Qing XIE, Shuyi CHENG, Fangcheng LÜ

Hebei Provincial Key Laboratory of Power Transmission Equipment Security Defence, North China Electric Power University, P.R.China

Partial Discharge Location in Oil Using Ultrasonic Phased Array

Abstract. *A new PD-locating method based on an ultrasonic phased array was proposed. First, a PD-locating system was established. Second, TCT algorithm was used to focus the wide-band signals on the narrowband signals. Then, the improved MUSIC algorithm was used to detect the direction and elevation angles. Finally, we performed a global search of the min-distance function with the genetic algorithm to obtain the accurate geometric space coordinates of the PD source. The result from the experiment shows that the location error was 5.6 cm.*

Streszczenie. *W artykule przedstawiono metodę lokalizacji wyładowań niezupełnych, opartą na metodzie ultradźwiękowej PA. Opis składa się z czterech części, odnoszących się do etapów opracowywania. Algorytm poddano weryfikacji eksperymentalnej. (**Lokalizacja wyładowań niezupełnych w oleju z wykorzystaniem metody ultradźwiękowej PA**).*

Keywords: PD ultrasonic phased array, TCT algorithm, Improved MUSIC algorithm, multi-platform measuring direction
Słowa kluczowe: wyładowanie niezupełne, metoda ultradźwiękowa PA, algorytm TCT, algorytm MUSIC.

Introduction

The primary reason for the deterioration of insulation in electrical equipment is partial discharge (PD). The methods currently employed for location of PD source include the electric method [1], ultrahigh frequency method [2] and ultrasonic method [3]. These methods have their own particular advantages and limitations. The electric method works by detecting the pulse current flowing through the earthing wire at end of a conduit in electrical equipment. This method is difficult to apply on-line due to serious electromagnetic interference. In the ultrahigh frequency method, several sensors are positioned at different locations in order to receive ultrahigh frequency PD signals time difference which is used to locate the PD source. In this paper a method is proposed for locating partial discharge in oil based on an ultrasonic phased array. First, a PD localization experiment platform was established using a 4×4 ultrasonic phased array while the coordinates of PD source were set. Second, the array was then used to receive PD ultrasonic signals from three different positions. Then TCT and improved MUSIC algorithms were used to pre-process the signals and estimate the direction of arrival (DOA) from the PD source to the three sensors. Finally, the coordinates of PD source were accurately located according to minimum distance theory and genetic algorithm. The experimental results verified this method.

Obtaining the PD ultrasonic array signal

The 4 × 4 PD ultrasonic phased array comprises of array elements, a sound-absorbing back lining, an acoustic matching layer and an enclosure. Sensors were evenly spaced and arranged in a square (4 rows × 4 columns) with a distance of 5mm between the elements. Each array element was made of titanate with a center frequency of 150 kHz and thickness of 14 mm. The sound-absorbing back lining was made of tungsten powder and epoxy resin. The matching layer was made of silicon rubber and ensured the sensitivity of the array elements. A schematic diagram and a photograph of the finished product of 4×4 PD ultrasonic phased array used in this study is shown in Figure 1 (1: 25-core cable, 2: compression nut, 3: stainless steel cover, 4: lead or array element, 5: washer, 6: acoustic damping block, 7: piezoelectric array element, 8: stainless steel enclosure, 9: silicon rubber, 10: ceramic coating). The PD localization experiment platform established according to the 4×4 PD ultrasonic phased array consisted of a voltage booster, a system simulating discharge in oil, a signal receiving and transmitting system, a multi-channel synchronous data acquisition and processing system and a computer.

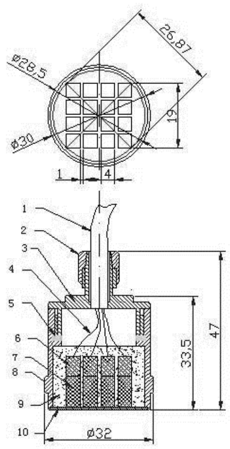

Fig.1. Section drawing of PD ultrasonic phased array

The schematic diagram of the system is shown in Figure 2. The voltage booster comprises of a voltage regulator (1) and boosting transformer (2). The simulated PD source (3) uses a 3-capacitor discharge tube to simulate partial discharge in oil. The simulated PD source can be placed at specified positions in experiment. The system simulating discharge in oil (4) comprised of an oil tank model and the simulated PD source. The oil tank model was made by welded a uniform steel plate onto the three sides and glass plate on one side. All four sides were marked with scales to determine the mounting position of the sensor array. The tank dimensions are 150cm long, 100cm wide and 120cm high with steel plate thickness of 5mm and (5) is the finished ultrasonic phased array . The multi-channel data acquisition system (6) is shown in Figure 3. Sampling frequency range is 1kHz-10MHz and sampling length range is 1k-512k. Each channel can realize 20 kHz-312.5 kHz band pass filtering with adjustable amplification factor 1-256 and linked to the computer (7).

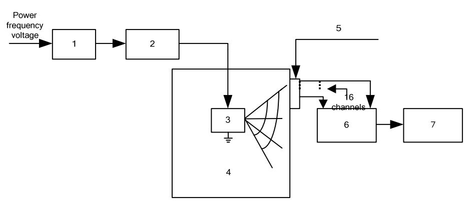

Fig.2. Schematic of system for PD localization experiment

In the experiment the following parameters were used: the sampling frequency of 10MHz, filtering range of 60 kHz-200 kHz and a amplification of 256. As shown in Figure 4, (30, 45, 25) cm are set as the spatial coordinates of the PD source and the sensors are arranged at positions 1 (50, 0, 0) cm, 2 (0, 30, 0) cm and 3 (20, 150, 0) cm.

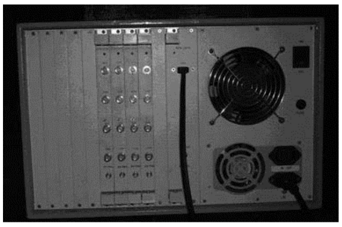

Fig. 3 Multi-channel synchronous data acquisition system

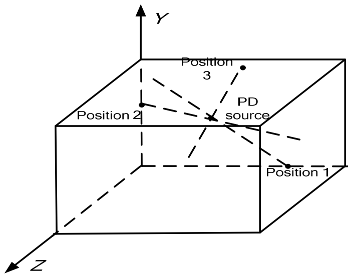

Fig.4. Schematic diagram of the experiment

Therefore, the theoretical azimuth angles and pitch angles can be determined: azimuth angles: $\theta_1 = 114^\circ$, $\theta_2 = 26^\circ$, $\theta_3 = 85^\circ$; pitch angles: $\phi_1 = 27^\circ$, $\phi_2 = 37^\circ$, $\phi_3 = 13^\circ$.The signals measured are shown in Figure 5.

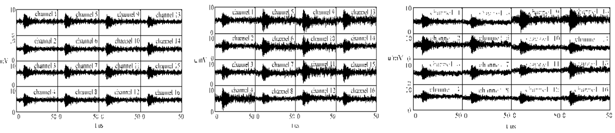

Fig.5. Oscillograms of ultrasonic array signals at position 1,2,3

DOA estimation for the PD source

1. Preprocessing

The PD ultrasonic signal in oil is a wideband signal, hence directly using the DOA algorithm of narrow-band array signal to estimate the DOA of PD ultrasonic signal will result in a large decrease in location accuracy or even failure. The acquired PD ultrasonic wideband array signals therefore have to be first focused [4].

Assuming that the model of wideband array signals is $X(f_j){=}A_\theta(f_j)S(f_j)+N(f_j) \quad j=1,2,\cdots,J$. where, $X(f_j)$ is received data vector of array signals; A_θ is a M x N matrix and the wideband consist of J narrow-bands; $S(f_j)$ is the data vector of original signals; and $N(f_j)$ is the spatial data matrix of noise received in j^{th} section.

The transformation matrix $T_\beta(f_j)$ is used to transform data with J different frequency ranges into data with a same center frequency. Assuming that the transformation matrix is:

(1) $$T_\beta(f_j)A_\beta(f_j)S(f_j) = A_\beta(f_0)S(f_0)$$

Since the data vector of signal $S(f_j)$ cannot be determined from the received data, calculation of the covariance matrix for both left and right of this equation simplify to(If the error is considered):

(2) $$\min_{T_\beta(f_j)} \left\| P(f_0) - T_\beta(f_j)T_\beta^H(f_j) \right\|_F \qquad j = 1,2,\cdots,J$$

where $P(f_j) = A_\beta(f_j)R_S(f_j)A_\beta^H(f_j)$ and the covariance matrix $R_S(f_j) = S(f_j)S^H(f_j)$., the above equation transforms into: Appling a normalization constraint on the focusing matrix to this equation:

(3) $$T_\beta^H(f_j)T_\beta(f_j) = I$$

Gives

(4) $$T_\beta(f_j) = \vec{Q}_\beta(f_0)\vec{Q}_\beta^H(f_j)$$

where $\vec{Q}_\beta(f_0)$ and $\vec{Q}_\beta(f_j)$ are the eigenvectors of P_0 and P_j respectively.

2 PD ultrasonic array signal direction-finding algorithm based on improved MUSIC

2.1 Principle of classic MUSIC algorithm

The Multiple Signal Classification algorithm (MUSIC algorithm for short) [6] is a classical approach to spatial spectrum estimation based on an analysis of the feature structure. The MUSIC algorithm utilizes the orthogonality between signal subspace and noise subspace to construct a spatial spectrum function and then detect the DOA of signal by searching for the spectral peak. When considering the incidence of D narrow-band signals $(S_1, S_2, \cdots, S_d)$ onto an array, consisting of M elements with the distance between elements of d, the output vector of array represented as:

(5) $$X(t) = A(\Theta)S(t) + N(t)$$

where Θ is a parameter containing the azimuth angle θ and the pitch angle φ of signal source. The covariance matrix R of array output vector $X(t)$ is given by:

(6) $$R{=}E\left[XX^H\right] = AE\left[SS^H\right]A^H + \sigma^2 I = AR_S A^H + \sigma^2 I$$

where $R_S{=}E\left[s(t)s(t)^H\right]$ is the covariance matrix and $\sigma^2 I = E\left[n(t)n(t)^H\right]$. Rows in array manifold A are independent from each other, when incident signals are uncorrelated, R is a nonsingular matrix, so

(7) $$rank(AR_s A^H) = D$$

Since R_s is a positive definite matrix, the matrix $AR_s A^H$ is a nonnegative definite one having D positive eigenvalues and (M-D) eigenvalues of 0. The $\sigma^2 \geq 0$, AR_sA^H is nonnegative definite and R is a full-rank matrix, so that R has M true positive eigenvalues. Carrying out eigen-decomposition on the covariance matrix of array R, gives:

(8) $R=\sum_{i=1}^{M}\lambda_i e_i e_i^H = U_s\Sigma_s U_s + U_n\Sigma_n U_n^H$

Using $\lambda_1, \lambda_2, \cdots, \lambda_M$ to represent the eigenvalues of covariance matrix of array R and ranking the eigenvalues in descending order, gives:

(9) $\lambda_1 > \lambda_2 > \cdots \lambda_D > \lambda_{D+1} = \lambda_{D+2} = \cdots \lambda_M$

Where the subspace spanned by eigenvectors corresponding to D big eigenvalues of R is signal subspace, the subspace spanned by eigenvectors corresponding to (M-D) small eigenvalues is noise subspace. The classical MUSIC algorithm is proposed on the basis of this feature, however since the length of actual data matrix is finite, maximum likelihood estimation of covariance is given by:

(10) $$\hat{R}=\frac{1}{N}\sum_{i=1}^{N}XX^H$$

The eigenvector matrix of noise subspace can be worked out by carrying out eigen-decomposition on $\hat{R}$. $a(\Theta)$ is not fully orthogonal to $\hat{U}_n$ due to noise, therefore the DOA is detected through minimal optimization of search:

(11) $$\Theta_{MUSIC}=\underset{\Theta}{\operatorname{argmin}}\, a^H(\Theta)\hat{U}n\hat{U}n^H a(\Theta)$$

Hence the spatial spectrum estimation equation based on classic MUSIC algorithm is given by:

(12) $$P_{MUSIC}=\frac{1}{a^H(\Theta)\hat{U}n\hat{U}n^H a(\Theta)}$$

2.2 DOA estimation based on improved MUSIC

The classical MUSIC algorithm has become a mature system and can be readily programmed; however research has shown that directly using it for detecting PD in oil in electric equipment, the resolution and the estimation accuracy are poor. This paper therefore proposes an improved MUSIC algorithm to estimate the DOA of PD in oil using the following procedures:

(1) Provided J is an $M \times M$ reversed unit matrix:

(13) $$J=\begin{bmatrix}0 & 0 & \cdots & 0 & 1\\ 0 & \cdots & 0 & 1 & 0\\ \vdots & \cdots & & \cdots & \vdots\\ 1 & 0 & \cdots & 0 & 0\end{bmatrix}$$

$R_X = R + JR^*J$, where $R=E[XX^H]$ is the covariance matrix of array signal and R^* is conjugated to R . (2) Singular value decomposition on R_X gives:

(14) $$[U,S,V]=svd(R_X)$$

where U is the covariance matrix of noise and V is the eigenvector corresponding to the eigenvalues of covariance matrix of received signals. Take $V_U = U(;,D+1:M)$ as the eigenvector corresponding to eigenvalues of noise. (3) we can use the low-rank matrix R_1 to replace the full-rank matrix R_X and carry out singular value decomposition on R_1 to get $[U_U, S_{SS}, V_V]=svd(R_1)$ whilst taking $V_{UU}=U_U(;,D+1:M)$ as the eigenvector corresponding to eigenvalues of noise.

(4) Determine the weighted average of two eigenvectors of noise:

(15) $$V_n = (V_{UU}+V_U)/2$$

(5) Using equation (18) to work out the azimuth angle and the pitch angle of PD ultrasonic array signal gives:

(16) $$P_{MUSIC}=\frac{1}{a^H(\Theta)\hat{V}_n\hat{V}_n^H a(\Theta)}$$

Determining direction of PD ultrasonic signals

Preprocess the three groups of array signals in section 2.3 and then use the improved MUSIC algorithm to determine the direction to obtain the azimuth angles θ and pitch angles φ being $\theta_1=116.8^\circ$, $\theta_2=28.3^\circ$, $\theta_3=87.9^\circ$, $\phi_1=30.1^\circ$, $\varphi_2=39.2^\circ$ and $\varphi_3=16.5^\circ$. The spectrums and contour maps are shown in Figure 6 to Figure 8. The errors from theoretical calculations results are (2.8°,3.1°), (2.3°,2.2°) and (2.9°,3.5°), it can be observed that the accuracy of DOA estimation by improved MUSIC algorithm is very high.

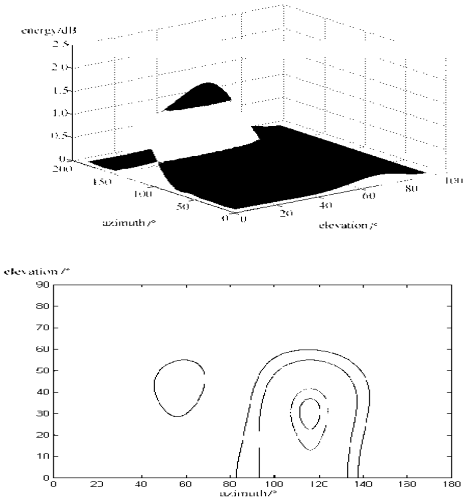

Fig.6. The spectrum and contour map at position 1

Spatially location of the PD source

This paper establishes an equation to calculate the sum of distances from a point to above-mentioned three direction-finding lines and the sum of distances which is the minimum is considered as the spatial position of PD source. The schematic diagram is shown in Figure 9. Providing the position of PD source is $S(x,y,z)$, the direction vectors of direction-finding lines of sensor t (coupling position is $A_t(x_t,y_t,z_t)$) are $\overline{S_t}\{m_t,n_t,p_t\}$, its azimuth and pitch angle are (θ_t,φ_t) and the direction vector of XOY plane is $\overline{n_t}(0,0,1)$, the equation for the direction-finding line of array sensor t is given by:

(17) $$\frac{x-x_t}{\cot\theta_t}=\frac{y-y_t}{1}=\frac{z-z_t}{\tan\varphi_t\cdot\csc\theta_t}$$

Thus the equation for calculating the distance from PD source to each direction-finding line is given by:

(18) $$d_t=\frac{\left|\overline{A_tS}\times\overline{S_t}\right|}{\left|\overline{S_t}\right|}$$

where $\overline{A_tS}=(x-x_t,y-y_t,z-z_t)$. So the sum of the distances is:

(19) $$d=\sum_{t=1}^{n}d_t=d_1+d_2+\cdots+d_n=\sum_{t=1}^{n}\frac{\left|\overline{A_tS}\times\overline{S_t}\right|}{\left|\overline{S_t}\right|}$$

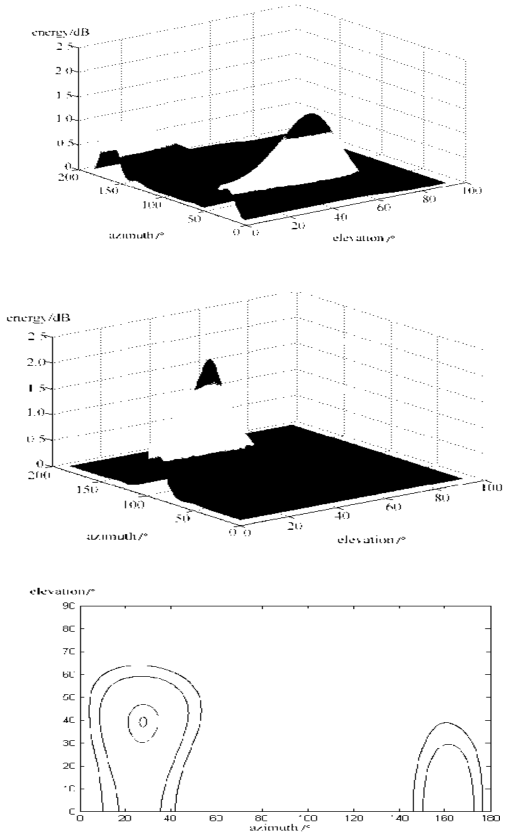

Fig.7. The spectrum and contour map at position 2

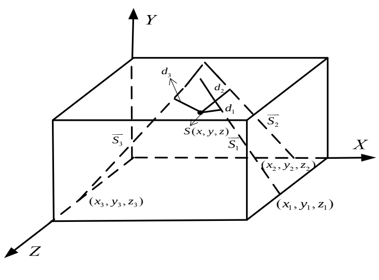

Fig.9. Diagram of direction-finding and localization of PD source

Then the genetic algorithm [7] is used to search the coordinates of PD source, the result is (33.7, 48.6, 27.1) cm with localization error of 5.6cm using above method.

Conclusions

The PD ultrasonic array signal in electric equipment can be received by an ultrasonic phased array having a 4 rows × 4 columns planer structure. The PD ultrasonic array signal can be focused and the direction of arrival estimated accurately by using TCT and improved MUSIC algorithms. The deduced PD source coordinates equation and the results determine by universally searching for PD source coordinates based on genetic algorithm have small errors, hence can be applied to engineering.

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***Authors:** dr. Qing XIE, School of Electrical &Electronic Engineering, North China Electric Power University, Baoding, Hebei, China. E-mail:xq_ncepu@126.com; dr.Shuyi Cheng, School of Electrical &Electronic Engineering, North China Electric Power University,Baoding, Hebei, China. E-mail: chengshuyi198657@163.com;prof.Fangcheng Lü, School of Electrical &Electronic Engineering, North China Electric Power University,Baoding, Hebei, China. E-mail: lfc@ncepu.edu.cn.*