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Development of Earth Parameter Estimation Software and its Application in the Design of Ground Grid

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Abstract: Earth parameters have a tremendous impact on the performance of grounding system; therefore, in the design of ground grid, earth parameters must be firstly estimated by measured apparent resistivity with the aid of Wenner method. In this study, a software for earth parameter estimation is developed on the platform of MATLAB and VC++6.0. Based on electromagnetic theory, it can optimize the resistivity and thickness of each layer by Particle Swarm Optimization (PSO). Case study demonstrates that PSO has the advantage over Artificial Neural Network (ANN) in earth parameter estimation. With the optimized resistivity, the software is applied in the computation of ground potential rise and ground impedance of two-layer earth model to design ground grid. Ground impedance is 6.305 Ω. According to GB/T 197949.1-200, it satisfies the requirements of ground impedance in high resistivity area.

Key words: Ground grid, multi-layer earth, parameter estimation, PSO, ground potential rise

INTRODUCTION

In electrical substations, ground grid has significant importance for the safety of personnel and delicate equipment (IEEE Std 837-2002, 2002). Ground impedance, Ground Potential Rise (GPR), touch, step, mesh and transferred voltages are the specified safety parameters which are severely influenced by soil characteristics (IEEE Std 80-2000, 2000). To perform safety evaluation of ground grid in substation, it is necessary to know the accurate soil parameters.

Apparent resistivity can directly reflect the earth parameters. It is usually defined as the resistivity of a uniform half-plane in response to the different measurement parameters (such as: The location, injection current, etc). In the research of soil parameters estimation, the uniform and two-layered earth structures are chosen as the standard models in GB/T 17949.1-2000 and IEEE 80-20000 (Peng *et al*., 2011; IEEE Std 80-2000, 2000). The two-layered models have a broad range of applications (Seedher and Arora, 1992) and show a relatively higher accuracy in some instances. Alamo adopted six two-layered models to analyze and compare the performance of eight techniques, and pointed out that those algorithms were not effective to solve non-linear issues with inequality constraints (Del Alamo, 1993). To get more accurate estimation, some work began to focus on multi-layer earth structures. Takahashi first derives the theoretical equations for calculating earth resistivity in order to prepare the ρ-α curves (Takahashi and Kawase, 1990). To overcome the improper integral of apparent resistivity, Complex Image Method (CIM) is introduced to simplify the expression and then earth parameters are optimized by BFGS involving with intractable differentiation and inverse of matrix (Zhang *et al*., 2005). Thereafter, evolution algorithms were employed to estimate the non-uniform earth structure with constraint equations. Lee *et al*. (2005) employed ANN to train network weight and approximate the non-linear characteristic of soil parameters. However, the network weight was tough to encode because it varied according to the ability of expert and initial value problem. GA algorithm (Zhiqiang and Bin, 2011; Gonos and Stathopulos, 2005) could obtain a better results; Calixto *et al*. (2010) proposed a new way to predetermine the earth structures.

In this study, the aim is to develop a suite of software on the platform of MATLAB and VC++6.0 to design ground grid. It is composed of earth parameter estimation module, ground grid model generation module and safety parameter computation module. With regard to two-layer earth and high resistivity area, a typical ground grid is designed.

MATERIALS AND METHODS

In this study, a suite of software is developed for the design of ground grid based on the combination of

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electromagnetic and circuit theory. On the platform of MATLAB and VC++6.0, Particle Swarm Optimization (PSO) is adopted to estimate earth parameters using the simplified expression of apparent resistivity; the ground potential rise and ground impedance are computed in the design of ground grid.

Measured apparent resistivity (ρ^{α}_{md}): Wenner method usually has a remarkable advantage (Tsourlos *et al*., 1995) and is recommended to measure apparent resistivity in IEEE Std80-2000. The electrode spacing d is a constant between any two adjacent electrodes. As shown in Fig. 1, electrodes (M, N) inject current into the ground and two additional electrodes (A, B) are used to measure the generated earth voltage.

$$V_{AB} = \frac{I\rho^{a}_{md}}{4\pi}\left[\frac{1}{d} + \frac{2}{\sqrt{1+(\frac{2t}{d})^{2}}} - \frac{2}{\sqrt{2^{2}+(\frac{2t}{d})^{2}}}\right] \tag{1}$$

Where: ρ^{α}_{md} is the measured apparent resistivity; I is the injected current; V_{AB} is the potential difference between electrodes A and B; t is the burial depth of the electrodes; d is the electrode spacing. With the assumption of d>10t, the simplified equation Eq. 2 can be deduced:

$$\rho^{a}_{md} = \frac{2\pi d V_{AB}}{I} \tag{2}$$

Computed apparent resistivity (ρ^{α}_{cd}): The equation to compute ρ^{α}_{cd} is obtained by the expansion of Possion's equation of point current source in multi-layer earth media:

$$\rho^{a}_{cd} = 2d\rho_1\int_0^{\infty}\alpha_1(\lambda)[J_0(\lambda d) - J_0(2\lambda d)]d\lambda \tag{3}$$

$$\begin{gathered}\alpha_1(\lambda) = 1 + \frac{2K_1 e^{-2\lambda h_1}}{1-K_1 e^{-2\lambda h_1}}, K_1 = \frac{\rho_2\alpha_2 - \rho_1}{\rho_2\alpha_2 + \rho_1}\\ \alpha_i(\lambda) = 1 + \frac{2K_i e^{-2\lambda h_i}}{1-K_i e^{-2\lambda h_i}}, K_i = \frac{\rho_{i+1}\alpha_{i+1} - \rho_i}{\rho_{i+1}\alpha_{i+1} + \rho_i}\\ i = 1, 2, 3, \ldots, i, \ldots, n-1\end{gathered} \tag{4}$$

where, J_0 (λd) is the zero order Bessel's function of the first kind; h_i and ρ_i are the thickness and the resistivity of the ith layer, respectively.

In this study, CIM is adopted to deal with Eq. 3 with the kernel of Green's Function and the simplified equation to be implemented in the iteration of MATLAB program is shown as Eq. 5:

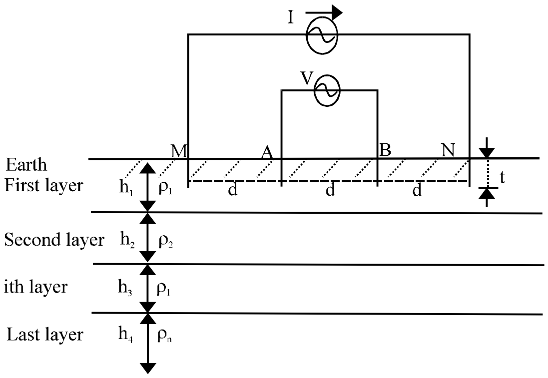


Fig. 1: Wenner method for the measurement of apparent resistivity

$$\rho^{a}_{cd_i} = 2d_i\rho_1\sum_{k=1}^{ni}\eta_k\left(\frac{1}{\sqrt{\mu_k{}^2 + d_i{}^2}} - \frac{1}{\sqrt{\mu_k{}^2 + (2d_i)^2}}\right) \tag{5}$$

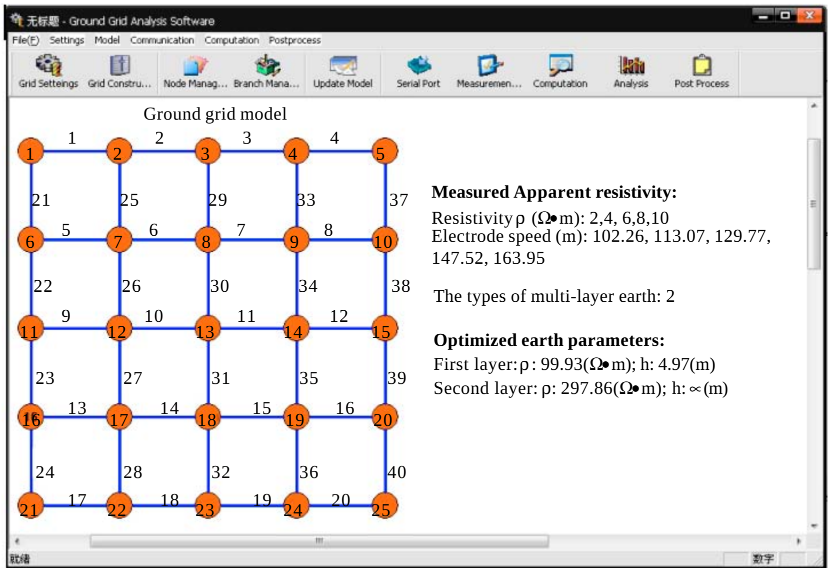
where, n is the number of earth structures. η_k and μ_k are the complex coefficients and ni = 4 is the terms of the expansion.

Software design: A software suite is developed on the platform of VC++6.0 and MATLAB. The MATLAB engine library contains routines and it can be called by the main function in VC++6.0 to colorfully plot 2/3D figure. The interface of this software in VC ++6.0 was terse, friendly, shown as Fig. 2. It includes earth parameter estimation module, ground grid model generation module and safety parameter analysis module:

- **Earth parameter estimation module:** It can display the measured apparent resistivity with regard to electrode spaces and the types of earth structures. The optimized earth parameters can be shown, after the main function in VC++6.0 call PSO to implement the optimization. Figure 3 is used to describe moving in the iteration of PSO

  In PSO, suppose that the dimension of searching space is D and the size of swarm is N, therefore, the ith current positions and velocities of particles in the space is given by a vector $X_i = (x_{i1}, x_{i2}, \ldots, x_{iD})^T$ and $V_i = (v_{i1}, v_{i2}, \ldots, v_{iD})^T$, respectively. In this study, t = (D+1)/2 indicates the number of earth layers and X_i represents $\rho_{i1}, \rho_{i2}, \ldots, \rho_{it}, h_{i1}, h_{i2}, \ldots, h_{i(t-1)}$:

$$\begin{gathered}V_i^{k+1} = \omega(i)V_i^{k} + c_1r_1(P_i - X_i^{k}) + c_2r_2(P_{best} - X_i^{k})\\ X_i^{k+1} = V_i^{k+1} + X_i^{k}\end{gathered} \tag{6}$$



Measured Apparent resistivity:

Resistivity ρ (Ω•m): 2,4, 6,8,10

Electrode speed (m): 102.26, 113.07, 129.77, 147.52, 163.95

The types of multi-layer earth: 2

Optimized earth parameters:

First layer: ρ: 99.93(Ω•m); h: 4.97(m)

Second layer: ρ: 297.86(Ω•m); h: ∞(m)

Fig. 2: Self-made earth parameter estimation software

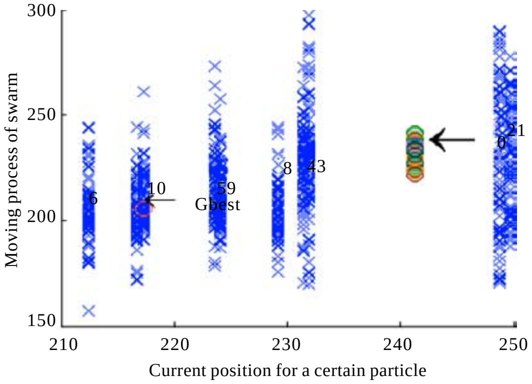


Fig. 3: Scheme of particle moving in the iteration of PSO

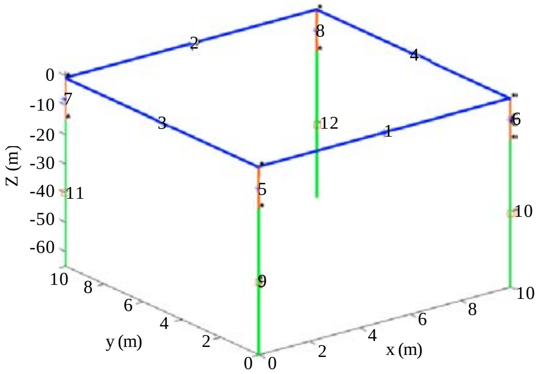


Fig. 4: Structures of ground grid and the visible numberings of its branches

where, $P_i = (p_{i1}, p_{i2},...,p_{iD})$, i = (1, 2, ..., N) is its previous best position and the best particle in the population is represented by $P_{best} = (p_1, p_2, ..., p_D)$. Particle i is indicated by index i; the superscripts (k and k+1) denote the iteration

- **Ground grid model generation module:** The connections and coordination of nodes are listed automatically in tables and the corresponding ground grid is plotted in MATLAB. For example, a rectangular ground grid shown as Fig. 4 is buried at the depth of -0.8 m in two-layer earth and the top layer is 5 m and the long vertical rods is 64.2 m; the numberings of its branch is visible
- **Safety parameter analysis module:** Based on the combination of electromagnetic and circuit heory, collocation method is utilized to compute the leakage current, ground potential rise and the ground impedance. The equations to compute leakage current is introduced as Eq. 7-10:

$$\sum_{i=1}^{N} R_i I_i = \varphi_j \tag{7}$$

$$R_i = \frac{\rho}{4\pi L_i}\int_{L_i}\frac{1}{r_i}dl_i \tag{8}$$

$$\begin{bmatrix} R_{11} & R_{12} & \cdots & R_{N1} & -1 \\ R_{21} & R_{22} & \cdots & R_{N2} & -1 \\ & & \vdots & & \vdots \\ R_{N1} & R_{N2} & \cdots & R_{NN} & -1 \\ 1 & 1 & 1 & 1 & 0 \end{bmatrix}\begin{bmatrix} I_1 \\ I_2 \\ \vdots \\ I_N \\ \varphi \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \\ I_s \end{bmatrix} \tag{9}$$

$$R_{ij} = \frac{\rho}{4\pi L_i L_j}\int_{L_j}\int_{L_i}\frac{1}{r_i}dl_i dl_j \tag{10}$$

where, Eq. 8 and 10 are in the form of green's function; I_i is the leakage current; φ_j is the potential the jth section and φ is the generalized expression, i, j = {1, 2, 3, ..., N}.

RESULTS AND DISCUSSION

In this study, the measured apparent resistivity is adopted from Lee *et al.* (2005), in which ANN is the tool for analyzing 20 sets of data; however, ANN has a serious difficulty in encoding because it differs from each other according to the complex numerous calculations and initial value problems. Unlike ANN, PSO won't need to artificially regulate those parameters and can simply and easily solve the multi-objective function. Utilizing the self-made ground grid analysis software and proposed algorithm, optimized earth parameters can be easily obtained.

In case study, the Case 16 and 17 in Lee *et al.* (2005) are selected and the measured data are listed in Table 1. After the earth parameter estimating module is called, the optimized parameters are automatically generated and displayed: Case16: 924.58 (Ω•m), 2533.38 (Ω•m), 2.22 m; Case17: 996.42 (Ω•m), 2727.18 (Ω•m), 2.14 m. The measured and computed apparent resistivity are separately plotted with the legends in Fig. 5. The RMSE of PSO is 0.052 and 0.0779 while that of ANN is 0.0566 and 0.0796; therefore, it turns out that PSO can obtain a better earth parameter estimation.

The soil of case 16 and 17 are satisfied with:

$$K_1 = \frac{\rho_2 - \rho_1}{\rho_2 + \rho_1} > 0$$

and both of their lower earth of resistivity ρ_2 are very large.

In this study, the optimized parameters of case 16 are selected. When a 100*100 (m^2) of square ground grid with 4 vertical rods (10 m of each section and 50 m long vertical rods) is chosen, there are 220 branches and 129 nodes. The self-developed software automatically generates the table of nodal coordination and connections as well as the numberings of branches of ground grid with vertical rods. After computation, the distribution of potential is shown as Fig. 6 and ground

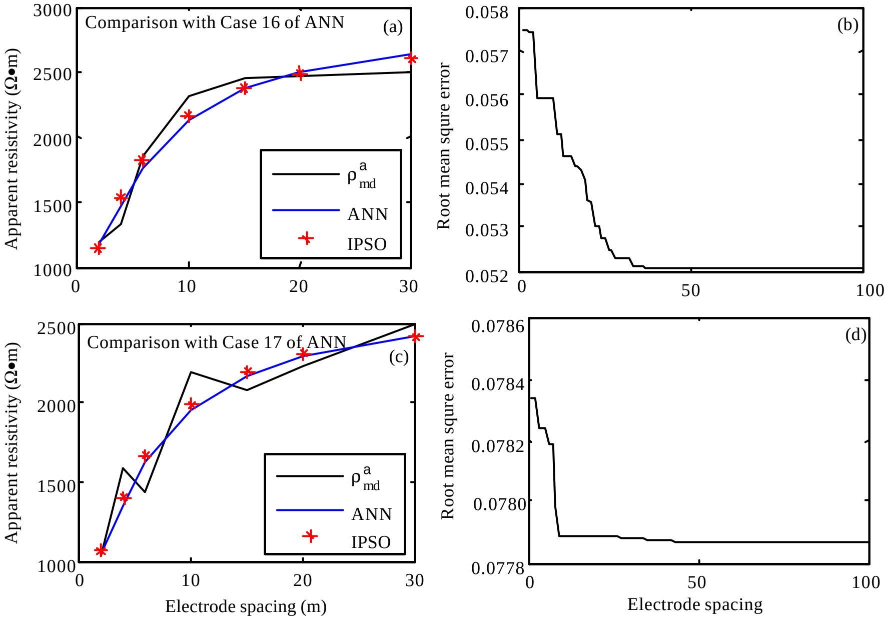


Fig. 5(a-d): Comparison of the fitted apparent resistivity by ANN and PSO respectively in the optimization of earth parameter, (a) Case 16, (b) Corresponding RMSE of PSO, (c) Case 17, (d) Corresponding RMSE of PSO

Table 1: Measured apparent resistivity with respect to the electrode spacing of case 16 and 17 in Lee *et al.* (2005)

Parameters	Values						
Case16							
Electrode spacing (m)	2	4	6	10	15	20	30
Apparent resistivity (Ω•m)	1200.8	1333.8	1850.5	2318.0	2455.8	2470.5	2500.0
Case17							
Electrode spacing (m)	24	6	10	15	20	30	
Apparent resistivity (Ω•m)	1031.8	1587.3	1428.5	2182.5	2083.3	2223.3	2500.0

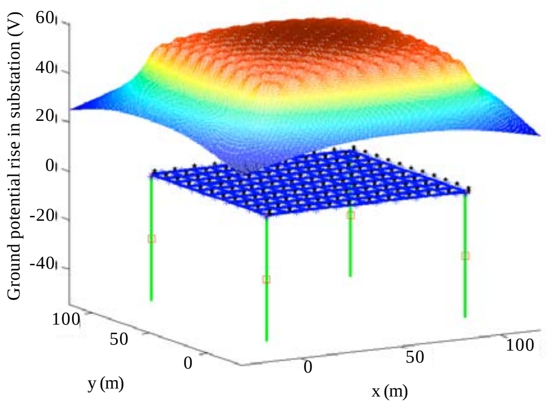


Fig. 6: Analysis of ground potential rise of substation ground grid buried in two-layer earth using the earth parameters of case 16

impedance is 6.305 Ω. According to the standards, the ground impedance must be less than 10 Ω; therefore, the designed ground grid satisfy the requirements.

CONCLUSION

In this study, a software suite is developed for the design of ground grid on the platform of MATLAB and VC++6.0. It can implement the earth parameter estimation based on PSO, generate and construct the ground grid model and compute the safety parameters of substation grounding system. Using the self-developed software, case study is introduced and its optimized earth parameters are chosen to design the ground grid with vertical rods. It demonstrated that the self-made software suite is user friendly and efficient to design ground grid and do the related analysis.

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