Analysis and Application of Inverse Detecting Method Based on Local Electric Field

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Abstract **─** This paper investigates the time-efficient fault detection problem with applications in electric fields. A novel inverse approach based on a non-trivial combination of the fast multipole scheme and traditional simulation charge method is proposed. The fundamental principle is to take several samples of the intensity in the given local electric field at properly selected known locations nearby. Electric accessories are then used to analyze the signals in the framework of the traditional simulation charge method. Moreover, a new genetic algorithm, combined with the Tikhonov regularization, is proposed to further speed up the inverse process of fault detection in electric fields. The performance of the proposed approach is evaluated by the simulation results for the computation of the distribution of voltages in 110 kV high-voltage insulator lines. The superiority of the new inverse approach, in terms of time efficiency and accuracy for fault detection, is demonstrated by the simulation results. The present work aims to stimulate future studies on fault detection in electric fields.

Index Terms **-** Electric fields, fast multipole method, genetic algorithms, inverse problems, Tikhonov regularization.

I. INTRODUCTION

Online fault detection and condition maintenance without switching off the system are the most challenging problems in electric fields. These are very important factors that must be taken into account in the design of high-voltage electrical systems [1]. The safety and regular operation in power systems must always be ensured. The current research focused its attention on these factors and on measurements of insulation resistance, hyper frequency, acoustics and supersonics, as well as on the infrared imaging method. However, few relevant research materials have focused on the accuracy of fault detection in electric fields, which is one of the most important metrics for evaluating the performance of methodologies.

The present paper takes the electric-field intensity as the main metric for received signals. It is not only a very important factor to be monitored, it is also easily captured. From the analysis of the samples on the electric-field intensity of several properly preselected locations nearby, as well as the electric equipment combined with a new geometry model from a tuning version of the traditional simulation charge method, this paper compares the practical voltage distribution of the high voltage electrical equipment derived by the proposed inverse approach with standard voltage distribution. Consequently, the locations of the fault devices are detected.

II. CALCULATION PRINCIPLE

A. Model and the inverse approach for the simulation charge method

Establishing a proper calculating model is very crucial in deriving efficiency in

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computations. According to high voltage power frequency electric properties and the superiority of the simulation charge method in the calculation of open domain problems, the calculation model is derived from the simulation charge method (SCM) [2,3]. The theoretical basis of SCM is the uniqueness principle of the electric fields based on imaging methods. Instead of unevenly and continuous distributed charges on the conductor surface, this work uses a set of simulation charges that meet the given boundary conditions to formulate a solution for the entire field. According to the simulation theory in literature, the shape of the simulation charge is random. The shape of the actual electric field source and the feature of the electric field usually serve as the reference when selecting the shape of the simulation charge to simplify the calculations. For instance, an infinitely long line of charge is simulated by the high voltage (HV) transmission line, whereas the ring simulated charge is used to substitute the chained charges on the surface of the insulators.

Detailed steps on establishing the relationship between the electric field and the source using SCM are as follows. The first step is to conduct a qualitative analysis of the feature of the electric field and set several simulation charges outside the corresponding calculation field. The second step is to configure the matching points with exactly the same number as the simulation charges. The third step is to establish the potential SCM expressions according to the superposition principle. In solving the corresponding SCM equations, several checkpoints on the surface of the electrode are selected to evaluate the precision of the calculations. The selection processes for the simulation charges, in terms of locations, are completed until the calculation precision meets the predefined requirement threshold. Finally, the potential or intensity of the electric field on the randomly selected points would be determined according to the final values of the selected simulation charges.

This work takes the seven-piece insulators of a 110 kV line as an example. The process of the calculation model is illustrated using the SCM as follows. Simulation uses the two-ring simulation charges. Each corresponding insulator has two matching points on the surface. Each matching point has the exact same Z-coordinates as the corresponding simulation charge. The employed geometric model is shown in Fig. 1.

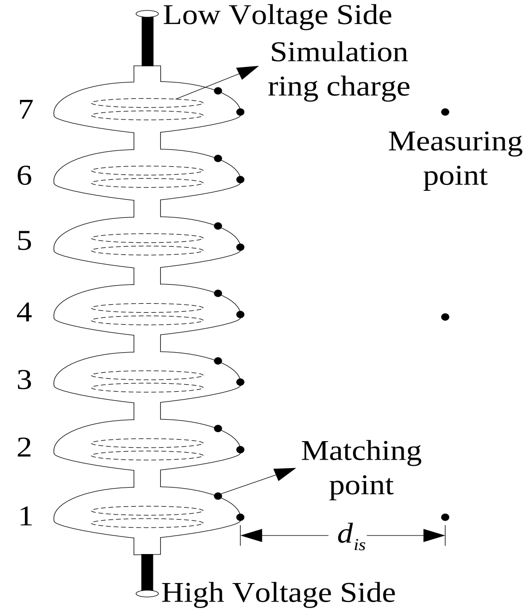


Fig. 1. Configuration of the simulation charges and matching points of the insulator of the 110 kV line.

Each corresponding piece of the insulator is numbered from 1 to 7, scaled from high voltage to low voltage. Assuming that the charges for the simulation ring are Q_1, $Q_2 \ldots Q_{14}$ and the corresponding potentials of the matching points are φ_1, $\varphi_2 \ldots \varphi_{14}$, respectively, $\boldsymbol{P}$ denotes the potential coefficient matrix. Consequently, the potential expressions based on SCM are expressed as follows.

$$\boldsymbol{U} = \boldsymbol{P}\boldsymbol{q}, \quad (1)$$

$$\boldsymbol{f}_r \boldsymbol{q} = \boldsymbol{E}_r, \quad (2)$$

$$\boldsymbol{f}_z \boldsymbol{q} = \boldsymbol{E}_z, \quad (3)$$

where $\boldsymbol{q}$ and $\boldsymbol{U}$ are the charge single matrix and the voltage single matrix, respectively. $\boldsymbol{E_r}$ and $\boldsymbol{E_z}$ denote the r-axis and z-axis components of the electric-field intensity matrix in the cylindrical coordinate, respectively. $\boldsymbol{f_r}$ and $\boldsymbol{f_z}$ are the r-axis and z-axis components of the electric-field intensity coefficient matrix in the cylindrical coordinate, respectively.

By solving the quantity of the simulation charges (e.g., equation (1)), the potential distribution or electric-field distribution is determined. This process is an electric-field forward problem used to figure out the potential distribution or electric-field distribution in the field through solving for the potential or electric-field intensity of matching points, whereas the electric-field inverse problem refers to the calculation of the potentials of the boundary points in the corresponding electric fields. In the insulator model described above, the inverse application of the SCM is aimed to estimate the electric-field intensity of several points near the insulator string and to calculate the potential distribution values on the surface of the insulator string using an optimization algorithm. The location of the fault insulators is identified by comparing the computed distribution with the standard distribution. Figure 1 illustrates the model, in which three measuring points are chosen with exactly the same level as the pieces of No. 1, No. 4, and No. 7 in the 110 kV insulator.

B. Fast multipole preprocessing

To reduce the workload for the measurements, fewer points are selected in building the calculation model of the HV electric accessory by the traditional simulation charge method. When the number of measuring points is less than the number of simulation charges, the calculation of the fundamental equation for the inverse problem is underdetermined by the system of equations [4], abstracted by the model for the problem with n source points and corresponding m field points ($n>m$). By solving the least squares solution with a certain constraint, the potential is obtained at every point. However, the traditional method needs an extremely high calculation complexity to calculate each corresponding field point and source point in the original electric field. To improve the efficiency of the matrix multiply vector and to reduce the dimension of the coefficient matrix, the fast multipole method is used to preprocess the traditional SCM model. This model simplifies the electric relationship between the field points and source points through the procedure of “polymerization-transition-disposition”. The main idea of the fast multipole method is to polymerize the effects of n source points to the center point O of the source points and to shift the effects of the center point O to the center point O' of the field, followed by the calculation of the electric-field intensity of each field point from center point O' [5].

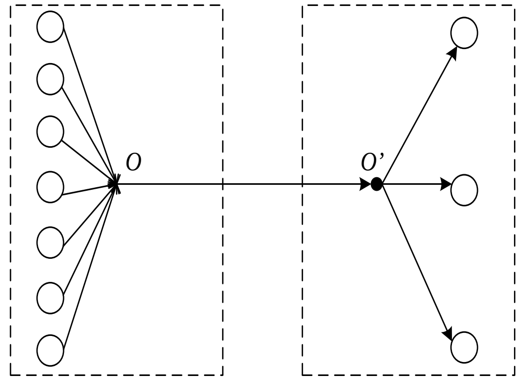


Fig. 2. Schematic diagram of the fast multipole method

According to the principle of superposition, the potentials of n simulation charges at the ith matching point is calculated as follows,

$$\varphi_i = \sum_{j=1}^{n} p_{ij} q_j \, , \tag{4}$$

where p_{ij} is the potential coefficient for the jth simulation charge with the corresponding ith matching point. For the accumulation problem, such as in equation (4), the calculation complexity is bounded by O (m*n). The values of the potential coefficients have nothing to do with the quantity of charges. However, it is determined by the shapes and positions of simulation charges, the geometric positions of field points, and dielectric constants of the mediator. To improve the calculation complexity and solve equation (4), p (r, z) is expanded as follows.

$$p(r,z) \approx \sum_{k=1}^{N} \phi_k (r - R_x) W_k (R_x - R_y) \psi_k (z - R_y), \tag{5}$$

$$\left| R_x - R_y \right| > \left| (r - R_x) - (z - R_y) \right|, \tag{6}$$

where ϕ_k, W_k, and ψ_k are the shape functions, independent of the potential, R_x and R_y, which are the points near r and z, respectively. To further improve the calculation speed, n source points are divided into M group, G_x, x = 1, 2 … M. For each corresponding group G_x, the close and far field groups are found first. Afterward, different calculation methods are used to handle the close and far field groups, which are computed directly by the methods of “polymerization-transition-disposition”.

However, in the insulator string model mentioned above, both the source points and field points are illustrated vertically. Consequently, the distance between the source points and field points are relatively uniform. In this case, the calculation is simplified, e.g., all groups are considered as a far field group. That is, for point q of each group G_x, multi-stage expansion is used to calculate φ_i. The specific computation formula is shown in equation (7).

$$\varphi_i\Big|_{q\in I_x} = \sum_{k=1}^{N} A_{x,k}\phi_k\left(r - R_x\right). \quad x = 1, 2, \cdots, M \tag{7}$$

where

$$A_{x,k} = \sum_{I_y} W_k\left(R_x - R_y\right)B_{y,k}, \quad x = 1, 2, \cdots, M;\ k = 1, 2, \cdots, N \tag{8}$$

$$B_{y,k} = \sum_{r\in I_y} q_j\psi_k\left(r - R_y\right), \quad y = 1, 2, \cdots, M;\ k = 1, 2, \cdots, N \tag{9}$$

where equations (7), (8), and (9) denote the field effects from the source of each group to the center. The field effects are due to the shifting from the field of the group center to the corresponding points of the group, as well as the assignments of the field effects of the group center to each of the field points in the corresponding group, respectively. The proposed approximation scheme above heavily reduces the complexity of the computation.

III. INVERSE DETECTING METHOD

Based on the analysis mentioned above, the implementation steps of the inverse detecting method based on electric field intensity are given as follows.

Step 1: Derive a qualitative analysis for the awaiting detection equipment and surrounding field. Simulate the awaiting detection equipment using the traditional simulation charge method. Determine the shape, quantity, and position of simulation charge. Set as few measuring points near the equipment as possible to reduce the measuring workload, in accordance with the principle of balance. Obtain the coordinates of each simulation charge, matching point, and measuring point. Build the calculation model, thus forming the SCM basic relation between the field and source, such as in equations (1), (2), and (3).

Step 2: Obtain the electric-field intensity distribution of the measuring point by measuring the apparatus online. Establish the set of equations, such as in equation (4), according to the principle of superposition. Treat them according to equations (5) and (6). Serve all simulation charges as source points. Divide them into several groups and find the close field group as well as the far field group. Perform the preconditioning of the fast multipole, such as in equations (7), (8), and (9).

Step 3: Choose the optimization method. Establish the target function. Optimize and calculate the inverse problem on the basis of fast multipole preconditioning. Obtain the actual potential distribution on the surface of the equipment. The actual potential distribution curves are compared with the national standard reference data. Then, check for faults and fault positions, thus realizing inverse detection based on the signal of the electric field.

IV. OPTIMIZATION ALGORITHM

This section will show how to derive an optimal allocation with the application of the SCM elementary model by the fast multipole method. The main principle for such an approach is to reverse the calculation of the source parameter by measuring the electric field intensity of certain points near the insulators. This procedure aims to extrapolate “the reason” based on the measured “effect”. In real situations, proper solutions to these problems are normally difficult to obtain with the absence of special methods. Therefore, the key to the solution of the electric-field inverse problem is to seek a proper optimization algorithm as well as to solve the corresponding inverse problem. The solution should show the way to work out fault detection in electric fields. This paper employed genetic algorithm (GA) and the regularization technique [6, 8].

A. Analysis of GA

The operation of GA is based on the code of parameters instead of the parameter itself. This does not require functional continuity or differentiability. GA calculates the match value through the objective function and does not require other derivation and subsidiary information, thus having less dependency on the problem itself. The insulator inverse problem (Fig. 1) is taken as an example to analyze GA optimization procedure through real coding in the electric-field inverse problem. GA with the real number coding avoids the coding and decoding procedures. Therefore, it improves the calculation efficiency.

In the process of the application of GA to solve the insulator inverse problem, the potential distribution $\boldsymbol{U}$ is considered as an optimization variable, and the object function is defined as follows:

$$\min f = \frac{1}{n}\sum_{i=1}^{n}\left|\sqrt{\boldsymbol{E}_{ir}^2+\boldsymbol{E}_{iz}^2}-\boldsymbol{E}_{0i}\right|, \quad (10)$$

where E_{0i} is the measured value of the i^{th} point, E_{ir} and E_{iz} are the r-axis and z-axis components of the calculated values, respectively.

More precisely, the application of GA in the insulator inverse problem takes the following steps.

Step 1: Initialize the position of the simulation charges, matching points, and the intensity $\boldsymbol{E_0}$ of measuring points. Randomly generate 50 initial populations.

Step 2: Calculate the voltage distribution $\boldsymbol{U_0}$ of the matching points and potential coefficient matrix $\boldsymbol{P}$.

Step 3: Calculate the quantities of the simulation charges according to $\boldsymbol{q} = \boldsymbol{P}^{-1}\boldsymbol{U}_0$, and calculate the electric-field intensity coefficient matrix $\boldsymbol{f}_r$ and $\boldsymbol{f}_z$ of the measuring points and $\boldsymbol{E}_i=\sqrt{\boldsymbol{E}_{ir}^2+\boldsymbol{E}_{iz}^2}$.

Step 4: calculate the adaptive value $\min f = \frac{1}{n}\sum_{i=1}^{n}\left|\boldsymbol{E}_i-\boldsymbol{E}_{0i}\right|$ of the object function of the current population, and examine whether it meets the convergence criteria. If yes, let $\boldsymbol{U}$ be the actual voltage. Otherwise, it generates a new filial population from the selection. Crossover the variation calculations followed by Step 2 again.

B. Analysis of Tikhonov regularization

The condition of the inverse problem is contributed by the filtration function of the positive operator. The distinctness of the different solution is strained away after mapping by the positive operator. In addition, the data are obtained through discrete and finite observations after being polluted by noise, further intensifying the fault detection problem. To solve the fault detection problem, prior information binding into the regularization technique should be increased [7]. Coupling the prior information to the solving process of the inverse problem approximates the inverse operator through a better operator, thereby enabling the recovery of lost information.

The exact solution to the inverse problem is normally difficult to solve in a time-efficient manner. Therefore, the least squares method is employed to seek the approximate solution for the linear system of equations $\boldsymbol{Ax} = \boldsymbol{y}$, which is the minimum norm $\|\boldsymbol{Ax}-\boldsymbol{y}\|^2$. This paper transfers the inverse problem into the problem to solve $\boldsymbol{q}^*$ (e.g., a functional extreme problem) according to the least squares method:

$$\min_{q\in Q}\|\boldsymbol{fq}-\boldsymbol{E}\|^2, \quad (11)$$

where $\boldsymbol{E}$ is the measured value of the electric-field intensities from the measuring points. The charges on the surface of insulators are bounded. Equation (11) meets the boundary condition: $\sum_{i=0}^{m} q_i = 0$. Moreover, proof is presented that equation (12) is equivalent with the above extreme value problem, named the normal equation of equation $\boldsymbol{E} = \boldsymbol{fq}$:

$$\boldsymbol{f}^*\boldsymbol{fq}=\boldsymbol{f}^*\boldsymbol{E}, \quad (12)$$

where $\boldsymbol{f}^*$ is associated operator of $\boldsymbol{f}$. The normal equation (12) inherited and exacerbated the ill condition of the original equation, thus necessitating the increase of a penalty term $\alpha\|\boldsymbol{q}\|^2$ to punish $\boldsymbol{q}$, which is a norm that is too large to solve the fault detection of the above extreme value problem. To obtain better performance, equation (11) is rewritten as:

$$\min_{q\in Q}\left(\|\boldsymbol{fq}-\boldsymbol{E}\|^2+\alpha\|\boldsymbol{q}\|^2\right). \quad (13)$$

Therefore, $\|\boldsymbol{fq}-\boldsymbol{E}\|^2 + \alpha\|\boldsymbol{q}\|^2$ is transformed into a Tikhonov function and the solution $\boldsymbol{q}_\alpha$ of the extreme value problem such as that in equation (13). The only solution of the normal equation is

$$\boldsymbol{f}^*\boldsymbol{fq}_\alpha+\alpha\boldsymbol{q}_\alpha=\boldsymbol{f}^*\boldsymbol{E}. \quad (14)$$

Further calculation for the corresponding components is done by the following equation:

$$\boldsymbol{q}_\alpha=\left(\boldsymbol{f}^*\boldsymbol{f}+\alpha\boldsymbol{I}\right)^{-1}\boldsymbol{f}^*. \quad (15)$$

The next step is to determine the iterative method after having the optimal target function such as in Equation (13). The Newton iteration algorithm is adopted to solve the insulator electrical inverse problem. The concrete calculation process is given as follows:

Step 1: Choose the initial solution $\boldsymbol{q}_0$ and regularization parameter α. The selection method of the regularization parameter is given as a reference.

Step 2: Calculate the object function $J_\alpha(\boldsymbol{q})\|\boldsymbol{fq} - \boldsymbol{E}\|^2 + \alpha\|\boldsymbol{q}\|^2$.

Step 3: Examine the condition of the convergence. If the adaptive value satisfies the condition of convergence, it exits the procedure. Otherwise, it repeats Step 2.

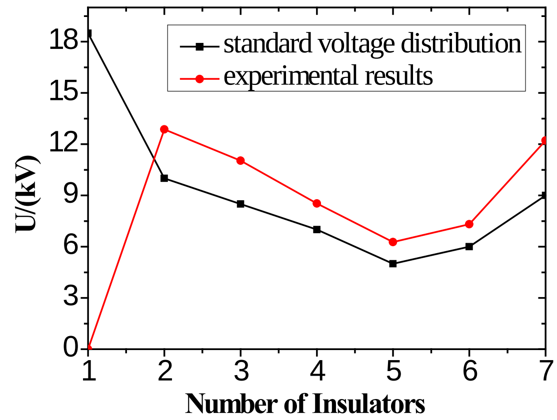
V. EXAMPLE CALCULATION AND ANALYSIS

Figure 1 shows one phase insulator string under 110 kV. Each insulator string has seven slices. The distribution of the charge is simulated by two ring simulation charges and two matching points chosen on the surface of each insulator. For the test, r=0.127m, h=0.146m, h_0=15m, l=0.5m, where r is the radius of each insulator; h is the actual height of each insulator; h_0 is the terrain clearance of the first insulator; l is the horizontal distance between the measuring point and insulator string. In addition, according to the principle of optimal radius, the radius of the ring simulation charge is 4 m.

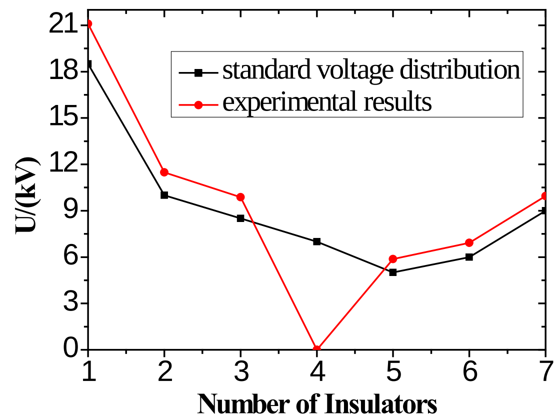
The normal voltage distributions of each insulator are in the order of 18.5, 10.0, 8.5, 7.0, 5.0, 6.0, and 9.0 kV (from number 1 to 7). Through the measurement of the insulation resistance, the fault insulator may be obtained from the power supply company. In this work, number 1, 4, and 7 insulators are separately replaced as fault insulators. Thus, in this case, the measured value of three groups of the electric field intensity in three measuring points would be obtained by the measuring apparatus. Table 1 illustrates the experimental results in the case with l=0.5 m.

Table 1: Electric-field intensity at 3 measuring points (kV/m)

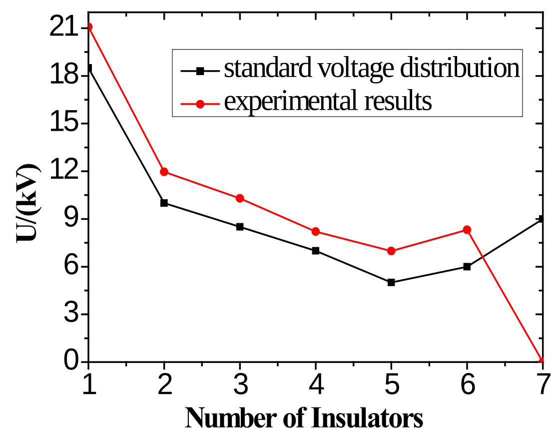
Number	Without faulty	No. 1 insulator is fault	No. 4 insulator is fault	No. 7 insulator is fault
1	9.0475	3.6718	8.9915	9.2796
2	5.0248	4.9232	3.3699	5.6537
3	4.3841	4.7398	4.2103	2.8172



(a) Scenario under a faulty No.1 insulator



(b) Scenario under a faulty No.4 insulator



(c) Scenario under a faulty No.7 insulator

Fig. 3. Comparison between actual and normal values.

After inducing the model parameters and electric field intensity of the measuring points in the calculation program, the voltage distribution curve of every insulator is obtained through either GA or Tikhonov regularization. The calculation results show that the proposed method obtains the expected one. The trend of the curve is given as follows.

The experimental calculation results show that the relative errors are controlled within the allowed interval. The errors caused by the shift of the measuring points are indispensable. Therefore, this work aims to analyze the errors caused by the shift in the measuring points. The conclusions are given as follows.

(1) Voltage distribution changes significantly when the measuring points shift at the horizontal direction. The analysis shows that the corresponding error is less than 20% when the shift distance of the corresponding measuring points is approximately 0.5 m at the horizontal direction based on the GA. However, the voltage distribution changes very little when the measuring points shift at the vertical direction.

(2) By inducing more parameters into the calculation program of the Tikhonov regularization, the errors are reduced to 13%. Further, the intervention of the regularization technique is helpful to speed up the process.

VI. CONCLUSION

This paper proposed a novel inverse approach for the fault detection problem in electric fields. The approach is based on a non-trivial combination of the fast multipole scheme and traditional simulation charge method. Moreover, a new genetic algorithm combined with the Tikhonov regularization is proposed to speed up the inverse process for fault detection in electric fields further. The superiority of the proposed new inverse approach, in terms of time efficiency and accuracy for fault detection, was demonstrated by the simulation results. The present work hopes to stimulate future studies on fault detection tasks in electric fields.

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