Acoustic Imaging Detection Technology of Electrical Equipment Based on Passive Sound Source Ranging

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***Abstract*—Many abnormal states of electrical equipment will produce abnormal sound. Through the detection and analysis of abnormal sound signals of electrical equipment, the spatial distribution information of abnormal sound can be obtained. In the acoustic imaging detection of electrical equipment, different grid point distance will affect the sound source distance detection and sound source location detection, unreasonable grid division method will greatly reduce the detection effect. When the traditional detection method is used for the acoustic imaging detection of electrical equipment, when the acoustic source distance is inconsistent with the pre-specified detection distance, a large error will be produced. Therefore, this paper proposes an acoustic imaging detection technology for electrical equipment based on passive sound source ranging. This technology adopts dynamic grid method to optimize the detection accuracy. It can not only invert and calculate the distance between the electrical equipment abnormal sound source and the array plane, but also make the selection of acoustic power as the scanning plane more scientific, so that the acoustic cloud image detected by the scanning plane can be obtained. It can be fused with visible image proportionally without error, which improves the accuracy of acoustic imaging detection of electrical equipment.**

Keywords—electrical equipment, acoustic imaging detection, passive sound source ranging, microphone array

I. Introduction

In recent years, with the expansion of the scale of the power grid and the increase of the load, the abnormal sound of the electrical equipment in the substation often occurs. Among them, a kind of abnormal noise is caused by short-time heavy load operation. This kind of abnormal noise will disappear with the load returning to normal level; The other is that after long-term operation of the equipment, potential defects appear in the body. Such defects may exist for a long time or may disappear soon. However, if some abnormal noise is not handled in time, it is easy to cause equipment failure [1].

At present, the detection of abnormal sound of electrical equipment mainly includes manual inspection method, vibration acceleration detection method, acoustic signal detection method and acoustic imaging detection method. Artificial inspection method uses ear listening to find the location of sound source, which is subjective and easy to miss and misjudge. Compared with manual inspection, other detection methods collect vibration or sound signals through sensors for analysis, so it is more objective. In 2000, researchers took vibration signal as a state quantity to analyze the running state of transformer [2]. Later, relevant scholars used vibration signal analysis method in on-load tap switch, GIS equipment and other electrical equipment, so that this method has more applications. However, this method needs to set measuring points in different parts of the device body, and the operation is tedious. Sound is generated by vibration, so it can be used for non-contact detection of power equipment. Some scholars use two pressure-sensitive microphones to collect transformer noise, and judge whether the transformer fails by measuring the intensity and intensity of the sound [3]. The test results show that this method can measure transformer noise signal in the environment containing background noise. In recent years, with the development of audio technology and equipment, the United States physical acoustics company, the United Kingdom EA company, France ALSTOM transmission and distribution Bureau, Tsinghua University, Chongqing University, State Grid Shanghai Electric Power Company and other institutions have carried out acoustic-based electrical equipment detection technology research.

Acoustic signal detection by analyzing the sound emitted by electrical equipment to diagnose the running state, simple and convenient operation, high detection efficiency [4]. Common acoustic detection uses a single sensor to collect sound signals, which is easy to be affected by environmental noise and sensor placement, and difficult to locate the fault location of electrical equipment. Therefore, some researchers are looking to acoustic imaging detection technology. The feature of this technology is that it uses several microphones to collect sound signals at the same time, which can not only analyze the running state of the equipment under test, but also process the sound signals collected by different microphones at the same time, so as to directly reflect the location of defects in the equipment.

In the acoustic imaging detection of electrical equipment, it is necessary to scan the plane of acoustic power, so as to obtain the spatial distribution of sound source [5]. The usual practice is to scan the plane of the specified distance, and then the acoustic power distribution cloud image and visible image in proportion fusion, to obtain acoustic imaging image. However, this method is difficult to match the equipment with more voltage levels. When the specified distance is much different from the actual distance, the calculated acoustic power distribution will also appear errors. Therefore, this paper proposes an acoustic imaging detection technology for electrical equipment based on sound source ranging. The technology collects acoustic signals of electrical equipment through microphone array. According to the acoustic signal characteristics of electrical equipment, the method of matrix optimization diagonal is used for denoising, and the denoised signal is used to locate the distance between the electrical equipment sound source and the microphone array plane. The detection plane of acoustic imaging is determined by the detection distance to improve the acoustic imaging detection effect of electrical equipment.

II. Array Signal Denoising Method Based on Optimal Diagonal

For an array composed of a group of microphones, the received signal model can be expressed as:

$$\boldsymbol{X} = \boldsymbol{S} + N \tag{1}$$

In formula, $\boldsymbol{S}$ is sound source signals, $\boldsymbol{N}$ is noise signal.

If K independent narrow-band signals with the same center frequency come in θ in different directions, $\boldsymbol{S}$ can be expressed as:

$$\boldsymbol{S} = \sum_{k=1}^{K} \boldsymbol{a}(\theta_{sk}) \otimes \boldsymbol{s}_k \tag{2}$$

$\boldsymbol{a}(\theta_{\mathrm{sk}})=[1,\exp(\mathrm{j}2\pi d\cos\theta_{\mathrm{sk}}/\lambda),\ldots\ldots, \exp(\mathrm{j}2\pi d\cos\theta_{\mathrm{sk}}(L\text{-}1)/\lambda)]$ is the direction vector, L is number of microphones, $\boldsymbol{s}_k$ is the amplitude of the kth signal, $\otimes$ represents the Kronecker inner product.

When the fast beat number is N_S, the cross-spectral matrix of the received data can be further obtained:

$$\boldsymbol{R} = \frac{1}{N_S} \boldsymbol{X}\boldsymbol{X}^H \tag{3}$$

The cross-spectral matrix can be rewritten as:

$$\boldsymbol{R} = \boldsymbol{R}_{ss} + \boldsymbol{R}_{nn} \tag{4}$$

$$\boldsymbol{R}_{ss} = \frac{1}{N_S} \boldsymbol{S}\boldsymbol{S}^H \tag{5}$$

$$\boldsymbol{R}_{nn} = \frac{1}{N_S} \boldsymbol{N}\boldsymbol{N}^H \tag{6}$$

In the case where the source signal is unrelated to the noise. They represent the cross-spectral matrix of sound source signal and noise respectively.

The noise covariance matrix can be split as follows [6]:

$$\boldsymbol{R}_{nn} = \boldsymbol{R}_{nn\text{-}u} + \boldsymbol{R}_{nn\text{-}nu} \tag{7}$$

In formula,

$$\boldsymbol{R}_{nn\text{-}u} = \min\{r_{null}\} \boldsymbol{I} \tag{8}$$

and,

$$\boldsymbol{R}_{nn\text{-}nu} = diag(r_{nu11}, \cdots, r_{null}) - \min\{r_{null}\} \boldsymbol{I} \tag{9}$$

The influence of noise can be reduced by reducing the influence of noise cross-spectrum matrix, which can be written as:

$$\boldsymbol{R}_{DD} = \boldsymbol{R} - \boldsymbol{R}_{nn\text{-}u} \tag{10}$$

III. Sound Source Distance Estimation Method Based on Microphone Array

When using acoustic imaging technology to detect electrical equipment, the usual practice is to determine the detection distance in advance, then calculate the size of the detection plane according to the detection distance and equipment size, and fuse the acoustic cloud image generated by acoustic power scanning of the detection plane with the visible image to generate acoustic imaging detection image. However, as acoustic imaging technology is applied to more electrical equipment, it is difficult to determine the detection distance and detection plane a priori due to the different safety distance and volume of different electrical equipment, resulting in errors in detection results. The sound source distance estimation method based on microphone array can obtain the distance information of the fault sound source while conducting acoustic imaging detection of electrical equipment, so that the acoustic imaging detection has a higher accuracy, and can remind the operation and inspection of the current detection distance, so as to improve the safety of detection.

When the sound source distance is estimated, two parallel detection planes are first selected and the planes are divided into grids. The coordinates of each grid point on the two planes can be expressed as:

$$\boldsymbol{N_1} = \begin{bmatrix} (x_{11}, z_{11}) & \cdots & (x_{1n}, z_{11}) \\ \vdots & \ddots & \vdots \\ (x_{11}, z_{1n}) & \cdots & (x_{1n}, z_{1n}) \end{bmatrix}$$
$$\boldsymbol{N_2} = \begin{bmatrix} (x_{21}, z_{21}) & \cdots & (x_{2n}, z_{21}) \\ \vdots & \ddots & \vdots \\ (x_{21}, z_{2n}) & \cdots & (x_{2n}, z_{2n}) \end{bmatrix} \tag{11}$$

The cross-spectrum matrix after noise reduction is used to calculate the beam output of each grid point. The beam output of each point on two planes is shown as follows [7]:

$$\begin{cases} b_{1k} = \boldsymbol{w}_{1k}^H \boldsymbol{R_{DD}} \boldsymbol{w}_{1k} \\ b_{2k} = \boldsymbol{w}_{2k}^H \boldsymbol{R_{DD}} \boldsymbol{w}_{2k} \end{cases} \tag{12}$$

Where, H represents the conjugate transpose of the matrix, $\boldsymbol{w}_{1k}=[\boldsymbol{w}_{11}, \boldsymbol{w}_{12},\ldots\ldots, \boldsymbol{w}_{1L}]$, it is the first scanning plane beamforming weight vector matrix, The second scanning plane beamforming weight vector matrix is $\boldsymbol{w}_{1k}=[\boldsymbol{w}_{11}, \boldsymbol{w}_{12},\ldots\ldots, \boldsymbol{w}_{1L}]$.

Usually, in order to improve detection efficiency, the grid will be divided sparsely, but this will lead to a large deviation in the location of the strongest sound source detected. Therefore, a dynamic grid method is proposed to optimize the estimation of sound source distance. As shown in " Fig. 1", in the acoustic power scanning of different grid points on the plane, the grid points with the maximum acoustic power can be found by the calculation of equation (12). However, for sparse scanning grids, there is a large error between the actual loudest power points and the calculated loudest power grid points, which will cause a large error in the following calculation. Thus, there is a large error in the detection of sound source distance.

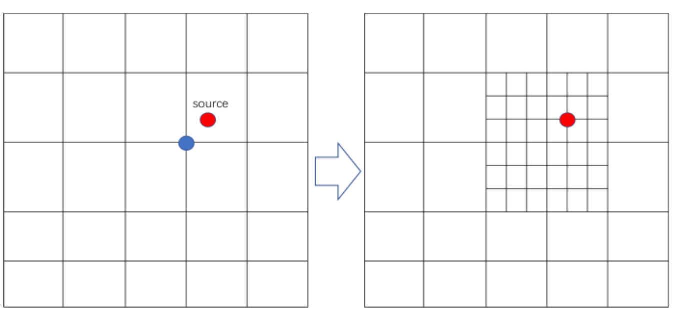

Fig. 1. Dynamic meshing

Therefore, it is necessary to adopt optimization method to improve the accuracy of detection. In this paper, the dynamic grid method is adopted to improve the accuracy of locating the maximum sound source points. After locating the grid points with the maximum sound power distribution, the grids around the grid points are further divided, and the new grid as shown in Fig. 1. is constructed. The new grid only encrypted the grid points near the grid points with the maximum sound power distribution, and the number of grid points increased is small. However, it can greatly improve the accuracy of the loudest power detection and further improve the accuracy of the sound source distance detection.

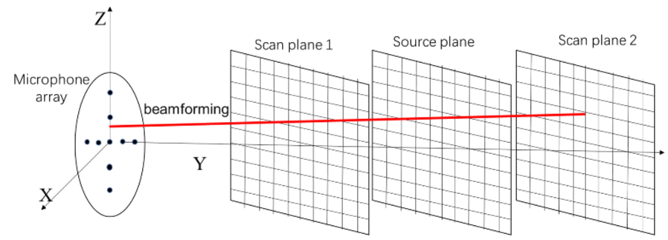

Fig. 2. Beamline diagram

In order to reduce the amount of calculation, only the acoustic power distribution at the encrypted grid points can be calculated. Then the new scanning grid can be expressed as follows:

$$\begin{cases} \boldsymbol{N}_1' = \begin{bmatrix} \left(x_{11}', z_{11}'\right) & \ldots & \left(x_{1n}', z_{11}'\right) \\ \vdots & \ddots & \vdots \\ \left(x_{11}', z_{1n}'\right) & \ldots & \left(x_{1n}', z_{1n}'\right) \end{bmatrix} \\ \boldsymbol{N}_2' = \begin{bmatrix} \left(x_{21}', z_{21}'\right) & \ldots & \left(x_{2n}', z_{21}'\right) \\ \vdots & \ddots & \vdots \\ \left(x_{21}', z_{2n}'\right) & \ldots & \left(x_{2n}', z_{2n}'\right) \end{bmatrix} \end{cases}. \tag{13}$$

The beam output of each grid point obtained by recalculation is:

$$\begin{cases} b_{1k}' = \boldsymbol{w}_{1k}'^H \boldsymbol{R_{DD}} \boldsymbol{w}_{1k}' \\ b_{2k}' = \boldsymbol{w}_{2k}'^H \boldsymbol{R_{DD}} \boldsymbol{w}_{2k}' \end{cases} \tag{14}$$

By calculating b'_{1k} and b'_{2k}, the position of the grid point of the maximum sound source on the two scanning planes can be obtained respectively. Suppose the distance between the two scanning planes and the array plane is y_1 and y_2, then the position of the grid point of the maximum loud power on the two planes can be obtained: (x_{1_max}, z_{1_max}), (x_{1_max}, z_{1_max}). The intersection point between the source beam and the array plane can be calculated from equation (15) : (x_{array}, z_{array}).

$$\begin{cases} x_{array} = x_{2\_max} - \dfrac{x_{2\_max} - x_{1\_max}}{y_2 - y_1} y_2 \\ z_{array} = z_{2\_max} - \dfrac{z_{2\_max} - z_{1\_max}}{y_2 - y_1} y_2 \end{cases} \tag{15}$$

The distance between different planes and the array plane can be expressed by the following formula:

$$\boldsymbol{Y} = \left[y_1, y_2, \cdots\cdots, y_L\right]^T \tag{16}$$

Where, y_k represents the distance between different planes and array planes respectively.

According to Equation (16), the position of the loudest power distribution on different scanning planes can be obtained:

$$
\begin{cases}
\boldsymbol{X} = x_{array} + \dfrac{x_{2\_max} - x_{1\_max}}{y_2 - y_1}\boldsymbol{Y} \\
\boldsymbol{Z} = z_{array} + \dfrac{z_{2\_max} - z_{1\_max}}{y_2 - y_1}\boldsymbol{Y}
\end{cases} \tag{17}
$$

A 16-element microphone array is set up. The array adopts the structure of multi-arm spiral arrangement, with four cantilevers and four microphones on each cantilever. The distance between the two initial scanning planes and the array plane is set to be 3m and 6m respectively. When the distance of the sound source is different, the influence of grid spacing on detection is shown in Fig. 3 and Fig. 4.

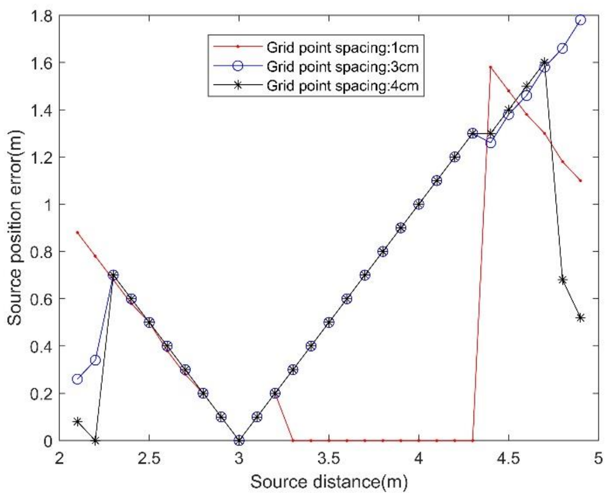

Fig. 3. Relation between source position error and source distance

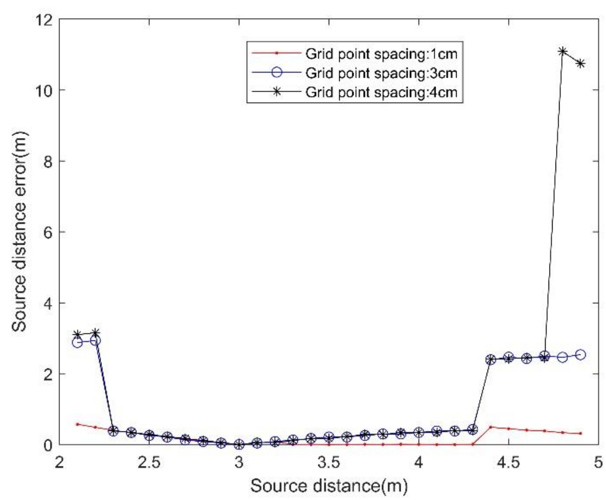

Fig. 4. Relation between source distance error and source distance

As can be seen from Fig. 3, as the spacing of grid points decreases, the sound source position detection error decreases overall. When the sound source is 4.4m away from the array plane, the grid spacing of 1cm has a large error of the sound source position detection, but the error is close to the error of the grid point spacing of 3cm and 5cm. Except for individual distances, the sound source distance detection error of 1cm grid point spacing is smaller than that of other two larger grid points.

As can be seen from Fig. 4, as the spacing between grid points decreases, the sound source distance detection error decreases overall. When the grid point distance is 3cm or 5cm, the sound source distance detection error is not stable, and may even produce a large error. When the spacing of grid points is 1cm, the error of sound source distance detection is always in a small range.

IV. Acoustic Imaging Detection Method for Electrical Equipment Based on Sound Source Ranging

The common practice of acoustic imaging detection of electrical equipment is to determine the detection distance in advance, and then calculate the size of the detection plane according to the detection distance and the size of the equipment. The acoustic cloud image generated by acoustic power scanning of the detection plane is fused with the visible image to generate the acoustic imaging detection image. However, with the application of acoustic imaging technology to more electrical equipment, it is difficult to determine the detection distance and detection plane a priori due to the different safety distance and volume of different electrical equipment. In this case, the location of the acoustic beam to the array plane is not necessarily in the center of the array, so for those sound sources whose intersection point between the beam and the array is not in the center of the array, the detection error will be generated, and the detection error will vary with the distance between the sound source and the array plane and the distance between the intersection point between the beam and the array center.

As can be seen from “Fig. 5” and “Fig. 6”, when the detection distance is inconsistent with the sound source distance, there will be errors in the detected mainlobe area and the highest sidelobe peak.

As can be seen from “Fig. 5”, as the detection distance gradually shifts away from the sound source distance, the error proportion of the main lobe area presents a nonlinear change, and the larger the offset distance, the larger the error proportion. When the detection distance is less than the distance between the sound source and the array plane, the closer the detection distance is to 4m, the smaller the change rate of the error ratio. When the detection distance is greater than the distance between the sound source and the array plane, the greater the detection distance, the greater the rate of change of the error ratio. When the detection distance reaches 4.8m, the difference between the detection distance and the sound source distance is 0.8m, accounting for 20% of the detection distance. At this time, the error ratio of the main lobe area exceeds 100%. When the detection distance is 4m, the main lobe area detected by the two methods is equal, and no error occurs. However, as long as the detection distance is not equal to the actual sound source distance, there will be error. In order to avoid errors in the main lobe area, the distance between the detection plane and the array plane should be equal to the distance of the sound source as much as possible.

As can be seen from Fig. 6, as the detection distance gradually shifts away from the sound source distance, the proportion of the highest sidelobe peak error shows a nonlinear change, and the proportion of the highest sidelobe peak error increases with the increase of the offset path as a whole. When the detection distance is larger than the distance between the sound source and the array plane, the proportion of the peak error of the sidelobe fluctuates and increases. When the detection distance is equal to 4.3m, the difference between the detection distance and the sound source distance is 0.3m, accounting for 7.5% of the detection distance, and the sidelobe peak error ratio appears another minimum value, and the sidelobe peak error ratio is close to zero. When the detection distance is greater than 4.6m, the proportion of sidelobe peak error increases rapidly as the distance between the detection distance and the sound source distance increases. In order to avoid the error of sidelobe peak value in detection, the distance between detection plane and array plane should be equal to the distance of sound source as much as possible.

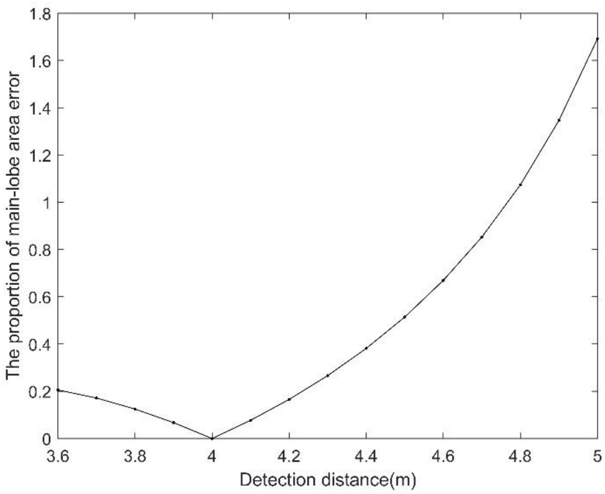

Fig. 5. Proportional relationship between detection distance and main lobe area error

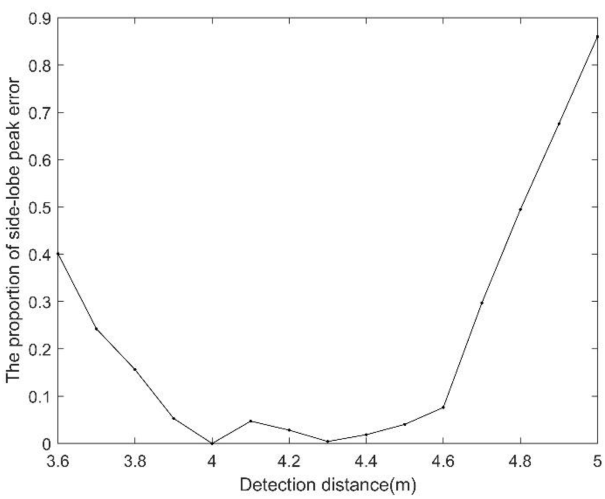

Fig. 6. Proportional relation between detection distance and sidelobe height error

Therefore, an acoustic imaging detection method for electrical equipment based on sound source ranging is proposed in this paper. Firstly, the distance of the sound source is calculated, and the scanning plane is determined according to the distance, which can obtain a more accurate sound source location and sound power distribution. At the same time, the sound source distance information obtained by detection can also remind the transportation and inspection personnel of the current detection distance and improve the safety of detection.

V. CONCLUSION

In this paper, an acoustic imaging detection technology for electrical equipment based on passive sound source ranging is proposed. The technology adopts array signal processing method to invert and calculate the distance between the electrical equipment abnormal sound source and the array plane. The influence of grid point spacing on sound source detection is analyzed, and a dynamic grid division method is proposed. This method hardly affects the calculation amount, but it can improve the accuracy of sound source distance detection and sound source position detection obviously. When the traditional detection method is used for the acoustic imaging detection of electrical equipment, when the acoustic source distance is inconsistent with the pre-specified detection distance, a large error will be produced. The distance information of abnormal sound source of electrical equipment can not only provide more safety information for inspection personnel, but also make the selection of scanning plane of sound power more scientific, so that the acoustic cloud image detected by scanning plane can be fused with visible image proportionally-without error, thus improving the accuracy of acoustic imaging detection of electrical equipment.

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