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NEWTON ITERATIVE ALGORITHM BASED ON GAUSS METHOD FOR LOCATING PARTIAL DISCHARGE IN TRANSFORMERS

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Abstract: Locating Partial Discharge (PD) sources accurately in power transformers is of great importance for maintenance scheduling, maintenance efficiency and even operational risk analysis. Techniques for locating the source of PD are constantly a hot research topic. Location algorithm is one of the research contents. At present major problems existing in locating algorithms are being sensitive to time-delay error, local convergence or divergence and a large amount of computational time. To solve these problems, Newton iterative algorithm based on the Gauss method is suggested in this paper. At the end, PD location experiments and calculations were carried out on a real power transformer to verify the algorithm.

1 INTRODUCTION

Partial Discharge Location in Power Transformers by Ultra-Wideband (UWB) RF Detection is one of the research focus[1-10]. It is a novel technology based on antenna array detection and time-difference algorithm for power transformers. PD electromagnetic radiation signals are received by 4 sensors array which are fixed on the transformer to get 3 time difference of arrival (TDOA) value, together with the PD radiated electromagnetic propagation speed, the time delay equations set is obtained. Finally certain algorithms such as Time-Difference Algorithm are used to finish the location calculation. Compared with other methods such as Ultrasonic Method and Electrical Method, the sensors are motionless which are fixed on the transformer; The velocity of UHF electromagnetic wave is very fast. So it can be seen that the traditional algorithm is sensitive to the time delay measurement error, if there is a slight delay value of the parameter error (1ns error or less), it will likely lead to algorithm results divergence or large error. When it is carried out on the real transformer, because of the real structure of transformer and the complexity of propagation mechanism of radio frequency electromagnetic wave and the background noise level and other factors, it is not conducive for the precision measurement of time delay values. Therefore it is necessary to improve the algorithm to reduce the influence of the measurement error, velocity and other parameters for the location.

Article [11]-[16] put different optimization algorithms to solve the problems appeared in the process of solving the Hyperbolic equations; [11]-[12] combined with Newton iterative method and other methods, put forward the optimization algorithm. [13] proposed global search strategy based on genetic algorithm. [14] used annealing algorithm and clustering theory to improve the genetic algorithm, which overcomes the problem that traditional genetic algorithm can easily fall into local optimal solution caused by precocious phenomena, and it has good convergence properties. [15] described the application of the Improved ant colony search algorithm in PD location, improving the accuracy and stability of the locating result. [16] used particle swarm optimization (PSO) algorithm, which can effectively avoid stagnation phenomenon caused by the single search mechanism, and avoid the algorithm oscillating even divergent in boundary, numerical simulation proved the effectiveness of the method.

In addition to the optimal algorithms introduced above, [17] described the pattern recognition method. The transformer will be divided into several modules, take the theory distances from each module centre to each sensor as a standard model, and the calculating distances based on the actual delay time measured as a model to be determined. Make the standard model which is the nearest to the model to be determined as the last locating area. Its accuracy is high, and it avoids the problem of selecting the initial point, local convergence or divergence problems in existing algorithms. However, the calculation time is too long, and this method is the discrete algorithm, the locating result is not the optimal solution because of the existence of measurement errors.

So it can be seen that the sensitive to the time-measurement error, local convergence or divergence, slow speed of operation are the three major difficulties in the locating algorithms. In order to overcome these three difficulties, Gauss-Newton algorithm is proposed. And at the end, PD location experiments and calculations are carried out on a real power transformer to verify the algorithm proposed.

2 UHF PARTIAL DISCHARGE LOCATION MODEL

With a four-sensor array to detect the RF PD signals, 3 time-delay vectors can be achieved. Then the hyperboloid equations set are established, we can get the coordinate of PD source (x, y, z) by solving the equations set.

Provided the propagation time of PD source P(x, y, z) to sensor S1(x_1, y_1, z_1) is t_1, then the distance from P to S1 is r_1:

$$r_1 = \sqrt{(x-x_1)^2 + (y-y_1)^2 + (z-z_1)^2} = c \cdot t_1 \qquad (1)$$

Where: c = The velocity of EM waves.

With reference sensor S1, assume that the time-delay(TD) of the signal is $\tau_{1i} = t_i - t_1$, i=2,3,4, then the coordinates of P and Si satisfy Eq (2):

$$\begin{cases} r_1 = \sqrt{(x-x_1)^2 + (y-y_1)^2 + (z-z_1)^2} = c \cdot t_1 \\ r_2 = \sqrt{(x-x_2)^2 + (y-y_2)^2 + (z-z_2)^2} = c \cdot (t_1 + \tau_{12}) \\ r_3 = \sqrt{(x-x_3)^2 + (y-y_3)^2 + (z-z_3)^2} = c \cdot (t_1 + \tau_{13}) \\ r_4 = \sqrt{(x-x_4)^2 + (y-y_4)^2 + (z-z_4)^2} = c \cdot (t_1 + \tau_{14}) \end{cases} \qquad (2)$$

By measuring each TD, with c(=20.3cm/ns) is already known, then the coordinates of P could be obtained using appropriate algorithm. In this paper, the Newton iterative method is used to linearize and solve the equations set.

2.1 The Newton form of the Hyperbolic equations set

Newton iterative method is a classical method to solve nonlinear equations. Newton iteration, also known as Newton-Raphson method, is proposed by Newton in the 17th century as an approximation method to solve equations in the real domain and complex domain. The basic idea is to make the nonlinear equations linearized and make the solution of linear equations approach to the solution of nonlinear equations as close as possible.

Eq (2) can be written as follows:

$$\begin{cases} f_1(\mathrm{x,y,z,t_1}) = (\mathrm{x}-\mathrm{x}_1)^2 + (\mathrm{y}-\mathrm{y}_1)^2 + (\mathrm{z}-\mathrm{z}_1)^2 - c^2\mathrm{t}_1^{\,2} = 0 \\ f_2(\mathrm{x,y,z,t_1}) = (\mathrm{x}-\mathrm{x}_2)^2 + (\mathrm{y}-\mathrm{y}_2)^2 + (\mathrm{z}-\mathrm{z}_2)^2 - c^2(\mathrm{t}_1+\tau_{12})^2 = 0 \\ f_3(\mathrm{x,y,z,t_1}) = (\mathrm{x}-\mathrm{x}_3)^2 + (\mathrm{y}-\mathrm{y}_3)^2 + (\mathrm{z}-\mathrm{z}_3)^2 - c^2(\mathrm{t}_1+\tau_{13})^2 = 0 \\ f_4(\mathrm{x,y,z,t_1}) = (\mathrm{x}-\mathrm{x}_4)^2 + (\mathrm{y}-\mathrm{y}_4)^2 + (\mathrm{z}-\mathrm{z}_4)^2 - c^2(\mathrm{t}_1+\tau_{14})^2 = 0 \end{cases} \qquad (3)$$

Summarized as follows:

$$f_i(x,y,z,t_1) = (x-x_i)^2 + (y-y_i)^2 + (z-z_i)^2 - c^2(t_1+\tau_{1i})^2 = 0 \qquad (4)$$

(3) is a quaternary quadratics equations set, we can expand f(X) into Taylor series near the point of its solution X_0 (x_0, y_0, z_0, t_{10}), ignore the quadratic remainder terms of Taylor series, and make $f = (f_1, f_2, f_3, f_4)^T$, $X = (x, y, z, t_1)^T$,where X is the solution vector. Then Eq (5) can be obtained:

$$f(\mathbf{X}) = f(\mathbf{X}^0) + \sum_{i=1}^{4} \frac{\partial}{\partial \mathbf{X}_i} f(\mathbf{X}^0) \cdot (\mathbf{X}_i - \mathbf{X}_i^{\,0}) \qquad (5)$$

Expressed as the form of Newton iteration:

$$\mathbf{X}^1 = \mathbf{X}^0 - \mathbf{J}^{-1} \cdot f(\mathbf{X}^0) \qquad (6)$$

Where J is Jacobian determinant.

$$\mathbf{J} = \begin{bmatrix} \frac{\partial f_1}{\partial x} & \frac{\partial f_1}{\partial y} & \frac{\partial f_1}{\partial z} & \frac{\partial f_1}{\partial t_1} \\ \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots \\ \frac{\partial f_4}{\partial x} & \frac{\partial f_4}{\partial y} & \frac{\partial f_4}{\partial z} & \frac{\partial f_4}{\partial t_1} \end{bmatrix} \qquad (7)$$

Then select the appropriate initial value X_0 (x_0, y_0, z_0, t_{10}) for iteration, set the bound δ based on the principle of the least square error, and set the accuracy bound ε, iterations are completed when it satisfies the following conditions Eq (8), the solution is the locating result.

$$\left|\sum_{i=1}^{4} f_i^{\,2}\right| \le \delta \quad \delta>0,\ \varepsilon>0 \qquad (8)$$
$$\left|\mathbf{X}^1 - \mathbf{X}^0\right| \le \varepsilon$$

Since the Newton iteration is local convergence, therefore, it requires the initial value selected in the vicinity of the true solution, if not, it will be difficult to guarantee the convergence of the algorithm. In practice, the location of the initial value is difficult to establish. Gauss iteration is a kind of method to solve linear or nonlinear equations. The choice of its initial value is not strict. Using this characteristic, this paper presented Gauss-Newton iteration method. It uses the result calculated by the Gauss iteration in the first few steps as the initial value of Newton iteration, the iteration stops when it meet the constraints of Eq (8), the output is the locating results.

2.2 Gauss iteration Method for the initial value

Gauss iteration method can solve linear equations or nonlinear equations. It is widely used to solve the Power Flow problem in the 1950s. The iterative schemes of Gauss method can be obtained by some modifications of Eq (3):

$$\begin{cases} x^{(k+1)} = \sqrt{c^2 t_1^{(k)2} - (z^{(k)} - z_1)^2 - (y^{(k)} - y_1)^2} + x_1 \\ y^{(k+1)} = \sqrt{c^2 (t_1^{(k)} + \tau_{12})^2 - \left(z^{(k)} - z_2\right)^2 - \left(x^{(k+1)} - x_2\right)^2} + y_2 \\ z^{(k+1)} = \sqrt{c^2 (t_1^{(k)} + \tau_{13})^2 - \left(y^{(k+1)} - y_3\right)^2 - \left(x^{(k+1)} - x_3\right)^2} + z_3 \\ t^{(k+1)} = \dfrac{\sqrt{(x^{(k+1)} - x_4)^2 + (y^{(k+1)} - y_4)^2 + (z^{(k+1)} - z_4)^2}}{c} - \tau_{14} \end{cases} \quad (9)$$

Iteration can start after setting the initial value($x^{(1)}$,$y^{(1)}$,$z^{(1)}$,$t_1^{(1)}$), then we can use the result after several iterations as the initial value of Newton iteration.

3 EXAMPLES AND ANALYSIS

To test the practical effect of localization algorithm, an experiment was carried out in a 220kV three-phase two-winding transformer.

3.1 Test equipment and set

We detected partial discharge signals with the four special high-frequency sensors installed in the transformer, shown in Figure 1.

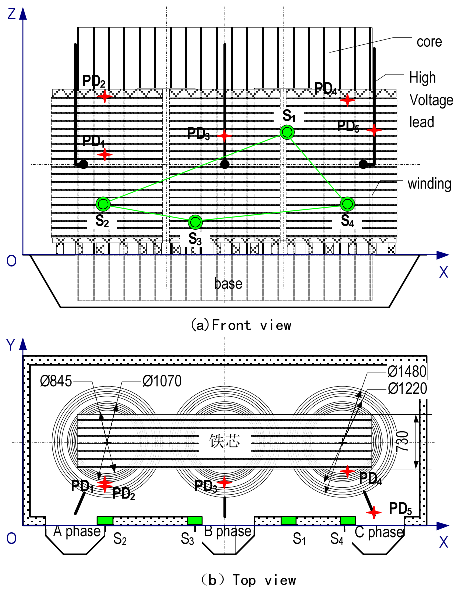

Fig. 1 The location of the PD model and sensors

With the vertex of the bottom of A phase high voltage side as coordinate origin O, the length of the transformer as the X-axis direction, the thickness direction as the Y-axis, the height direction as the Z-axis, the three-dimensional Cartesian coordinate system was established. The coordinates of the four sensors were: S1 (353,20,162), S2 (108,20,68), S3 (231,20,43), S4 (434,20,68).

In order to fully examine the practical effect of the location algorithm, we had set partial discharge models in the central and corner of the transformer, internal and external of the winding respectively. Coordinates of its location is shown in Figure 1 and Table 1.

Table 1: Coordinates of PD sources

No.	Location of the discharge model	Coordinate/cm
1	A phase	(112,56,130)
2	A phase	(112,52,216)
3	B phase	(275,55,130)
4	C phase	(392,83,215)
5	C phase	(461,36,148)

We use Lecory8620A high-speed four-channel digital oscilloscope as the signal acquisition unit, its analog bandwidth is 0-6GHz, single-channel sampling rate is 20GS/s, sampling interval is 0.05ns.

3.2 The measurement and locating results

The theoretical delay time τ_{li1} (i=2,3,4) can be calculated by using the coordinates of the PD model and the sensors, and the real-measured delay time τ_{ci1} can be estimated by reading the reaching time from the PD source to the sensors, and then the measurement errors of the delay time $\Delta\tau_{i1}$ can be calculated by using the following formula:

$$\Delta\tau_{i1} = \tau_{ci1} - \tau_{li1} \quad (10)$$

We use Gauss-Newton iteration method to calculate equations set based on the measured delay time, and pattern recognition method is also provided as a comparative analysis.

The delay time values and calculation results of the 5 discharge models are shown in Table 2.

Table2 The date of measured time-delay and calculated PD location

NO.	Theoretical delay time (ns) τ_{li1},i=2,3,4	Measured delay time (ns) τ_{ci1},i=2,3,4	Measurement errors (ns) $\Delta\tau_{i1}$,i=2,3,4	Gauss-Newton method locating result(cm)		Pattern recognition method locating result(cm)	
				Coordinates	Error	Coordinates	Error
1	-8.58,-4.67,4.12	-9.07,-4.88,4.02	-0.49,-0.21,-0.10	(104,65,123)	13.9	(108,56,124)	7.2
2	-4.81,-1.83,5.24	-5.12,-2.01,5.33	-0.31,-0.18,0.09	(118,20,208)	33.5	(108,18,214)	34.3
3	4.45,0.59,4.05	4.05,0.40,4.10	-0.40,-0.19,0.05	(270,60,131)	7.1	(270,58,132)	6.2
4	11.59,7.54,3.64	11.63,7.71,3.75	0.04,0.17,0.09	(396,79,230)	16.0	(396,78,228)	14.5
5	12.44,7.08,-1.18	12.96,7.55,-1.44	0.52,0.47,0.26	(481,20,158)	27.5	(508,20,172)	55.4

3.3 Locating calculation results analysis

(1) The convergence of Gauss-Newton method

Set the conditions for the ending iterative: $\delta = 10^{-4}\,\varepsilon = 10^{-1}$, then the convergence can be achieved by no more than 20 iterations according to Eq (8).

(2)The influence of measurement errors for the locating results

The measured error in this experiment is between 0 and 0.5ns, the locating result errors are less than 30cm, which meet the practical engineering requirements.

In Table 2, the measurement error of model 1 or 3 is larger than model 2, but the locating error is less than model 2. So the locating error is not proportional to the measurement error.

(3)The locating accuracy of Gauss-Newton iteration

In Table 2,the locating error of Gauss-Newton method is greater than pattern recognition method for model 1; for model 2、3 and 4,the locating errors of two methods are considerable; for model 5,the error of Gauss-Newton method is less than pattern recognition method. So the effect of two methods is considerable.

Given that the convergence conditions of Gauss-Newton method are very harsh, so it can be considered the iteration result is the true solution. While the pattern recognition method is a discrete algorithm based on the space meshing, whose optimal solution depends on the spatial grid size and the coordinate of the centre, the error of its optimal solution can not be estimated.

(4)The computational speed of Gauss-Newton method

The iterations of Gauss-Newton method is not more than 20 times in each calculation, the overall computation time is in ms level. While the pattern recognition method have to split the transformer and compute each grid one by one; Take the transformer in this paper for example, its volume is about $5\times2.6\times4m^3$, if the mesh size is 2cm, the time-consuming of one locating operation will be more than 10 minutes.

Actually, in order to improve the reliability and accuracy of PD location, it needs for dozens of computing, which will make higher demands on the speed of location algorithm. Gauss-Newton algorithm is undoubtedly of great advantage.

4 CONCLUSION

Locating algorithm has a very important role and significance for the UHF locating technology. This paper analyzes the advantages and problems of several locating algorithms, and put forward that the sensitivity to time-error, local convergence or divergence, slow speed of operation are the three major difficulties in the existing locating algorithms. In order to overcome these three difficulties, Gauss-Newton algorithm is introduced. And test the practical effect of the algorithm by an experiment carried out in the real transformer: (1)The locating accuracy meets the need for engineering application; (2)The Gauss-Newton algorithm has global convergence;(3)This algorithm has fast speed of convergence, the computation time is in milliseconds.

Because of the real structure of transformer and the complexity of propagation mechanism of radio frequency electromagnetic wave and the backg-round noise level, it is not conducive for the accurate measurement of time-delay values. This could seriously affect the locating result. To improve the precision further more, a statistical analysis for the calculated results is needed; and statistical methods need to be further explored.

Existing locating algorithms have a low locating accuracy for the corner point in the transformer, so it also needs to optimize the locating algorithm and sensor array layout scheme.

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