation of the constants K_m, K_S, K_i, and further details on ground grid design can be found in IEEE Std. 80 [24].

III. PROPOSED OPTIMIZATION PROBLEM

The proposed problem identifies the Pareto frontier using the *Multi-objective Genetic Algorithm* solver available in MATLAB Software, which implements the *Elitist Genetic Algorithm*, a variation of the *NSGA-II.* This algorithm is designed to find a set of non-dominated solutions (solutions that are not outperformed by any other point) that adhere to the specified constraints, following the principle of Pareto optimality, for F.O.1, F.O.2, or additional objectives [30], [31]. In the proposed methodology, the Pareto frontier and the parallel coordinate plots, applying multi-objective optimization, to obtain all feasible solutions of the grounding system design subject to technical and safety constraints.

The multi-objective optimization problem is composed of the following functions: objective function 1, which consists of the conductor length. Objective function 2 is composed of the number of rods (Eq. (11)).

Multi-Objective Function:

$$\begin{cases} F.O.\,1: \; min \; L_C, \\ F.O.\,2: \; min \; n_R \end{cases} \tag{11}$$

Subject to:

Conductor length and Rods restrictions:

$$L_C = \left(\frac{L_x}{D_x} + 1\right) \cdot L_y + \left(\frac{L_y}{D_y} + 1\right) \cdot L_x \tag{12}$$

$$L_C^{min} \leq L_C \leq L_C^{max} \tag{13}$$

$$L_C^{min} = 2 \cdot (L_x + L_y) \tag{14}$$

$$D_x - D_y = 0 \tag{15}$$

$$0 \leq D_x \leq L_x \tag{16}$$

$$0 \leq D_y \leq L_y \tag{17}$$

$$0 \leq n_R \leq n_R^{max} \tag{18}$$

Restrictions for resistance calculation:

$$R_g = \rho\left[\frac{1}{L_T} + \frac{1}{\sqrt{20A}}\left(1 + \frac{1}{1 + h\sqrt{20/A}}\right)\right] \tag{19}$$

$$0 \leq R_g \leq R_g^{max} \tag{20}$$

Inequality Constraints for GPR:

$$GPR < E_{touch} \tag{21}$$

$$0 \leq GPR \tag{22}$$

Inequality constraints for maximum step and mesh voltages:

$$E_m \leq E_{touch} \tag{23}$$

$$E_s \leq E_{step} \tag{24}$$

The Eq. (12) calculates the conductor length based on Eq. (13), (14), (15), (16), and (17). The minimum conductor length L_C^{min} is determined by the perimeter of the grounding grid, in Eq. (14). The spacing between conductors on the "x" and "y" axes of the grid is defined by Equations (16) and (17), considering maximum spacings as the lengths L_x and L_y of the grid. In Eq. (15), it is assumed that the conductor spacings D_x and D_y are equal, when such symmetry is required by the design. Otherwise, this constraint can be removed.

The resistance of the grounding system is determined using Eq. (19), considering the constraint defined in Eq. (20), where L_T is the total effective length of the grounding system conductors, including both the grid and the ground rods; A is the area of the grid; and h is the burial depth of the grid conductors.

In Eq. (21), the first condition to verify is whether the GPR is lower than E_{touch}. If this condition is satisfied, the design is considered safe. Otherwise, it is necessary to evaluate the constraints given by Eqs. (23) and (24), where E_s is the step voltage, E_m is the mesh voltage, and E_{touch} and E_{step} represent the maximum tolerable touch and step voltages for humans, respectively. These equations define the safety constraints for human exposure to touch and step potentials.

IV. GROUNDING SYSTEM SIMULATION

A. Case Study

The proposed multi-objective optimization model is evaluated using a case study based on Example B.2 of IEEE Std. 80, with the input data presented in Table IV [24]:

TABLE IV
DATA FROM EXAMPLE B2. IEEE STD. 80

Description	Unids	Value
L_x	(m)	70
L_y	(m)	70
L_r	(m)	7.5
ρ	$(\Omega \cdot m)$	400
ρ_s	$(\Omega \cdot m)$	2500
h	(m)	0.5
h_s	(m)	0.102
h_0	(m)	1
t_f	(s)	0.5
d	(mm)	0.0105
I_G	(A)	1908
n_b, n_c, n_d	-	1
K_{ii}	-	1

$Kii = 1$ Applies to grids that include ground rods positioned along the perimeter or located at the corners of the grid.

B. Results and Analysis

1) Multi-objective: Conductor length - Number of rods: Fig. 1 shows the Pareto frontier with the optimal quantities of conductors and rods in the design, subject to the constraints of the optimization problem.

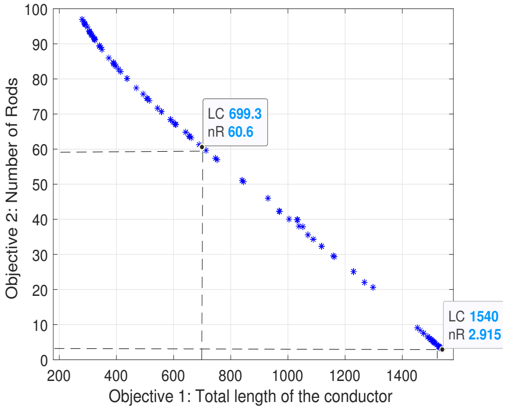


Fig. 1. Pareto Front: Conductor Length vs. Number Rods.

The points shown correspond to all the optimal solutions for conductor quantity (X-axis) and rods (Y-axis) of the mesh, considering the design safety constraints set in the optimization problem according to the IEEE Std. 80 standard.

TABLE V
OPTIMIZATION WITH ETAP SOFTWARE

Scenario	Material cost conditions for L_C and n_R	Results of the ETAP	
		n_R (#)	L_C (m)
1	Cheap rods and expensive conductor	59	700
2	Expensive rods and cheap conductor	4	1540

The results obtained in example B.2 of the IEEE Std. 80 (1540 m of conductor and 20 rods) do not represent an optimal design, as these quantities from example B.2 do not belong to the Pareto frontier.

A simulation was performed using the ETAP software optimizer [28], and the results are shown in Table V. The rod and conductor quantities obtained from the ETAP optimizer lie on the Pareto frontier depicted in Fig. 1, indicating that the solutions are optimal. However, the ETAP software provides only two feasible solutions based on the costs of the conductor and rods. In contrast, the proposed method generates a complete Pareto frontier that encompasses all feasible solutions, regardless of material costs, while adhering to the safety constraints for substation personnel. This approach enables designers to select the most suitable optimal solution for their specific requirements.

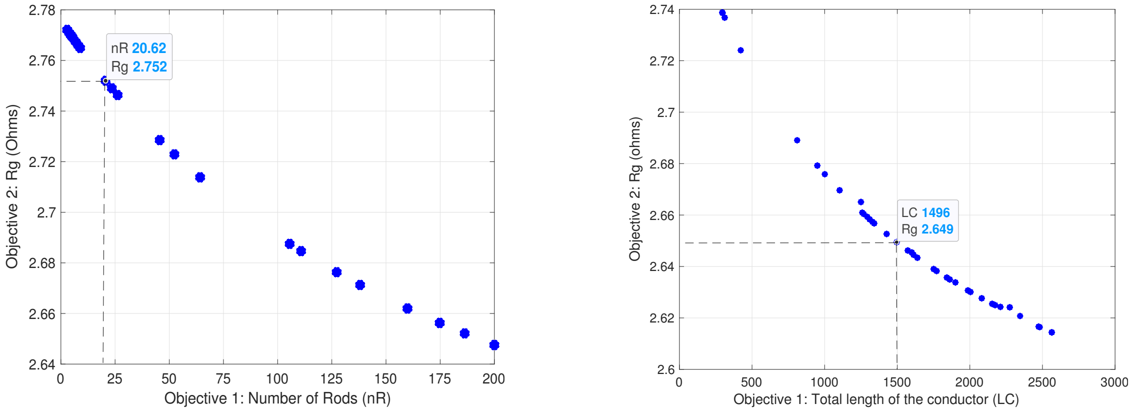
2) Multi-objective: Number of rods and conductors vs. resistance: In this analysis, objective function 1 is the grounding resistance (R_g), while objective function 2 is the number of rods. In addition, the quantity of conductor in the mesh is also simulated. The Pareto frontier shown in Fig. 2a and Fig. 2b illustrates the sensitivity of R_g with respect to the number of rods and the amount of installed conductor. The sensitivity of the grounding system resistance to the inclusion of rods and/or conductors is minimal. That is, even with the addition of multiple rods and conductors, the resistance of the grounding mesh does not exhibit a significant improvement. The resistance range varies between 2.6 Ω and 2.78 Ω. In this case study, these results indicate to grounding system designers that increasing the number of rods and the amount of conductor is not a viable approach to reducing the grounding resistance (R_g). Instead, they should explore alternative design strategies to achieve a lower R_g, while maintaining compliance with personnel safety constraints.

C. Multi-objective Ground Grid Optimization with Multiple Objective Functions

In this case study, three and four objective functions are proposed to analyze the sensitivity between these variables.

1) Simulation 1.- Objective functions: L_C, n_R and R_g: To the objective function in Eq. 11, an additional objective function is added with the variable R_g, linked to the constraint Eq. 19, to determine the entire range of solutions of R_g, depending on the amount of conductor and rods. The three objective functions are shown in Eq. (25).

$$Multi-Objective\ Function: \begin{cases} F.O.\,1:\ min\ L_C, \\ F.O.\,2:\ min\ n_R, \\ F.O.\,3:\ min\ R_g \end{cases} \quad (25)$$



(a) (b)

Fig. 2. Pareto Front (a) Number of Rods Vs. Resistance Rg (b) conductor length Vs. Resistance Rg.

In Fig. 3, the parallel coordinate plot is shown, which allows us to visualize in a different way the sensitivity of resistance R_g versus materials L_C and n_R. Each line color represents a feasible solution. This parallel coordinates plot complements the analysis of results obtained in Fig. 2a and 2b.

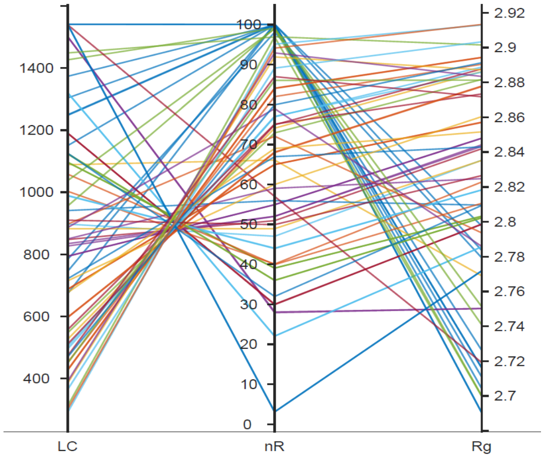


Fig. 3. Parallel Coordinates Plot: L_C, Rods n_R Vs. Resistance R_g.

2) Simulation 2.- Objective functions: L_C, n_R, Em and Es: In addition to the objective function presented in Eq. 11, two additional objective functions are introduced that incorporate the variables E_m and E_s, as defined in Eqs. 9 and 10, respectively. These functions are subject to the constraints specified in Eqs. 23 and 24 to ensure that the tolerable limits for personnel in the substation are not exceeded. This extended formulation enables the determination of the entire range of solutions, while facilitating a sensitivity analysis based on the amount of conductor and the number of rods. The four variables considered in the objective functions are L_C, n_R, E_m and E_s.

Using the parallel coordinates plot in Fig. 4, the sensitivity between conductor length, number of rods, and their effects on the mesh voltage (E_m) and the step voltage (E_s) can be analyzed. The variable L_C ranges from 280 m to 1540 m, while the number of rods (n_R) varies between 17 and 100, resulting in values E_m ranging from 477 V to 840 V and E_s values between 280 V and 518 V. For example, with 1540 m of conductor and 100 rods, the mesh voltage E_m is 478 V, and the step voltage E_s is 392 V. All lines in the parallel coordinates plot represent feasible solutions within the Pareto optimal set, considering the safety constraints for the substation personnel. It can be observed that there are no feasible solutions when small quantities of conductors and rods are combined. In other words, feasible solutions require a complementary balance between the quantities of conductor and rods. Both quantities cannot be low simultaneously, as insufficient material fails to control the potentials generated below the ground. Furthermore, it can be observed that large quantities of rods can effectively control and reduce the values of E_m.

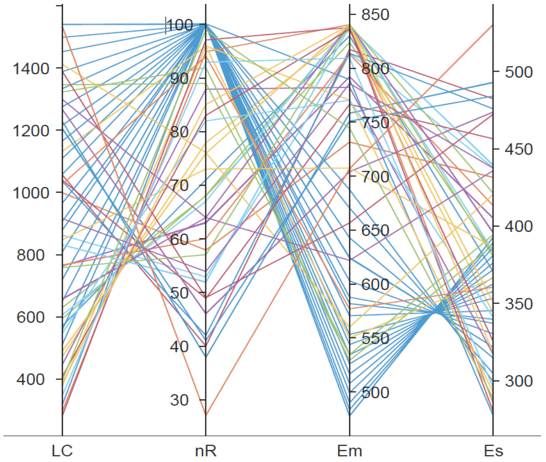


Fig. 4. Conductor length L_C, Rods n_R, Mesh voltage E_m and Step voltage E_s.

3) Simulation 3.- Objective functions: ρ, R_g, E_m and E_s: The objective functions are defined using ρ, R_g, E_m, and E_s to analyze the sensitivity of all feasible solutions of R_g, E_m, and E_s with respect to ρ within a range of 40 Ω·m to 800 Ω·m for the ground, while adhering to the safety constraints for substation personnel as specified in Eqs. (23) and (24).

In Fig. 5, the parallel coordinate plot displays the entire range of solutions. The resistance to grounding R_g is directly proportional to the resistivity of the soil ρ, as described by Eq. (19). Similarly, the calculations of the mesh voltage E_m and the step voltage E_s are also directly proportional to ρ, according to Eqs. (9) and (10). This direct relationship with ρ results in parallel lines in the plot, highlighting the critical importance of maintaining low soil resistivity in a grounding grid. Alternatively, a soil conditioner could be applied to reduce ρ, thereby enhancing the performance of the grid.

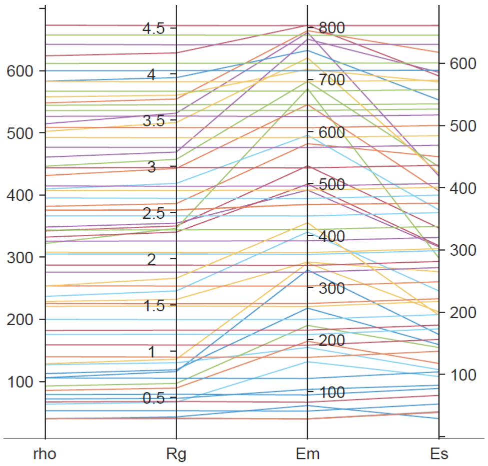


Fig. 5. Soil resistivity ρ, Grounding system resistance R_g, Mesh voltage E_m and Step voltage E_s.

V. DISCUSSION AND LIMITATIONS

A. Discussion

1) Simulation variables and sensitivity analysis: The variables R_g, E_m and E_s were selected for sensitivity analysis because they represent the outcomes of the substation grounding system design. The input parameters for the calculations are the soil resistivity ρ, the conductor length L_C, and the number of rods n_R. In the design process, L_C and n_R are initially assigned random values. Therefore, it is essential to have a computational tool that can determine the full range of solutions, subject to the constraints of the problem. Without a computational tool, one might propose rod quantities and conductor lengths that satisfy the design's safety requirements, but they may not necessarily utilize the optimal amounts of materials.

2) ETAP software results: The proposed methodology, using the Pareto frontier and parallel coordinates plots, delivers all optimal solutions while satisfying both technical constraints and personnel safety requirements. In contrast, the ETAP software provides two discrete solutions that are technically and economically optimal and lie on the Pareto frontier; however, it does not allow for a comprehensive graphical analysis of the sensitivity to the input variables of the problem, as is possible with the proposed approach.

B. Limitations

The proposed methodology is applicable exclusively to uniform grounding grids designed using the analytical equations provided in IEEE Std. 80, such as those developed by Sverak. These equations assume homogeneous soil conditions and are not suitable for implementations based on the Finite Element Method (FEM) or other numerical approaches.

While commercial software such as ETAP and CYMGRD allows for two-layer soil modeling using FEM or extended analytical models, the methodology presented in this paper is limited to homogeneous soils, in line with the assumptions of IEEE Std. 80.

Additionally, the model supports different grounding grid geometries (e.g., square, rectangular, T-shaped, L-shaped) under symmetric layout assumptions. As future work, this multi-objective optimization approach could be extended to support stratified soil conditions, through FEM-based simulation or adapted analytical formulations.

VI. CONCLUSIONS

This work presents a multi-objective problem for the design of substation grounding systems. The problem considers design limits based on IEEE Std. 80, which were turned into constraints such as maximum conductor length, number of rods, and touch and step voltage limits tolerable by the human body. The results are validated against example B2 of the IEEE Std. 80 standard and indicate that the proposed methodology meets the objective, allowing for an optimal grounding system design. In this way, designers have a tool that enables them to obtain optimal designs without inflating project costs with oversized designs.

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REFERENCES

[1] J. G. Sverak, "Optimized grounding grid design using variable spacing technique," *IEE Transactions on Power Apparatus and Systems*, vol. PAS-95, no. 1, pp. 3217–3221, 1976. DOI: https://doi.org/10.1109/T-PAS.1976.32113.

[2] R. Giordano, D. A. Mark, C. J. Rostkowski, B. Schall, and K. O. Sommer, "Computer Assisted Design of Substation Grounding," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-104, no. 7, pp. 1864–1867, 1985. DOI:https://doi.org/10.1109/MPER.1985.5528485.

[3] J. G. Sverak, "Simplified Analysis of Electrical Gradients Above a Ground Grid-I How Good Is The Present IEEE Method? (A Special Report For WG 78.1)," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-103, no. 1, pp. 7–25, 1984. DOI: https://doi.org/10.1109/TPAS.1984.318567.

[4] J. Sverak, "Simplified analysis of electrical gradients above a ground grid. II. The beauty of improper approximations for an efficient optimization of progressively spaced grids under a dominant safety constraint," *IEEE Transactions on Power Delivery*, vol. 4, no. 1, pp. 272–281, 1989. DOI:https://doi.org/10.1109/61.19214.

[5] Z. He, X. Wen, and J. Wang, "Optimization Design of Substation Grounding Grid Based on Genetic Algorithm," in *Third International Conference on Natural Computation (ICNC 2007)*, vol. 4, pp. 140–144, 2007. DOI:https://doi.org/10.1109/ICNC.2007.523.

[6] 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," *Int. Conf. Electr. Eng. ICEE 2015*, pp. 13–16, 2015. DOI:https://doi.org/10.1109/INTEE.2015.7416675.

[7] 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. DOI:https://doi.org/10.1109/TPWRD.2015.2445979.

[8] X. Wu, Q. Zhang, and J. He, “Substation grounding system optimization with utilizing a novel MATLAB application,” in *2016 IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC)*, pp. 628–633, 2016. DOI:https://doi.org/10.1109/APPEEC.2016.7779580.

[9] K. A. Vyas and J. G. Jamnani, “Optimized Design of Substation Grounding System Using Newly Developed IEEE Compliant Software,” *International Journal of Engineering Development and Research*, vol. 2, no. ISSN 2321-9939, 2014. URL:https://www.rjwave.org/ijedr/papers/IJEDRCP1402018.pdf.

[10] M. S. Hossain, R. Ahmed, and S. Hossain, “Design and Optimization of Substation Grounding Grid for Ensuring the Safety of Personnel and Equipment,” *Journal of Electrical Power & Energy Systems*, vol. 5, no. 1, pp. 71–80, 2021. DOI:https://doi.org/10.26855/jepes.2021.08.001.

[11] S. Ghoneim, H. Hirsch, A. Elmorshedy, and R. Amer, “Optimization Technique for Grounding Grids Design,” *Journal of Electrical and Electronic Systems Research*, vol. 1, no. ISSN 1985-5389, pp. 57–64, 2008. URL:https://ir.uitm.edu.my/id/eprint/61849.

[12] N. Filipe, “Optimization Design of Substation Grounding Grid,” *Semanticscholar*, 2011. URL:https://api.semanticscholar.org/CorpusID:127992641.

[13] Q. Zhang and X. Wu, “Software development of optimal substation ground grid design based on genetic algorithm and pattern search,” in *2014 North American Power Symposium (NAPS)*, pp. 1–6, IEEE, 2014. URL:https://doi.org/10.1109/NAPS.2014.6965440.

[14] F. Aboura and O. Touhami, “Grounding system cost reduction using multi-objective optimisation method,” *IET Science, Measurement & Technology*, vol. 14, no. 10, pp. 893–900, 2020. DOI: https://doi.org/10.1049/iet-smt.2019.0575.

[15] J.-W. Perng, Y.-C. Kuo, and S.-P. Lu, “Grounding system cost analysis using optimization algorithms,” *Energies*, vol. 11, no. 12, p. 3484, 2018. DOI: https://doi.org/10.3390/en11123484.

[16] N. N. Cvetković, M. Barukčić, and D. B. Jovanović, “Optimization of grounding system using evolutionary algorithm,” *Safety Engineering*, vol. 10, no. 2, pp. 63–68, 2020. DOI: https://doi.org/10.5937/SE2002063C.

[17] M. Lucero-Tenorio and A. C. V. Rojas, “Multi-objective optimization of power substation grounding grids,” in *2023 IEEE Colombian Caribbean Conference (C3)*, pp. 1–6, IEEE, 2023. DOI: https://doi.org/10.1109/C358072.2023.10436251.

[18] M. L. Tenorio and A. C. V. Rojas, “Multi-objective grounding system optimisation using nsga-ii,” *Transactions on Energy Systems and Engineering Applications*, vol. 5, no. 2, pp. 1–14, 2024. DOI: https://doi.org/10.32397/tesea.vol5.n2.616.

[19] AIEE, “No.80-1961, AIEE Guide for Safety in Alternating-Current Substation Grounding,” *American Institute of Electrical Engineers (AIEE)*, 1961. DOI: https://doi.org/10.1109/IEEESTD.1961.7728161.

[20] “IEEE Guide for Safety in Substation Grounding,” *IEEE Std 80-1976*, pp. 1–78, 1976. DOI:https://doi.org/10.1109/IEEESTD.1976.7185311.

[21] “IEEE Guide for Safety in AC Substation Grounding,” *ANSI/IEEE Std 80-1986*, pp. 1–370, 1986. DOI:https://doi.org/10.1109/IEEESTD.1986.81070.

[22] I. B. Simpson, D. J. Bensted, F. Dawalibi, and E. D. Blix, “Computer analysis of impedance effects in large grounding systems,” *IEEE transactions on industry applications*, no. 3, pp. 490–497, 1987. DOI:https://doi.org/10.1109/TIA.1987.4504936.

[23] “IEEE Guide for Safety in AC Substation Grounding,” *IEEE Std 80-2000*, pp. 1–192, 2000. DOI:https://doi.org/10.1109/IEEESTD.2000.91902.

[24] “IEEE Guide for Safety in AC Substation Grounding,” *IEEE Std 80-2013 (Revision of IEEE Std 80-2000/ Incorporates IEEE Std 80-2013/Cor 1-2015)*, pp. 1–226, 2015. DOI:https://doi.org/10.1109/IEEESTD.2015.7109078.

[25] 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 particle swarm,” in *2014 International Conference on Electrical Sciences and Technologies in Maghreb (CISTEM)*, pp. 1–8, 2014. DOI:https://doi.org/10.1109/CISTEM.2014.7077016.

[26] CYME, “CYME,CYMGRD, Substation Grounding Program.” URL:https://www.cyme.com/software/cymgrd/, 2024. Accessed: January 20, 2024.

[27] Integrated Grounding System Analysis program for Windows-WinIGS, “WinIGS.” URL:https://ap-concepts.com/apc-products/winigs/, 2024. Accessed: January 20, 2023.

[28] ETAP, Ground Grid Systems Software, “ETAP.” URL:https://etap.com/product/ground-grid-systems-software, 2024. Accessed: July 20, 2023.

[29] J. He, R. Zeng, and B. Zhang, *Methodology and technology for power system grounding*. John Wiley & Sons, 2012. URL:https://doi.org/10.1002/9781118255001.

[30] K. Deb, A. Pratap, S. Agarwal, and T. Meyarivan, “A fast and elitist multiobjective genetic algorithm: Nsga-ii,” *IEEE Transactions on Evolutionary Computation*, vol. 6, no. 2, pp. 182–197, 2002. DOI: https://doi.org/10.1109/4235.996017.

[31] K. Deb, “Multi-objective optimisation using evolutionary algorithms: an introduction,” in *Multi-objective evolutionary optimisation for product design and manufacturing*, pp. 3–34, Springer, 2011. DOI: https://doi.org/10.1007/978-0-85729-652-8_1.

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