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RESEARCH ARTICLE

Determination of Appropriate Soil Model and Parameters for Grounding System of Substation With High Voltage Via Kronecker-Sequenced Genetic Algorithms

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ABSTRACT

Accurate estimation of a suitable soil model and its parameters from field resistivity measurements, as well as the apparent soil resistivity based on this model, is vital for the reliable design of grounding systems in substations with high voltage. In this study, the two-layer soil model parameters are estimated based on The Institute of Electrical and Electronics Engineers (IEEE) Standards using Kronecker-sequenced genetic algorithms (GAs), with lower error values compared to those in the literature. The estimated parameters are upper and lower layer soil resistivities and upper layer depth. Furthermore, grounding grids are individually designed for both uniform and two-layer soil models using Kronecker-sequenced GAs. The design parameters are the number of rods, meshes, and grid burial depth. In the grounding grid designs, in addition to safety requirements, cost minimization is a key objective. Subsequently, the uniform soil model design parameters have been applied to the two-layer soil model, and the two-layer soil model design parameters to the uniform soil model. This approach enabled the assessment of whether the grounding grid design parameters obtained for one soil model type (uniform or two-layer soil models) could satisfy safety criteria when applied to the other. Thus, conclusions are drawn on the suitability and reliability of uniform and two-layer soil models for grounding system design. In this study, without using very expensive commercial software, Kronecker-sequenced GAs are employed for the estimation of two-layer soil model parameters and the apparent soil resistivity corresponding to the uniform soil model, the grounding grid design, and the evaluation of soil model suitability.

Index Terms—Appropriate soil model and parameters, genetic algorithms, Kronecker sequence, two-layer soil model, uniform soil model

I. INTRODUCTION

Substations with high voltage are crucial in the power transmission chain between the energy sources that generate electricity and the consumer sources. These substations take electrical energy from one or more high-voltage transmission lines, step it down to medium voltage via power transformers, and supply the energy to the distribution system [1].

The grounding system is an indispensable component in substations with high voltage because it is responsible for channeling electrical discharges to the ground caused by lightning strikes (approximately 40 lightning strikes occur worldwide per second, leading to 6000 to 24 000 fatalities annually) or temporary system faults [2].

Before building substations with high voltage, soil resistivity is measured to define soil structure. Based on this, the soil model and its parameters are defined, and the grounding grid is designed accordingly. The grounding system consists of a grid made of vertically driven rods and horizontally buried conductors (usually bare copper), all interconnected. Its main function is to transfer fault currents to the ground via the lowest-resistance path as quickly as possible. A reliable grounding system ensures the fast activation of protection systems, safeguarding both personnel and equipment [3]. The main functions of grounding grids are as follows:

1. To protect personnel and technical staff at the substation from electric shock; 2. To ground the neutral point of star-connected transformer windings; 3. To discharge lightning strikes or overvoltages to the ground through overhead ground wires and lightning rods; 4. To provide grounding connections for equipment and non-current-carrying metallic parts within the substation [4].

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Since soil structure affects grounding resistance, it must be considered in grid design. A low-impedance grounding system ensures safe dissipation of fault and lightning currents [5].

This study uses genetic algorithms (GAs) with an initial population based on Kronecker sequences to determine the two-layer soil model parameters. No study encountered in the literature uses Kronecker sequences as the initial population in GAs, which is one of the original contributions of this study. Based on soil resistivity measurements, the parameters of the two-layer soil model were determined using the Current Distribution, Electromagnetic Fields, Grounding and Soil Structure Analysis (CDEGS) software in [6], and the grounding grid was designed using different optimization schemes. In [7], the parameters of two-layer, three-layer, and four-layer soil models were determined using the CDEGS software. Various grounding resistance reduction methods (including grid burial depth, mesh compression ratio, addition of artificial soil, vertical ground rod length and number, number and length of horizontal grounding conductors, and the thickness of the exchanged soil) were compared in terms of cost-effectiveness. It was concluded that increasing the number and length of horizontal grounding electrodes is the most economical method. In [8], the grounding grid of an extra high-voltage substation was designed using a two-layer soil model in nonuniform soil with the Electrical Transient Analyzer Program (ETAP) software. Two-layer soil model parameters based on the Kriging model updating method were estimated in [9], where this method was compared with GAs, and although the error rate of GA was lower, the method was argued to be efficient. Most studies on two-layer soil model parameter determination and grounding grid design rely on costly commercial software. This study is able to predict two-layer soil model parameters and design grounding grids for both uniform and two-layer soil models with a minimal error rate, all without commercial software.

The reason for employing GA in determining the parameters of the two-layer soil model is the presence of numerous constraints, nonlinear, exponential, and irrational expressions, the inclusion of a summation term that may extend to infinity, the necessity of solving all these aspects with a single equation, and the ability to reach the optimal solution without being restricted by initial values. Kronecker sequences are employed in GA's initial population because their uniform distribution allows thorough exploration of the solution space, reducing the risk of trapping in false local solutions. It has also been compared with GA with a random initial population. After determining the uniform and two-layer soil model parameters from the measured soil resistivity, grounding grids for both models have been designed via Kronecker-sequenced GA. In the grounding grid designs, following the procedure outlined in IEEE Std. 80-2013, the criteria of touch voltage and step voltage have been considered along with the cost. For these purposes, the software has been coded in Matlab. After designing the grounding grid for both uniform and two-layer soil models, the design parameters (number of rods, meshes, and burial depth) from one model have been applied to the other. This checks whether the optimized parameters for each model meet safety requirements when applied to the other model. This is an original aspect of the study, as no literature addresses the mutual suitability of grounding grid designs based on the uniform or two-layer soil models for both models. While designs based on each model exist, none evaluate the safety of applying a uniform model design to a two-layer soil model or a two-layer model design to a uniform soil model.

Main Points

- The parameters of the two-layer soil model are predicted with a very low error rate based on the IEEE Std. 80-2013 via Kronecker-sequenced Genetic Algorithms (GAs).
- The grounding grids for the uniform and two-layer soil models have been designed based on the IEEE Std. 80-2013 via Kronecker-sequenced GAs.
- Even if the apparent soil resistivity of the two-layer soil model corresponding to the uniform soil model is very close to the apparent soil resistivity value calculated for the uniform soil model, grounding grid design parameters that are safely designed for one soil model (uniform or two-layer) may violate safety standards when applied to the other model (two-layer or uniform).
- To design a safe grounding grid, the suitability of the soil model used in the design must be verified.

II. KRONECKER SEQUENCED GENETIC ALGORITHMS

The Kronecker sequence is a low-discrepancy sequence, like Van der Corput, Halton, Hammersley, Faure, and Sobol. Compared to random sequences, low-discrepancy sequences are more uniformly distributed in solution space. The Kronecker sequence is easier to construct and code than other low-discrepancy sequences and can be generated using the fractional parts (decimal parts) of irrational numbers.

n = 1, 2, 3, … positive integers (natural numbers),

$\alpha_i = 1, 2, 3$; α irrational number (generally consecutive $\sqrt{\text{primenumber}}$),

{} represents the fractional part; for example, {5.3412} = 0.3412.

The s-dimensional Kronecker sequence is defined as in (1) [10].

$$\left(\{n\pm_1\},\{n\pm_2\},\{n\pm_3\},\ldots\{n\pm_s\}\right) \quad \text{mod1} \tag{1}$$

For example, if n = 1, $\alpha_1 = \frac{\sqrt{5}-1}{2}$, $\alpha_2 = \frac{\pi}{3}$, $\alpha_3 = \sqrt{7}$ is taken, the 3-dimensional Kronecker sequence;

$$\left(\left\{1\cdot\frac{\sqrt{5}-1}{2}\right\},\left\{1\cdot\frac{\pi}{3}\right\},\left\{1\cdot\sqrt{7}\right\}\right) \quad \text{mod1}$$

$$\left(\{0.61803\},\{1.04719\},\{2.64575\}\right) \quad \text{mod1}$$

(0.61803, 0.04719, 0.64575)

In Fig. 1, 2-dimensional random sequence with 100 points, the Kronecker sequence is shown as an example.

A. Genetic Algorithms

Genetic algorithms, which are particularly popular for optimization purposes, are inspired by the fundamental law of nature that "the

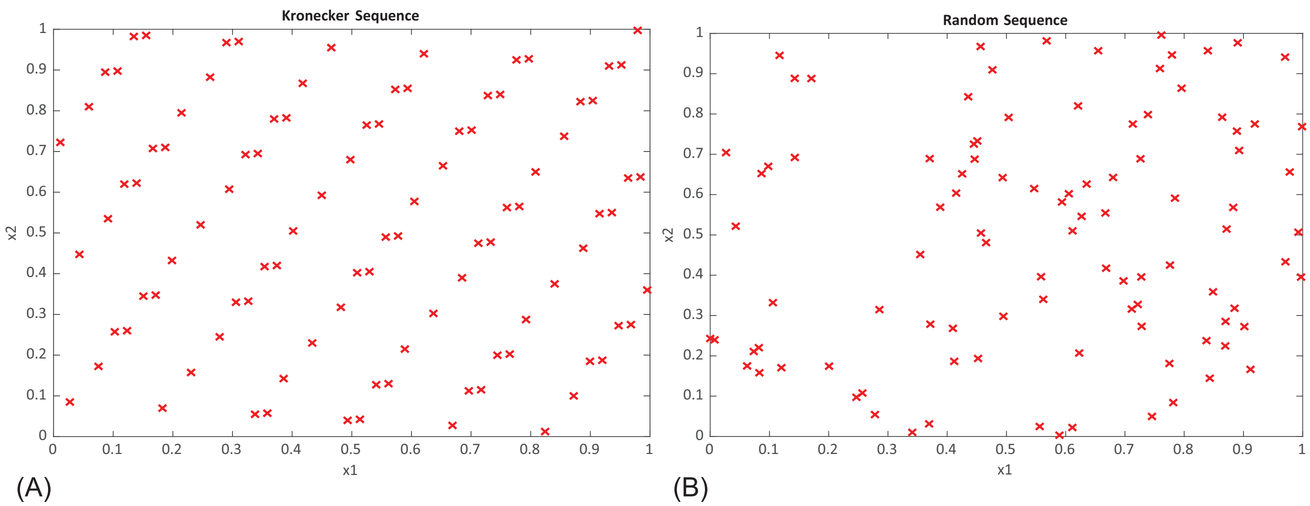

Fig. 1. (A) Kronecker sequence and (B) random sequence.

strongest survive, are nourished and reproduce." In these algorithms, individuals (chromosomes) continue their lives as long as they are strong, based on their fitness values, while those who are weaker or less fit may not survive and perhaps never reproduce during their lifetime. The basic operators of GAs include the generation of the initial population, determination of the fitness of chromosomes using the fitness function, crossover and mutation processes to create new, diverse, alternative chromosomes, selection, and the algorithm termination criterion. Each of these operators affects the solution success of the algorithm. In this study, Kronecker sequences are used in the initial population of GAs. In Fig. 2, the flow diagrams of the GA with random and Kronecker sequences are shown along with the crossover and mutation operators.

III. ESTIMATION OF SOIL MODEL PARAMETERS BASED ON SOIL RESISTIVITY MEASUREMENTS

Accurate characterization of the soil structure at the substation site is a fundamental prerequisite for the safe and effective design of the grounding system. The soil structure is determined through soil resistivity measurements. At the site where the substation is to be installed, soil resistivity measurements are conducted in multiple directions (e.g., east-west, north-south, northeast-southwest, etc.) and at several different points along each direction. There are several methods for measuring soil resistivity, which varies with the geological structure of the soil. In [11,12], these methods are referred to as the two-point method, three-point method, and four-point method (Equally Spaced or Wenner Arrangement, Unequally Spaced or Schlumberger–Palmer Arrangement). The dipole-dipole arrangement is also included among the four-point methods. Currently, the Wenner method is commonly used in the Turkish Electricity Transmission System [13].

A. Soil Resistivity Measurement With the Wenner Four-Electrode Method

This method involves supplying current to the soil via two current electrodes and measuring the resulting surface potential with two voltage electrodes. The soil structure is determined from the surface potential distribution. All four electrodes are equally spaced and aligned symmetrically. Fig. 3 schematically illustrates the soil resistivity measurement using Wenner's four-electrode method. A four-terminal soil tester is used for the soil resistivity measurement. Current is supplied to the soil through the C1-C2 electrodes, and the voltage drop in the soil is recorded via the P1-P2 electrodes. The resistance, R, between the P1-P2 electrodes ($V_{P1\text{-}P2}/I_{C1\text{-}C2}$) is found.

After the soil resistivity measurement, the apparent soil resistivity (ρ_a) is calculated using (2). ρ_a is assumed to be the apparent resistivity of the soil at depth *a* [14].

$$\rho_a = 2 \cdot \pi \cdot a \cdot R \tag{2}$$

a is the distance between the electrodes. In order to accurately characterize the soil properties, measurements should be conducted at multiple points (by varying the a spacing) and in multiple directions (routes).

B. The Soil Model for Grounding Grid Design

The soil model is merely an approximation of the actual soil conditions; an exact representation is not possible. The most common soil models are uniform and two-layer [14].

1) Uniform Soil Model:

If the measured soil resistivity values are very similar to each other, indicating a homogeneous soil structure, the uniform soil model shown in Fig. 4 can be used. The apparent soil resistivity is the arithmetic mean of the measurements, as in (3), where *n* is the number of measurements [14].

$$\rho_{a-uniform} = \frac{\rho_{a1} + \rho_{a2} + \rho_{a3} + \ldots \rho_{an}}{n} \tag{3}$$

2) Two-Layer Soil Model:

If soil resistivity measurements vary significantly, a two-layer soil model should be considered for a more accurate representation of soil conditions [14]. As illustrated in Fig. 5, the depth of the lower soil

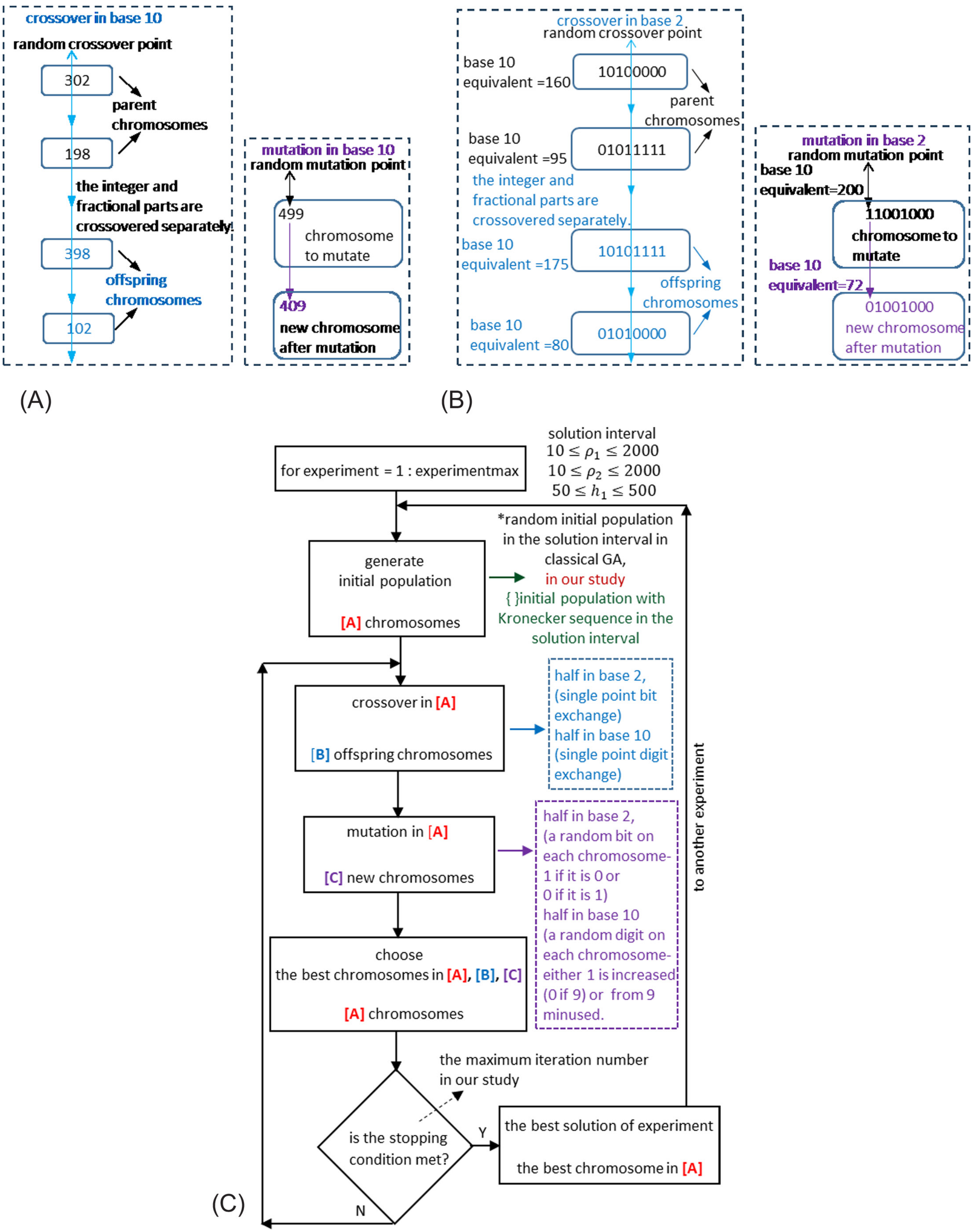

Fig. 2. (A) crossover, (B) mutation, (C) genetic algorithm running scheme.

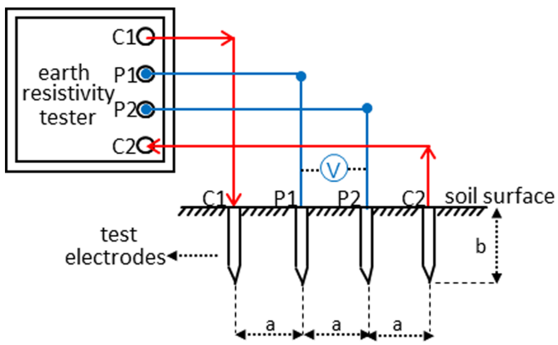

Fig. 3. Soil resistivity measurement using the Wenner method.

layer is considered infinite in this model. The apparent soil resistivity can be calculated as shown in (4) based on soil resistivity measurements [11,12]. The reflection coefficient *k* is given in (5).

$$\rho_{a-calculated} = \rho_1 \cdot \left\{ 1 + 4 \cdot \sum_{n=1}^{\infty} \frac{k^n}{\sqrt{1 + \left\{ \frac{2 \cdot n \cdot h_1}{a} \right\}^2}} - \frac{k^n}{\sqrt{4 + \left\{ \frac{2 \cdot n \cdot h_1}{a} \right\}^2}} \right\} \quad (4)$$

$$k = \frac{\rho_2 - \rho_1}{\rho_2 + \rho_1} \quad (5)$$

In (4) and (5), ρ_1 and ρ_2 represent the resistivity of the upper and lower soil layers (Ωm), respectively, h_1 represents the thickness of the upper layer (m), and *a* represents the distance (m) between electrodes in soil resistivity measurements. In this study, *n* is taken as 1 to 1000 $\left(n = \sum_{1}^{1000} \ldots \right)$. The apparent soil resistivity of the two-layer soil model corresponding to the uniform soil model is calculated as shown in (6) and (7) (if *h* is not significantly larger than *d*) (In this study, if d ≤ h ≤2d) [15].

$$\text{if } \acute{A}_2 < \acute{A}_1 \; \acute{A}_{a-two} = \frac{\acute{A}_1}{\left\{ 1 + \left[\left(\left(\frac{\acute{A}_1}{\acute{A}_2} \right) - 1 \right) \cdot \left(1 - e^{\frac{1}{k \cdot (h+2d)}} \right) \right] \right\}} \quad (6)$$

$$\text{if } \acute{A}_2 > \acute{A}_1 \; \acute{A}_{a-two} = \acute{A}_2 \cdot \left\{ 1 + \left[\left(\left(\frac{\acute{A}_2}{\acute{A}_1} \right) - 1 \right) \cdot \left(1 - e^{\frac{-1}{k \cdot (h+2d)}} \right) \right] \right\} \quad (7)$$

If h is significantly large (In this study, if h > 2d), (7) is modified as (8) [16-18].

$$\text{if } \acute{A}_2 > \acute{A}_1 \; \acute{A}_{a-two} = \acute{A}_1 \cdot \left\{ 1 + \left[\left(\left(\frac{\acute{A}_2}{\acute{A}_1} \right) - 1 \right) \cdot \left(1 - e^{\frac{-1}{k \cdot (h+2d)}} \right) \right] \right\} \quad (8)$$

In (6), (7), and (8) *h* represents the depth of the upper layer soil and *d* denotes the burial depth of the grounding grid. $\rho_{a\text{-two}}$ represents the equivalent apparent soil resistivity to be used in grounding system design, based on the two-layer soil model parameters determined using (4).

3) Applications:

In the uniform soil model, apparent soil resistivity can be determined using (3). Therefore, there is no need for an optimization process. In the two-layer soil model, (4), which represents the apparent soil resistivity, is an equation that contains irrational and exponential terms and includes a summation that extends to infinity (in this study, it is expanded up to 1000 terms). It is very difficult to analytically determine the parameters ρ_1, ρ_2, and h_1 using (4) and (5). Moreover, each parameter of the two-layer soil model has its own constraints (in this study: 10 ≤ ρ_1 ≤ 2000 Ωm, 10 ≤ ρ_2 ≤ 2000 Ωm, 50 ≤ h_1 ≤ 500 cm), and for each of these parameters, accurate initial values are essential in numerical optimization methods. In this study, the optimal values of the parameters ρ_1, ρ_2, and h_1 are obtained based on soil resistivity measurements by solving (4) within the fitness function using GA with Kronecker sequence. In the GA, the fitness function is defined as in (9) [11, 12, 19].

$$F_{fitness} = \sum_{i=1}^{\substack{number\,of \\ measurements}} \left\{ \frac{\rho_{measured} - \rho_{a-calculated(4)}}{\rho_{measured}} \right\}^2 \quad (9)$$

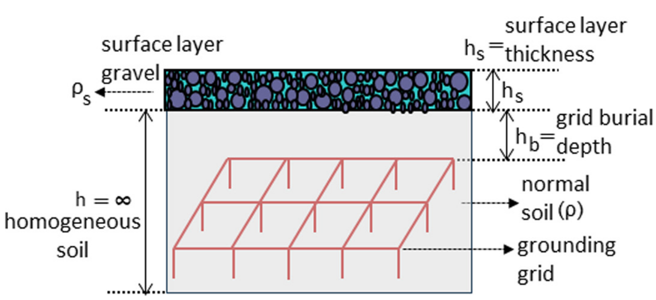

Fig. 4. Uniform soil model.

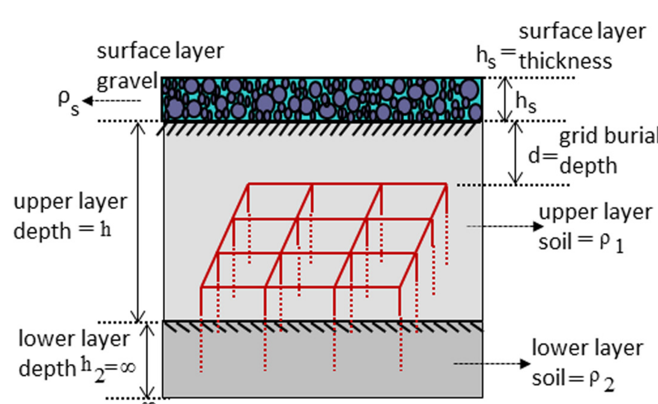

Fig. 5. Two-layer soil model.

TABLE I.
SOIL RESISTIVITY MEASUREMENTS

Measurement 1 [19-20]		Measurement 2 [21, 22]	
a (m)	**$\rho_{a\text{-measured}}$ (Ωm)**	**a (m)**	**$\rho_{a\text{-measured}}$ (Ωm)**
1	40.8	2	123.33
2	40.3	4	189.99
3	38.2	6	258.93
4	32.7	8	320.27
5	26.7	10	374.13
6	24.5		
8	20.1		
10	17.6		

In Table I, soil resistivity measurements are shown for two different substation areas.

Based on Table I measurements, the uniform and two-layer soil model parameters in Table II are obtained using the GA parameters also listed there. ρ_1 and ρ_2 are resistivities of the upper and lower soil layers (Ωm), h_1 upper layer depth (cm), $\rho_{a\text{-two}}$ apparent soil resistivity according to the two-layer soil model (6, 7, 8), $\rho_{a\text{-uniform}}$ apparent soil resistivity according to the uniform soil model (3), nc is the number of chromosomes, ng is the maximum number of generations, ne is the number of experiments, and afbi average fitness of the best individuals in each experiment.

In Fig. 6, the changes in fitness average, upper layer soil resistivity, lower layer soil resistivity, and upper layer depth with respect to the number of generations in the best experiment are shown for Measurement 1; in Fig. 7 for Measurement 2. In [19], for Measurement 1, $F_{best\ fitness} = 0.007$. In [20]'da for Measurement 1, $F_{bestfitness} = 0.0069$. In [21], for measurement 2, $F_{best\ fitness} = 3.8953 \times 10^{0-1-2-3-4}$. In [22], for measurement 2, $F_{best\ fitness} = 0.00025$. The two-layer soil model parameters are estimated by classical GA with random initial population based on the data in Table II, as shown in Table III. The objective function ($F_{best\ fitness}$) achieves better (lower) values with the Kronecker-sequenced GA.

IV. GROUNDING GRID DESIGN

In the case of a short-circuit fault, the conductors carrying the fault current to the ground through the grounding conductors must be capable of withstanding the maximum fault current without any melting or damage occurring during the fault duration. IEEE Std. 80-2013 [14], for the selection of the grounding conductor cross-section, recommends the "Onderdonk." In Turkey, the grounding conductor cross-section in substations with high voltage is limited to a minimum of 120 mm² [23]. In transmission substations, a high-resistivity material such as gravel is commonly laid on the soil surface above the grounding grid to increase the contact resistance between a person's foot and the ground. The resistivity and thickness of the high-resistivity surface material significantly affect the calculation of permissible touch and step voltages. The value of the surface layer correction factor C_s, is determined using (10).

$$C_s = 1 - \frac{0.09 \cdot \left(1 - \frac{\rho_a}{\rho_s}\right)}{2h_s + 0.09} \tag{10}$$

ρ_a is the apparent soil resistivity (both the uniform (3) and two-layer soil model (6, 7, 8)), ρ_s surface material resistivity (Ω·m), and h_s thickness of the surface material (m). For a body weight of 50 kg, the permissible maximum touch and step voltages are calculated using (11) and (12).

$$E_{maxtouch-50} = \frac{0.116}{\sqrt{t_s}} \cdot \left(1000 + 1.5 \cdot C_s \cdot \rho_s\right) \tag{11}$$

$$E_{maxtouch-50} = \frac{0.116}{\sqrt{t_s}} \cdot \left(1000 + 6 \cdot C_s \cdot \rho_s\right) \tag{12}$$

TABLE II.
UNIFORM AND TWO-LAYER SOIL MODEL PARAMETERS (INITIAL POPULATION WITH KRONECKER SEQUENCE)

GA Input Parameters		The Soil Model	Output Parameters	According to Measurement 1	According to Measurement 2
nc	60	Two layer soil model	ρ_1 (Ωm) (8)	42.6321	100.0251
			ρ_2 (Ωm) (8)	13.4985	998.4085
			h_1 (cm) (8)	326.1666	250.0166
ng	60		$\rho_{a\text{-two}}$ (Ωm) (6, 7, 8)	27.3793	331.6475
			$F_{best\ fitness}$	0.006784	$4.46978 \times 10^{0-1-2-3-4-5-6-7-8}$
ne	60		afbi	0.007227	$1.00412 \times 10^{0-1-2-3-4-5}$
		Uniform soil model	$\rho_{a\text{-uniform}}$ (Ωm) (3)	30.1125	253.33

GA, genetic algorithm.

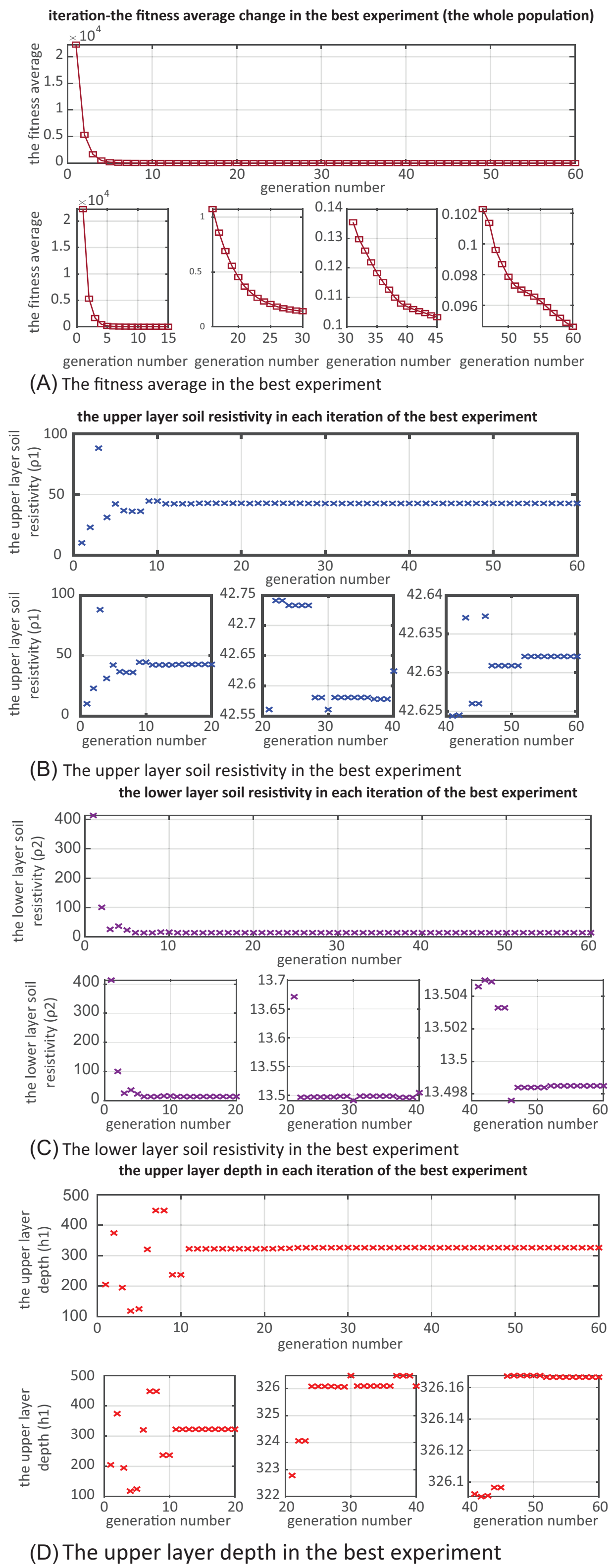

Fig. 6. Various parameters. (A) Fitness average, (B) upper layer soil resistivity, (C) lower layer soil resistivity, (D) upper layer depth depending on the generation number according to Measurement 1.

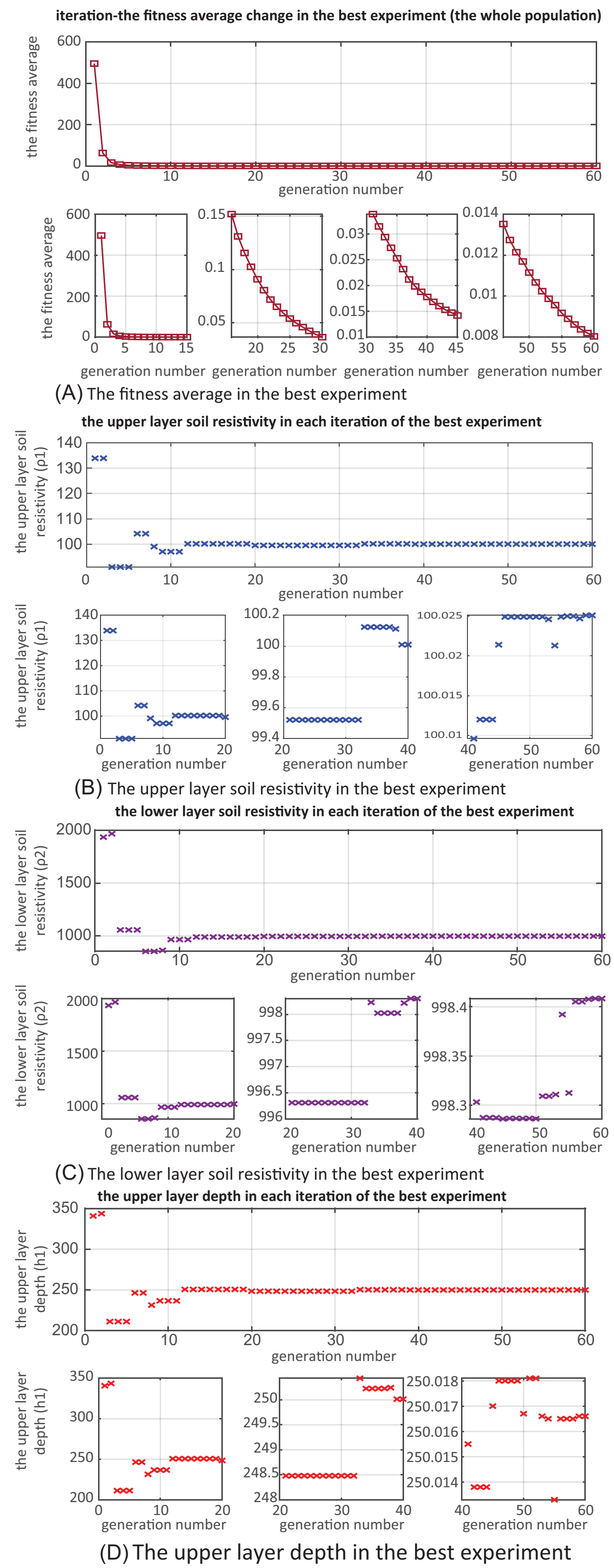

Fig. 7. Various parameters. (A) fitness average, (B) upper layer soil resistivity, (C) lower layer soil resistivity, (D) upper layer depth depending on the generation number according to Measurement 2.

In grounding grid design, one of the significant criteria is the calculation of mesh and step voltages. The mesh and step voltages are calculated as given in 13 and 14, respectively [14].

$$E_m = \frac{\rho_a \cdot K_m \cdot K_i \cdot I_G}{L_M} \tag{13}$$

$$E_s = \frac{\rho_a \cdot K_s \cdot K_i \cdot I_G}{L_S} \tag{14}$$

The terms (K_m, K_i, K_s, L_M, L_S, L_G) in these equations are shown in [14]. For the uniform soil model $\rho_a = \rho_{a-uniform}$ (3); for the two-layer soil model $\rho_a = \rho_{a-two}$ (6, 7 and 8).

A. Grounding Grid Design Via Genetic Algorithms

Genetic algorithms with Kronecker sequences have been employed in the design of grounding grids. The number of grounding rods, the grid burial depth, and the number of meshes along the longer side of the substation have been optimized. The optimization of the number of meshes along the longer side of the substation is required to ensure uniform distance (D) between conductors (equations K_m and K_s in [14]). Thus, the total conductor length to be used in the grounding grid can also be calculated.

The optimized parameters in this study:

10 ≤ number of grounding rods ≤ 255

2 ≤ number of meshes ≤ 255 (along the longer side)

50 ≤ grid burial depth ≤ 1000 cm

The fitness function used in GAs for grounding grid design is defined through the algorithm below, as expressed in (15). The aim is to minimize the fitness function.

if $E_m \geq E_{maxtouch-50}$ or $E_s \geq E_{maxstep-50}$

penalty = cost;

else ($E_m < E_{maxtouch-50}$ and $E_s < E_{maxstep-50}$)

penalty = 1;

end

$$\text{fitness function} = \left\{ \text{penalty} \cdot \left| E_m - E_{maxtouch-50} \right| \right\} + \text{cost} \tag{15}$$

The cost used in 15 is represented in 16.

The cost function = (price of 1 meter of conductor × total conductor length) + (price of 1 grounding rod × total number of grounding rods) + (labor cost for burying 1 meter of conductor × total conductor length) + (daily rental cost of the excavator × the number of working days of the excavator). Equation (16) illustrates how the cost function is calculated.

In this study, the cost of a 1-meter conductor with a cross-sectional area of 120 mm² is assumed to be \$16; the price of a single grounding rod with a length of 2.5 meters and a radius of 0.02 meters is \$90. The labor cost for laying 1 meter of conductor underground is \$1, and the daily rental cost of an excavator is considered to be \$300. (It is assumed that 1500 meters of conductor can be buried per day).

B. Grounding Grid Design Applications

In this section, based on the data presented in Table II, separately grounded grid designs have been performed for each of the two substations using both the uniform soil model (according to $\rho_{a\text{-uniform}}$) and the two-layer soil model (according to $\rho_{a\text{-two}}$). Subsequently, the optimal number of grounding rods, the optimal number of meshes and the optimal grid burial depths determined based on the design results using $\rho_{a\text{-uniform}}$ have been applied to the two-layer soil model ($\rho_{a\text{-two}}$). When the design results obtained from the uniform soil model have been applied to the two-layer soil model ($\rho_{a\text{-two}}$), the touch and step voltage safety requirements have been determined in the two-layer soil model. A similar comparison is also conducted by applying the design parameters obtained from the two-layer soil model to the uniform soil model. The optimal number of grounding rods, the optimal number of meshes and the optimal grid burial depths determined based on the design results using ρ_{two} have been applied to the

TABLE III.
UNIFORM AND TWO-LAYER SOIL MODEL PARAMETERS (RANDOM INITIAL POPULATION)

GA Input Parameters		The Soil Model	Output Parameters	According to Measurement 1	According to Measurement 2
nc	60	Two layer soil model	ρ_1 (Ωm) (8)	42.6099	100.0627
			ρ_2 (Ωm) (8)	13.4863	995.0617
			h_1 (cm) (8)	326.5371	249.821
ng	60		$\rho_{a\text{-two}}$ (Ωm) (6, 7, 8)	27.3963	330.4103
			$F_{best\ fitness}$	0.006785	$8.04145 \times 10^{0\text{-}1\text{-}2\text{-}3\text{-}4\text{-}5\text{-}6\text{-}7}$
ne	60		afbi	0.007891	$1.3989 \times 10^{0\text{-}1\text{-}2\text{-}3\text{-}4}$
		Uniform soil model	$\rho_{a\text{-uniform}}$ (Ωm) (3)	30.1125	253.33

GA, genetic algorithm.

TABLE IV.
INPUT PARAMETERS FOR THE GROUNDING GRID DESIGN

Number of experiments	30	Width of substation (m)	100	Surface material resistivity (Ωm)	5000	Price of one grounding rod ($)	90
Number of chromosomes	60	Length of substation (m)	150	Surface material thickness (m)	0.2	Price of 1 meter grounding conductor ($)	16
Maximum number of iterations	60	Maximum grid current (A)	20000	Grounding rod length (m)	2.5	Price of 1-day excavator rental ($)	300
		Maximum grid current duration (s)	0.5	Grounding rod radius (m)	0.02	The length of conductor that can be buried in one day (m)	1500

uniform soil model (ρa-uniform). When the design results obtained from the two-layer soil model have been referenced in the uniform soil model (ρa-two), the touch and step voltage safety requirements have been determined in the uniform soil model. In all designs, except for the apparent soil resistivity in the uniform and two-layer models, the other input parameters (Table IV) are the same.

1) Grounding Grid Design According to Measurement 1:
The grounding grid design results based on the uniform and two-layer soil models according to Measurement 1 (Table II) and Table IV are presented in Table V. Table VI shows a comparison of the safety parameters obtained when the grounding grid design results, based on the uniform soil model, are applied to the two-layer soil model. As shown in Table VI, if the grounding grid design results calculated for Measurement 1 using the uniform apparent soil resistivity ρ_a-uniform are applied to the two-layer soil model ρ_a-two, these uniform soil model design parameters will also satisfy the safety requirements in the two-layer soil model.

Table VII compares the safety parameters obtained when the design results from the two-layer soil model are applied to the uniform soil model. As shown in Table VII, when the design results from the two-layer soil model for Measurement 1 are applied to the uniform soil model, although the step voltage safety requirement is satisfied, does not meet the touch voltage safety requirement. The touch voltage criterion was not satisfied ($E_m > E_{maxtouch-50}$).

2) Grounding Grid Design According to Measurement 2:
The grounding grid design results based on the uniform and two-layer soil models according to Measurement 2 (Table II) and Table IV are presented in Table VIII. If the optimal number of grounding rods, the optimal number of meshes and the optimal grid burial depth determined in the grounding grid design based on the uniform soil model ("uniform" column in Table VIII) are applied to the two-layer soil model, it is shown in Table IX that these design parameters do not meet some of the safety requirements (the mesh voltage exceeds the permissible maximum value-$E_m > E_{maxtouch-50}$) in the two-layer soil model.

If the optimal number of grounding rods, the optimal number of meshes and the optimal grid burial depth determined in the grounding grid design based on the two-layer soil model ("two" column in Table IX) are applied to the uniform soil model, it is shown in Table X that these design parameters meet all of the safety requirements ($E_m < E_{maxtouch-50}$ and $E_{step} < E_{maxstep-50}$) in the uniform soil model.

TABLE V.
GROUNDING GRID DESIGN RESULTS ACCORDING TO MEASUREMENT 1 (UNIFORM MODEL APPARENT SOIL RESISTIVITY = 30.1125 ΩM, TWO-LAYER MODEL APPARENT SOIL RESISTIVITY = 27.3793 ΩM)

	Uniform	Two		Uniform	Two		Uniform	Two
Optimum number of rods	10	10	Grounding conductor cross-section (mm²)	120	120	Mesh voltage (V)	1169.706	1169.638
Optimum number of meshes along the long side of the substation	2	2	Distance between conductors (m)	75	75	Permissible maximum touch voltage (V)	1169.790	1169.666
Optimum grid burial depth (cm)	471.1329	159.5704	Number of conductors on the long edge	3	3	Step voltage (V)	46.026	111.127
			Number of conductors on the short edge	3	3	Permissible maximum step voltage (V)	4187.013	4186.519
			Optimum total conductor length (m)	750	750	Optimum total cost ($)	13 800	13 800

TABLE VI.
SAFETY CRITERIA IF THE DESIGN RESULTS FROM (10, 2, 471.1329) ARE USED FOR THE TWO-LAYER SOIL MODEL

	Uniform Soil Model (Apparent Soil Resistivity = 30.1125)	Two-Layer Soil Model (Apparent Soil Resistivity = 27.3793)
Mesh voltage (V)	1169.706	1063.536
Permissible maximum touch voltage (V)	1169.790	1169.666
Step voltage (V)	46.026	41.849
Permissible maximum step voltage (V)	4187.013	4186.519
Conclusion	The grounding grid design based on the uniform soil model is also suitable for the two-layer soil model.	

TABLE VII.
SAFETY CRITERIA IF THE DESIGN RESULTS FROM (10, 2, 159.5704) ARE USED FOR THE UNIFORM SOIL MODEL

	Two-Layer Soil Model (Apparent Soil Resistivity = 27.3793)	Uniform Soil Model (Apparent Soil Resistivity = 30.1125)
Mesh voltage (V)	1169.638	1286.399
Permissible maximum touch voltage (V)	1169.666	1169.790
Step voltage (V)	111.127	122.220
Permissible maximum step voltage (V)	4186.519	4187.013
Conclusion	The grounding grid design based on the two-layer soil model is not suitable for the uniform soil model.	

TABLE VIII.
GROUNDING GRID DESIGN RESULTS ACCORDING TO MEASUREMENT 2 (UNIFORM MODEL APPARENT SOIL RESISTIVITY = 253.33 ΩM, TWO-LAYER MODEL APPARENT SOIL RESISTIVITY = 331.6475 ΩM)

	Uniform	Two		Uniform	Two		Uniform	Two
Optimum number of rods	10	10	Grounding conductor cross-section (mm^2)	120	120	Mesh voltage (V)	1179.875	1183.404
Optimum number of meshes along the long side of the substation	47	62	Distance between conductors (m)	3.19149	2.4193	Permissible maximum touch voltage (V)	1179.878	1183.418
Optimum grid burial depth (cm)	51.0641	80.0253	Number of conductors on the long edge	48	63	Step voltage (V)	2228.951	2460.371
			Number of conductors on the short edge	33	43	Permissible maximum step voltage (V)	4227.368	4241.527
			Optimum total conductor length (m)	9750	12750	Optimum total cost ($)	168 600	220 200

TABLE IX.
SAFETY CRITERIA IF THE DESIGN RESULTS FROM (10, 47, 51.0641) ARE USED FOR THE TWO-LAYER SOIL MODEL

	Uniform Soil Model (Apparent Soil Resistivity = 253.33)	Two-Layer Soil Model (Apparent Soil Resistivity = 331.6475)
Mesh voltage (V)	1179.875	1544.636
Permissible maximum touch voltage (V)	1179.878	1183.418
Step voltage (V)	2228.951	2918.035
Permissible maximum step voltage (V)	4227.368	4241.527
Conclusion	The grounding grid design based on the uniform soil model is not suitable for the two-layer soil model.	

TABLE X.
SAFETY CRITERIA IF THE DESIGN RESULTS FROM (10, 62, 80.0253) ARE USED FOR THE UNIFORM SOIL MODEL

	Two-Layer Soil Model (Apparent Soil Resistivity = 331.6475)	Uniform Soil Model (Apparent Soil Resistivity = 253.33)
Mesh voltage (V)	1183.404	903.947
Permissible maximum touch voltage (V)	1183.418	1179.879
Step voltage (V)	2460.371	1879.363
Permissible maximum step voltage (V)	4241.527	4227.369
Conclusion	The grounding grid design based on the two-layer soil model is also suitable for the uniform soil model.	

V. CONCLUSION

In this study, the two-layer soil model parameters are determined via Kronecker-sequenced GAs based on soil resistivity measurements at two substations. Additionally, grounding grid designs for each substation are performed individually using both uniform and two-layer soil models with the same method. The designs are based on both minimum cost and safety requirements as fundamental criteria. The safety criteria involve ensuring that touch and step voltages do not exceed their permissible maximum limits. When grounding grid design results based on the uniform soil model are applied to the two-layer soil model, it has been determined that the safety requirements are not met with these design result parameters. The reverse situation is also encountered; when grounding grid design results based on the two-layer soil model are applied to the uniform soil model, the safety requirements are not met in the uniform soil model with these design result parameters. Even when the apparent soil resistivity values of the uniform soil model and the two-layer soil model are very close to each other, it has been shown that a grounding grid designed to be safe under one model may violate safety standards under the other. Therefore, the appropriate soil model must be selected for grounding grid design, and the soil model parameters must be accurately determined for grounding grid design. Whether the soil model is uniform or two-layer, regardless of which soil models are used in the design, the design results must also be applied to other soil models, and it must be definitively confirmed that the safety requirements are met in the other soil models as well. If necessary, the grounding grid design parameters (the length of grounding conductors, the number of rods, and the grid burial depth) should be revised to meet the safety requirements, and design parameters that are mutually compatible with the soil models should be identified.

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