Software Development of Optimal Substation Ground Grid Design Based on Genetic Algorithm and Pattern Search

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***Abstract*—Substation ground system serves to safety of personnel and as major equipment during earth faults, which deserves considerable attentions. Basic substation safety assessment quantities include ground grid resistance, mesh touch potential and step potential, moreover, optimal design of substation ground system should consider both safeness and cost. To fill the lack of such suitable and economical optimal design software in North American industry, a software package coded in MATLAB is developed and its core algorithm and main features are introduced in this paper. A novel hybrid GA-PS optimization or two-steps optimization method is developed, in which Genetic Algorithm (GA) is used firstly to search an approximate start point range for the further optimal searching, followed by Pattern Search (PS) to find the final optimal result. This software can give analysis of ground grid safety performance and is able to recommend optimal grid design for given safety constraints. In order to make sure the accuracy of this software, the results of grid safety assessment obtained here are also compared with the results calculated by using world-wide used software WinIGS.**

Keywords—Ground Grid Design, Safety Assessment, Cost of Ground Grid Construction, Two-steps Optimization Method, Genetic Algorithm, Pattern Search

I. INTRODUCTION

Substation ground system serves to safety of personnel and as major equipment during earth faults, which has already deserved a long history considerable attentions [1-18]. As defined in IEEE Std. 80 –2000 [19], basic substation safety assessment quantities including ground grid resistance, mesh touch potential, step potential and ground potential rise (GPR), should be limited as constraints in design for the sake of safety. Previous optimal ground design only used numerical calculation or "trail-and-error" [9-13], then different optimization modeling with corresponding optimization methods had been studied to count both safeness and cost [14-18]. Several commercial software [20-22] or self-developed software had also been developed [23].

There are four topics below related with optimal design of substation ground system, from which a simple review is made as followings:

The shape and mesh size of ground grid: this refers to the grounding grid shape, and the grid mesh size of equal [14,15] or un-equal spacing , e.g., exponent rule [13].

The equivalent circuit model of selected ground grid structure: this will heavily related with the soil is uniform soil model [17] or non-uniform soil model [10]. In this paper, a non-uniform two-layer soil model is used for the ground grid modeling.

Optimization model: As to the objective function, reference [23] considers the material cost, excavation cost, and weld cost which is almost the same as this paper. The constraints of ground grid can be obtained from IEEE Std.80-2000 [19].

Optimization algorithm: Mixed-integer linear programming was used [14-15] which should make the optimization model being linear, which is not applicable in most cases. To solving nonlinear problem, some heuristic methods were used, the generic algorithm (GA) was applied in [16-17]. The particle swarm optimization (PSO) was introduced in [18] and compared with GA in similar optimal results but with less computation time.

Three commercial software packages can make the simulation, i.e., WinIGS [20], EMTP [21], CYMGND [22], however, all of them can give the curves and result data sheets, but they are not open to public of their used functions or modeling methods. ETAP [21] and CYMGND [22] can optimize the ground system, but this kind of software is very costly.

In this paper, in order to meet a local power utility requirement, a MATLAB coded optimization design software is developed and introduced by the author. A mathematical model is described to compute the key safety assessment parameters of substation ground system as required in Section II. A hybrid GA-PS mixed algorithm is proposed based on genetic algorithm and pattern search method in Section III-IV. The software features different from the other is also discussed briefly in Section V. The conclusion and contribution of this paper are presented in Section VI.

II. SAFETY ASSESSMENT FOR GROUND SYSTEM DESIGN

In this paper, the rectangular-shape ground grid is mainly analyzed and designed for simplicity, the modeling and optimization method is fully applicable to the system with any other shapes. The ground grid can be composed of line conductors and each conductor can also be subdivided into small line segments. Those segments are both applied in horizontal mesh grid and vertical rods. By using complex images method and Green's functions [4], the current density in each segment is obtained. Besides, in order to improve the calculation accuracy, the two-layer soil model is considered rather than uniform soil model.

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A. Ground resistance

Assuming that horizontal mesh and vertical rods in the ground grid are divided into n segments, k is the *kth* segment in the total number of segments. Each segment of conductor is modeled as lumped resistance and self-resistance in the matrix r [4]. If j is equal to k, it is self-resistance r_{jj}; if j is not equal to k, it is mutual resistance r_{jk},. The sum of source currents from all segments should be equal to the fault current returning to the remote sources through the earth. Therefore, it has following two equations (1) and (2):

$$\sum_{k=1}^{n} r_{jk} i_k = v_j , j = 1,2,3,...n \quad (1)$$

$$\sum_{k=1}^{n} i_k = I_F \quad (2)$$

Then, by combining above two equations, it can form following matrix equation:

$$AX = b \quad (3)$$

Where,

$$A = \begin{bmatrix} r_{11} & \cdots & r_{1n} & -1 \\ \vdots & \ddots & \vdots & -1 \\ r_{n1} & \cdots & r_{nn} & -1 \\ 1 & \cdots & 1 & 0 \end{bmatrix}_{(n+1)\times(n+1)} ;$$

$$b = \begin{bmatrix} 0 \\ \vdots \\ 0 \\ I_F \end{bmatrix}_{(n+1)\times 1} \qquad X = \begin{bmatrix} i_1 \\ \vdots \\ i_n \\ v \end{bmatrix}_{(n+1)\times 1} ;$$

$$R_g = v / I_f \quad (4)$$

In matrix A, the values of self-resistance and mutual resistance can be obtained by using complex images method. Since the value of fault earth current I_f is also known, the unknown values include current density in every segment and GPR can be solved by the equation (3). And the resistance of ground grid is solved by following equation (4), therein v is the value of GPR.

B. Mesh touch potential

After obtaining the value of current density for all conductor segments and GPR, based on the method from [4] and by using Green function, the value of earth potential at a specific earth surface point can be solved. The detail of earth potential calculation is not discussed in this paper and it can be obtained from [4] and [26]. When the total earth potential at point A (E_A) is obtained, finally, the touch voltage at point A is

$$E_{touch} = GPR - E_A \quad (5)$$

C. Step potential

For the step voltage calculation, it is assumed that one person's two feet contact the earth at point A and B. Hence, it is necessary to use the same method discussed in [4] and [26] to calculate the earth potential at point B (E_B), and then the step voltage is:

$$E_{step} = E_B - E_A \quad (6)$$

However, in general case of a ground grid, the value of step voltage in the worst case is much lower than the value of mesh touch voltage in the worst case. Thus, if the touch voltage of a ground grid has been considered and restricted in the design process, the value of step voltage is unnecessary to be considered in the grid optimized model.

D. Results comparison with WINIGS

In order to make sure the accuracy of the modeling method presented in this paper, four cases are shown in following tables in comparison with results from WinIGS. As to the ground rod placement in this paper, all the rods are equally placed at the grid corner or around the grid.

The four cases are studied and compared here, where all the horizontal grid are 400 ft * 350 ft grid size, 10*10 number of meshes in both length and width direction, but with 0, 4, 8, 12 perimeter rods respectively.

In all four cases, the two layer soil is applied, the resistivity of surface layer is 100 ohm*m, the resistivity of lower layer is 30 ohm*m, thickness of surface is 10 ft; the length of rod is 30 ft and the diameter is 0.628 inches, the diameter of horizontal conductors is 0.528 inches; the fault earth current and fault duration time are 3.78 kA and 0.58 s respectively.

TABLE 1 MESH TOUCH POTENTIAL COMPARISON BETWEEN OUR PAPER AND WINIGS

Mesh touch potential (volts)			
	This paper	WINIGS	DIFFERENCE(%)
Case 1	252.6139	251.8000	-0.32%
Case 2	216.1831	217.0100	0.38%
Case 3	205.8610	208.9000	1.45%
Case 4	192.5256	199.5300	3.51%

TABLE 2 GRID RESISTANCE COMPARISON BETWEEN OUR PAPER AND WINIGS

Grid resistance (ohms)			
	This paper	WINIGS	DIFFERENCE(%)
Case 1	0.1698	0.1694	-0.24%
Case 2	0.1629	0.1628	-0.06%
Case 3	0.1585	0.1592	0.44%
Case 4	0.1536	0.1552	1.03%

From above TABLE 1 and TABLE 2, it can be seen that the result difference between the modeling method presented by this paper and WinIGS is less than 4%, thus it is still applicable for industry use. Because there must existing some differences of segmentation strategy between these two methods, the deviations shown in the table are reasonable.

III. Description of the Optimization Problem

In this paper, the purpose of the optimization is reducing the total ground grid construction cost. Based on some given safety requirement, the optimized ground grid design shall be constricted and built under IEEE safety conditions.

A. Mixed integer objective function

The objective function is the cost of the ground grid, including copper cost and construction labor cost. Based on the data from the local utility, which consists of (a) material cost of horizontal conductors and vertical rods is C_{cond}, \$3.77/ft; (b) material cost of exothermic is C_{exoth}, \$19.25 each; (c) cost of labor to trench, install and backfill conductors and rods are C_{trench}, \$10.0/ft and C_{drive}, \$32/ft respectively; (d) cost of labor to make exothermic connection of conductor to conductor or conductor to rod is $C_{connect}$, \$40 each. Thus, the objective function is obtained in below equation (7):

$$\begin{aligned} Obj\_\min.Cost(N_1, N_2, N_{rod}) \\ = (C_{cond} + C_{trench}) \bullet L_{cond} + (C_{rod} + C_{drive}) \bullet L_{rod} \\ + (C_{connect} + C_{exoth}) \bullet (N_{rod} + N_{exoth}) \end{aligned} \tag{7}$$

Where,

$$L_{cond} = (N_1 + 1) \bullet L_1 + (N_2 + 1) \bullet L_2$$

$$L_{rod} = l_r \bullet N_{rod}, l_r = 30\,ft$$

$$N_{exoth} = (N_1 + 1) \bullet (N_2 + 1)$$

In above equations, L_1 and L_2 are the given length and width of ground grid in ft. L_{cond} is the total length of horizontal conductors, L_{rod} is the total length of vertical rods, N_{expth} is the total number of exothermic connections.

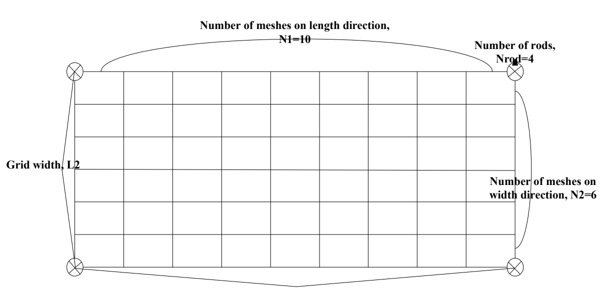

Fig.1 Example three ground grid optimal design variables: N_1, N_2 and N_{rod}

In the optimization model, there are three variables, N_1 is the number of meshes in grid length direction, N_2 is the number of meshes in grid width direction, N_{rod} is the number of rods in designed grid. And N_1, N_2 and N_{rod} are integer variables and an example of grid design is shown in below Fig. 1. In this example, N_1 is 10, N_2 is 6 and N_{rod} is 4.

B. Safety assessment and constraints

By considering ground system safety design requirement, the maximum allowable step potential and mesh touch potential of people weighting 50 Kg can be obtained from IEEE Std. 80-2000 [19] shown in following equations (8) and (9).

$$E_{touch\_allowable} = (1000 + 1.5\rho)\frac{0.116}{\sqrt{t_f}} \tag{8}$$

$$E_{step\_allowable} = (1000 + 6\rho)\frac{0.116}{\sqrt{t_f}} \tag{9}$$

Where ρ is the earth resistivity, which means it is the surface material resistivity if the high resistivity surface material exists or it is the upper-layer soil resistivity in the two layer soil model or it is the uniform soil resistivity in the uniform soil model, and t_f is the shock duration.

As to ground grid resistance, based on some industrial experience, the value of 0.5 ohms is applied as the maximum allowable ground resistance in this paper.

Furthermore, the mesh size for ground grid is restricted in the range of 8.5ft and 50ft, in order to avoid the grid mesh too small or too large. The number of rods is restricted between 4 and 12 for simplicity

Thus, all the inequality constraints and variable constraints for the optimization model are shown below:

$$E_{grid\_touch} \le E_{touch\_allowable} \tag{10}$$

$$E_{grid\_step} \le E_{step\_allowable} \tag{11}$$

$$R_g \le R_{allowable} \tag{12}$$

$$\frac{L_1}{50\,ft} \le N_1 \le \frac{L_1}{8.5\,ft} \tag{13}$$

$$\frac{L_2}{50\,ft} \le N_2 \le \frac{L_2}{8.5\,ft} \tag{14}$$

$$4 \le N_{rod} \le 12 \tag{15}$$

And N_1, N_2 and N_{rod} are integers

IV. OPTIMIZATION METHODOLOGY

A. *Algorithm selection and flowchart*

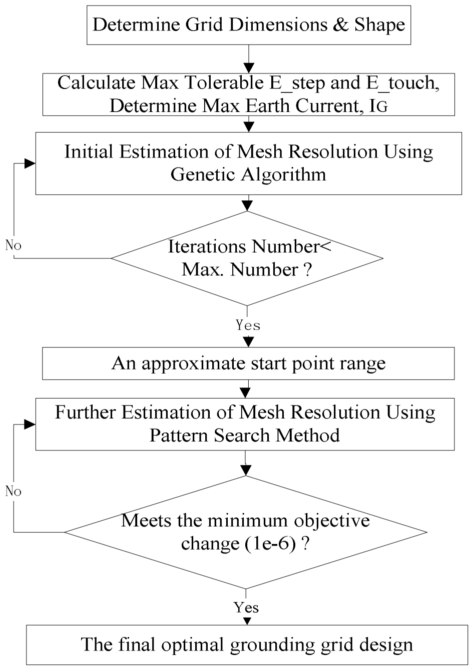

Fig.2 The flowchart of two-steps optimization method

It can be observed that the equivalent circuit model of ground grid or equation (3) is sectionalized linear depending on the depth of vertical nods, and the resistance Rg in formula (4) is in nonlinear, therefore, the optimization problem in objective function (7), equal constraints (3) (4), non-equal constraints (10)-(15) , is a nonlinear optimization problem. To tackle with such problem [24-26], GA is good at its global searching capability but with less efficiency. Therefore, GA is used first to have a gross optimum area search. Pattern search method (PS) is good at its accuracy of optimal point searching within a small searching space, therefore a hybrid GA-PS mixed algorithm in Fig.2 is developed to accelerate the searching speed with a good accuracy performance.

B. *Algorithm performance*

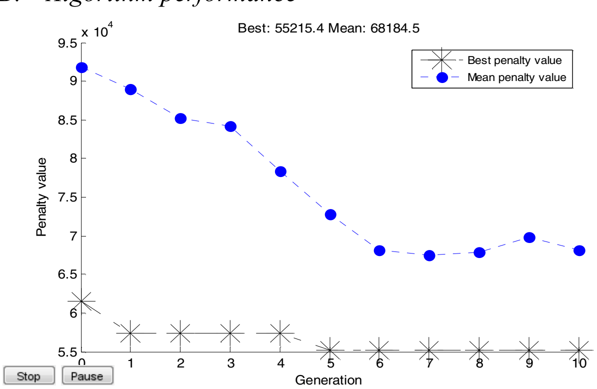

Fig.3 Example case for two-steps optimization method: Step 1, Genetic algorithm

An example is shown in Fig.3, the grid length is 200 ft and width is 150 ft. From Fig. 3 and Fig. 4, the performance of the whole two-step optimization process is displayed.

In Fig. 3, for each iteration, the mean value of objective function, which is also the grid construction cost, for all the generations in GA is represented by the solid point and the best value of objective function is represented by the star point. The distance between the solid point and the start point in every iteration can indicate the converge speed.

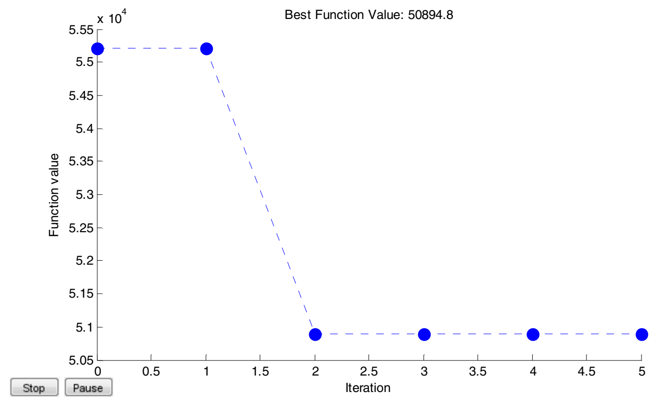

Fig.4 Example case for two-steps optimization method: Step 2, Pattern search

In Fig. 4, the value of objective function in each pattern search iteration is represented by the solid points and line. From the Fig. 4, since the start point range from the previous step is very close to the final optimal result, the PS is converged only after five iterations.

C. *Genetic algorithm to search approximate start point*

For simplicity, the detail of GA will not be discussed in this paper, the general introduction of GA can be obtained in [24-25]. The reason why using Genetic algorithm as first step to search the start point range is: (1) By using the fast convergence speed of GA, an approximate result can be obtained in only after 10 or 15 iterations. And an example is shown in next section. (2) In general cases, the approximate start point from GA is close to the final optimal result, which saves much running time for the further optimization work.

D. *Pattern Search to search final optimal result*

The pattern search (PS) is a direct search algorithm searches a set of points around the start point, looking for one optimal result where the value of the objective function is smaller than the value at the current point. The general introduction of this kind of heuristic method (also include GA) is discussed in [25].

It should be noticed that, the stopping criteria for PS is the minimum objective change is lower than 1e-6. Thus, the calculation accuracy and convergence speed are both guaranteed.

E. *Optimal result*

The optimal results of another case example of the grid size length is 400ft and width is 300ft by using two-step method and the ground grid system safety assessment are shown in below TABLE 3 and TABLE 4.

TABLE 3 GROUND GRID OPTIMIZED RESULT BY USING TWO-STEP OPTIMIZATION METHOD

Final Cost ($)	N_1	N_2	N_{rod}
80,127	8	14	4

TABLE 4 COMPARISON BETWEEN THE CONSTRAINT VALUES AND ALLOWABLE VALUES

	Optimal Results	Allowable Constraints
Etouch (V)	173.9940	175.1628
Rg (ohms)	0.163	0.500

From TABLE 4, it can be seen that the optimized results are lower than the allowable constraint values. And the value of the grid touch potential is just lower than and very close to the maximum allowable value. It means the design is acceptable and at least locally optimal.

V. SOFTWARE DEVELOPMENT FEATURES

A. Steps of the software processing

Before the optimization work, some input parameters are needed, which include the

1) Soil model parameters: upper layer resistivity ρ_1 (ohms*m), lower layer resistivity ρ_2 (ohms*m) and the depth of upper layers H_1 (ft).
2) Fault current I_f (kA) and fault duration time t_f (second) based on the voltage class of a substation in TABLE.5.
3) Shape of substation ground: rectangular shape, triangular shape, L-shape and trapezoidal shape.
4) Shape geometrical parameters, for example, when the rectangular ground grid is designed, the rectangular length (ft) and width (ft) are needed.

TABLE 5 RELATIONSHIP BETWEEN VOLTAGE CLASS AND FAULT DURATION TIME

Voltage class (kV)	Time (s)
>250	0.25
200 ~ 250	0.50
22~ 200	0.58
<22	1.10

For design part, following parameter sets are under optimized which are discussed as above in section III:

1) Number of meshes on the horizontal length direction N_1
2) Number of meshes on the horizontal width direction N_2
3) The number of rods N_{rod} in the grid corner or perimeter

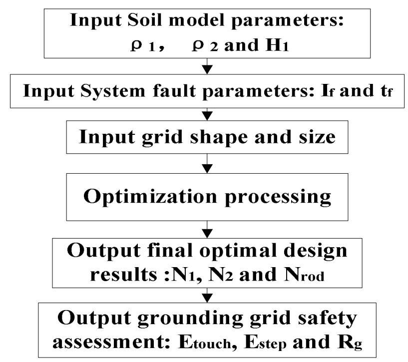

Fig.5 The flowchart of the software processing

The flowchart of the software processing is shown in Fig.5.

B. Interface of the software

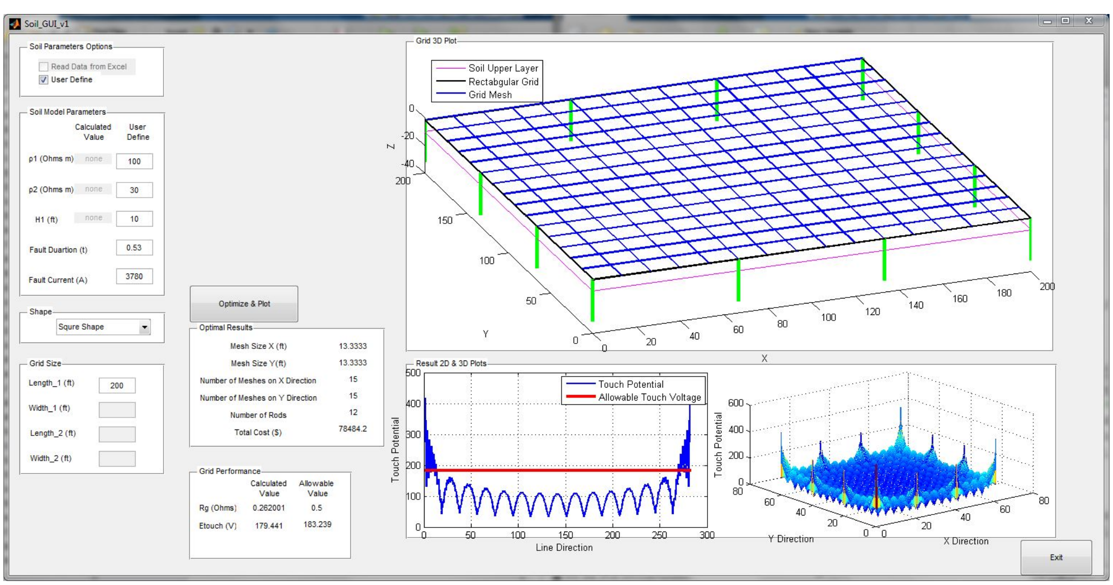

Fig.6 Interface of optimal software and an example result for optimal grid design

MATLAB is not so powerful for interface development, however, a good layout and human-friendly interface can be designed properly by using the function of Graphical User Interface (GUI). A simple view of our software interface and the result of the second example case in section IV are shown in Fig.6.

VI. Conclusion

Under a two-layer soil model, a horizontal square mesh and vertical rod equivalent circuits model has been built for the node voltage calculation. By comparing some results between our method and WinIGS, the accuracy of the grid modeling used in this paper is guaranteed. The optimal model with the objective function of the ground grid construction cost, under the step voltage, touch voltage and ground resistance constraints is presented. An algorithm using two-step optimization method with GA for global search and PS for finer search in sequence, has been developed with MATLAB. And by using the GUI function, a software interface is also developed and shown in this paper. A real application of this software will be applied by one local utility in Arizona, and much more detailed studies will be carried out in future works.

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