Research on the Detection Technology of Audible Noise Sources of UHVDC Transmission Lines

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Abstract. In order to directly and deeply study the law and characteristics of audible noise sources of UHVDC transmission lines, a method of detecting the sound intensity vector at the source position in the bundle conductor is proposed. First, the structure of the sound intensity detection device is designed, and the method for calculating the sound intensity vector is deduced based on this prototype. Then, the simulation of the electric field distribution on the surface of the device in the UHV extreme electric field environment is carried out. The change of the maximum electric field intensity and the influencing factors are obtained, which proves that the proposed detection device has the adaptability of the UHV electric field environment. Finally, the measurement error of the proposed detection device is analyzed. The results show that in the frequency range of 100~5000Hz, the theoretical error of the sound intensity vector components and the total sound intensity level obtained by the measurement device in three directions are less than 2dB, which can meet requirements of sound intensity detection at the sound source.

1. Introduction

With the increase of the voltage level of UHVDC transmission lines, corona discharge and the corona effects have become more serious and have attracted more and more attention [1-2]. Due to the adverse impact on people's lives and health, audible noise is one of the most concerned corona effects. In order to ensure that the level of audible noise meets environmental protection requirements, it is necessary to predict the audible noise according to the structural parameters of the conductor during project design [3]. However, due to the lack of understanding of the law and mechanism of UHV audible noise, the existing audible noise prediction models have many constraints and large prediction errors, which limit their practical application [4].

In order to study the laws and characteristics of corona audible noise, accurate measurement of audible noise is a prerequisite. The detection method of audible noise under overhead transmission lines is given in IEEE Standard 656 [5]. The method requires that the measuring point is 1.5m away from the ground, far away from external noise sources, and the environmental noise is at least 10dB lower than the transmission line noise. In [6], four sets of measurement points are placed around the corona cage to measure audible noise from different directions. But in these outdoor measurements, background noise will be mixed with corona audible noise and it is difficult to filter out. Meanwhile, due to the reflection of ground, buildings and trees, audible noise will produce a considerable degree of distortion [7-9]. In order to eliminate the background noise, an anechoic room with sound insulation materials is designed to isolate the audible noise from the background noise and suppress sound reflection [10]. In this way, the audible noise is evaluated in an experimental environment similar to...
the free field. In a semi anechoic chamber with sound-absorbing materials on all sides and top, the time-domain characteristics of single point noise of DC corona discharge are studied by using mesh corona cage [11].

In the above researches, the measuring points of audible noise are far away from the sound source. Audible noise, especially its high-frequency components, will be greatly attenuated when it propagates over long distances in the medium [6]. Due to the existence of charge distribution areas with different concentrations near the transmission line, which is quite different from the air medium, the audio parameter characteristics of the audible noise during the propagation process will also change [12]. Even in the laboratory environment, due to the limitation of the insulation safety distance, the measuring point is still far away from the sound source [13]. If the audible noise is directly detected at the sound source of the UHV line, many disadvantages of long-distance measurement will be overcome.

In order to deepen the understanding of the regularity of UHV audible noise and solve the many drawbacks of long-distance measurement of audible noise, we propose a method to directly detect noise information at the sound source location of UHV lines in this paper. The sound intensity measuring device in the audible noise source of UHV transmission line is designed, and the sound intensity calculation formula is given. The adaptability of the electric field environment of the device is verified by simulation, and the error of the sound intensity measurement method is analyzed, thereby verifying the feasibility of the method.

2. Measurement Principle
The full description of sound waves involves two fields, namely, the scalar pressure field and vector velocity field [14]. It is convenient to measure sound pressure in air with a microphone. Sound pressure can only describe the strength of sound fields, not vector information such as particle vibration velocity and propagation direction. In order to more completely characterize sound fields, this paper measures sound intensity to study the mechanism and characteristics of audible noise.

Sound intensity requires to measure sound pressure and particle velocity simultaneously, and the sound pressure can be measured with a microphone. There are two methods to measure sound intensity: (1) The \( p - u \) method, a combination of a pressure microphone with a particle velocity transducer, is limited for measuring the sound intensity in near fields, resistant fields and unsteady fields [15]. (2) The \( p - p \) method, making use of two closely spaced pressure microphones to obtain the particle vibration velocity, has been widely employed in engineering surveys [16–17].

According to the motion equation of sound wave, the relationship between particle velocity \( u \) and sound pressure \( p \) is given as

\[
    u = -\frac{1}{\rho_0} \int_{-\infty}^{t} \nabla p \, dt .
\]

where \( \rho_0 \) is the density of air.

As shown in figure 1, the sound pressure gradient at the point 0 in the x direction can be estimated by the sound pressure of two adjacent point 1 and point 2. \( d \) is the distance between the point 1 and point 2, and is much shorter than the wavelength of the measured sound wave. The distance between point 1 and point 0 is equal to that of point 2 and point 0.

![Figure 1. Schematic diagram of \( p - p \) method principle.](image)
Then the particle velocity in x direction is given as

\[ u = -\frac{1}{\rho_0} \int_{-\infty}^{t} \frac{\partial p}{\partial x} \, dt = -\frac{1}{\rho_0 d} \int_{-\infty}^{t} (p_2 - p_1) \, dt. \tag{2} \]

where \( p_1 \) is the sound pressure measured by microphone 1, and \( p_2 \) is the sound pressure measured by microphone 2.

The sound pressure at point 0 can be approximately given as the average of the sound pressure at the two adjacent points.

\[ p(t) = \frac{p_1(t) + p_2(t)}{2}. \tag{3} \]

Sound intensity is the sound energy flow passing through the unit area per unit time, which can be expressed as:

\[ I = \frac{1}{T} \int_0^T p(t)u(t) \, dt. \tag{4} \]

Then sound intensity can be obtained from the two microphone signals.

\[ I(\omega) = -\frac{\text{Im}[G_{12}]}{\omega \rho_0 d}. \tag{5} \]

where \( G_{12} \) is the single side cross-spectral density function of the sound pressure at point 1 and point 2, \( \omega \) is angular frequency.

3. Measurement Method at Sound Source

3.1. Detection Device

According to the \( p \rightarrow p \) method, for sound intensity detection in a certain direction, it is necessary to arrange two microphones with the same performance to collect sound pressure simultaneously. To improve the detection accuracy, more microphones can be deployed. This paper proposes a device for measuring the audible noise at sound sources of UHVDC transmission lines, which can be installed in the center of the bundled conductors. The device is considered to have a spherical structure, as shown in figure 2(a). We establish a space rectangular coordinate system at the center of the sphere, select the 6 intersection points of the coordinate axis and the sphere, and the center points of the 8 octants corresponding to the spherical cap. 14 microphones with the same performance are deployed on the spherical surface according to the points to form a microphone array, as shown in figure 2(b). Seven brackets are designed along the diameter, and each group of microphones is fixed on both ends of the bracket in a back-mounted type. Sound pressure is collected from the microphone array, and then the three-dimensional sound intensity vector at the center of the sphere is calculated.
3.2. Calculation of Sound Intensity Vector

As shown in figure 2(b), the center of the sphere is marked as origin O, the intersection points of the 3 coordinate axes and the sphere are marked as A, B, C, D, E, F, and the center points of the 8 octants corresponding to the spherical cap are marked as G, H, L, M, N, P, Q, R. Then, 14 sound pressure signals are collected synchronously, and two sound pressure signals in pairs are calculated according to equation (5).

The sound intensity components of point O in the three orthogonal directions of x, y, z are denoted as $I_x, I_y, I_z$, and the unit vectors in the three orthogonal directions are denoted as $\mathbf{i}, \mathbf{j}, \mathbf{k}$ respectively. Thus, the sound intensity at point O is $I_O = I_x \mathbf{i} + I_y \mathbf{j} + I_z \mathbf{k}$. The sound intensity values measured in each direction are actually the projections of $I_O$ in this direction, and can be regarded as the projections of $I_x, I_y, I_z$ in this direction. For example, the cosine values of the angle between $MR$ and the x-axis, y-axis, and z-axis can be given as

$$\cos \angle ROF = -\frac{\sqrt{3}}{3}, \cos \angle ROB = \frac{\sqrt{3}}{3}, \cos \angle ROD = -\frac{\sqrt{3}}{3}.$$  

The sound intensity $I_{MR}$ is calculated as

$$I_{MR} = -\frac{\sqrt{3}}{3} I_x + \frac{\sqrt{3}}{3} I_y - \frac{\sqrt{3}}{3} I_z.$$  

Similarly, the projection equations of other diameter directions can be calculated, and the following equations can be established as

$$\begin{align*}
I_x &= I_{RF} \\
I_y &= I_{AB} \\
I_z &= I_{CD} \\
-\frac{\sqrt{3}}{3} I_x + \frac{\sqrt{3}}{3} I_y - \frac{\sqrt{3}}{3} I_z &= I_{MR} \\
\frac{\sqrt{3}}{3} I_x + \frac{\sqrt{3}}{3} I_y - \frac{\sqrt{3}}{3} I_z &= I_{LQ} \\
-\frac{\sqrt{3}}{3} I_x + \frac{\sqrt{3}}{3} I_y + \frac{\sqrt{3}}{3} I_z &= I_{PH} \\
\frac{\sqrt{3}}{3} I_x + \frac{\sqrt{3}}{3} I_y + \frac{\sqrt{3}}{3} I_z &= I_{NG}
\end{align*}.$$  

\[\text{Figure 2. (a) Schematic diagram of microphone arrangement. (b) Location map of microphone array.}\]
where $I_{EF}, I_{AB}, I_{CD}, I_{MB}, I_{LQ}, I_{PH}, I_{NG}$ are the sound intensity in 7 specific directions.

Since the sound intensity is estimated by finite-difference method, the left and right sides of equation (8) are not completely equal. There are 3 unknowns and 7 equations in the equation system, which is an overdetermined linear equation system. In order to minimize the error of the solution of the equations, this paper proposes a method to calculate sound intensity vector. First, equation (8) is transformed in matrix form $Q \hat{x} = \hat{y}$.

$$Q = \begin{bmatrix}
1 & 0 & 0 \\
0 & 1 & 0 \\
0 & 0 & 1 \\
-\sqrt{3} & -\sqrt{3} & -\sqrt{3} \\
\frac{3}{3} & \frac{3}{3} & \frac{3}{3} \\
\frac{\sqrt{3}}{\sqrt{3}} & \frac{\sqrt{3}}{\sqrt{3}} & \frac{\sqrt{3}}{\sqrt{3}} \\
\frac{3}{3} & \frac{3}{3} & \frac{3}{3} \\
\frac{\sqrt{3}}{\sqrt{3}} & \frac{\sqrt{3}}{\sqrt{3}} & \frac{\sqrt{3}}{\sqrt{3}} \\
\frac{3}{3} & \frac{3}{3} & \frac{3}{3}
\end{bmatrix}, \quad \begin{bmatrix}
I_{x} \\
I_{y} \\
I_{z}
\end{bmatrix}, \quad \hat{y} = \begin{bmatrix}
I_{EF} \\
I_{AB} \\
I_{CD} \\
I_{MB} \\
I_{LQ} \\
I_{PH} \\
I_{NG}
\end{bmatrix}$$

We assume that $\hat{x}_{0}$ is the solution that minimizes the error of the equation system, which makes the norm $\|Q \hat{x} - \hat{y}\|$ reach the minimum. According to matrix theory, $\hat{x}_{0} = P\hat{y}$, where $P$ is the pseudo-inverse of the coefficient matrix $Q$.

$P$ can be obtained $P = \frac{2}{7}Q^{T}$. Then the optimal solution of the equations under this condition is calculated as

$$\hat{x}_{0} = \frac{3}{7}Q^{T}\hat{y}. \quad \#(10)$$

The three-dimensional sound intensity $I$ can be expressed as

$$I = \sqrt{(I_{x})^{2} + (I_{y})^{2} + (I_{z})^{2}}. \quad \#(11)$$

4. Adaptability of Detection Device in UHV Electric Fields

The detection device is installed near the UHVDC transmission lines to measure the audible noise at sound sources. The electric field distribution around the conductors is simulated. Taking positive wires in UHV corona cage as an example, its structure is shown in figure 3(a). The six-bundled conductor JL/G1A-720/50-45/7 is used in experiments, of which the bundle spacing and sub-line diameter are 0.45m and 36.2mm respectively. The corona cage is a 10-meter-side square. The voltage of the conductors is set to 1000kV. The distribution of electric fields around the bundled conductors is calculated, as shown in figure 3(b).
Electric field simulation shows that electric fields in internal space is much lower than that around the single conductor. That is because the electric fields generated by the six bundled conductors cancel each other out. In order to ensure the safety and reliability, the detection device should be installed in the centre of the bundled conductors. However, the sharp part of the surface of the microphone is easy to induce a strong distorted electric field in the UHV environment, which may damage the device. If the electric field intensity exceeds the inception value, corona discharge may occur on the surface of the device to generate additional audible noise sources and interfere with the measuring results. A spherical metal wire mesh is used to wrap the device, which can effectively reduce the distorted electric field and suppress corona without affecting the sound-wave propagation at the sound source.

In order to protect the device, the wire mesh and the bundled conductors are electrically connected with the earth wire of the detection device. When simulating the electric field in this area, the wire mesh is regarded as a hollow metal ball. The voltage of transmission lines is set to 1000kV, and the results are shown in figure 4(a).

**Figure 3.** (a) Schematic diagram of bundled conductors. (b) The distribution of electric fields around the bundled conductors.

**Figure 4.** (a) The distribution of electric fields. (b) The relationship between the maximum electric field and the radius.
The simulation results show that the electric field intensity in the wire mesh is maintained at a low level. Since the wire mesh and the six-bundle conductors have the same electric potential, the generated electric fields can cancel each other out. In the middle area of the wire mesh facing the six-bundle conductors, there are 6 symmetrical low-field-intensity areas, which appear as 6 blue elliptical areas in figure 4(a). In addition, there are 6 high electric field areas distributed on the surface of the wire mesh, which appear as 6 yellow semicircles in figure 4(a). As shown in figure 4(b), the high electric field area on the surface of the wire mesh is related to its radius and the voltage of transmission lines. It can be observed that the higher the transmission line voltage, the higher the maximum electric field on the wire mesh. With the increase of the radius, the maximum electric field decreases slowly at first, increases rapidly at the radius of 260mm–380mm, and then stabilizes.

Generally, the corona inception electric field can be calculated by Peek formula [18-20].

$$E = 33.7\delta k_1 k_2 \left(1 + \frac{0.24}{\sqrt{r}}\right)$$  \hspace{1cm} (12)

where $r$ is the radius of the conductors, $\delta$ is the relative air density, $k_1$ is the surface roughness, generally between 0.4 and 0.6, and $k_2$ is the correction factor of humidity.

The corona inception electric field near the wires in the harsh weather is 12.82kV/cm by equation (12). According to the curve in figure 4(b), for the UHVDC transmission lines whose voltage is less than or equal to 1000kV, the radius can be selected within 280mm. The wire mesh has a maximum electric field of 10.88kV/cm, which can prevent corona discharge on the surface of the device.

5. Numerical Simulation of Sound Intensity Measurement

The analytic model of the detection device is established to study the measurement theoretical error. The relative error function of the simulation result $I_s$ and calculation result $I_c$ is defined as follows

$$L_e = 10 \log \left(\frac{I_s}{I_c}\right).$$  \hspace{1cm} (13)

For a monopole sound source, ignoring the influence of wire mesh on sound propagation, the accuracy of the microphone array in three-dimensional sound intensity is studied. The propagation formula of the spherical wave in a free field is as follows:

$$p(r, t) = \frac{j\omega \rho_0}{r} p_a e^{j(\omega t - kr)}.$$  \hspace{1cm} (14)

where $r$ is the distance between a point in the sound field and the sound source, $p_a$ is a constant, and $k = \frac{\omega}{c_0}$ is the number of sound waves, $c_0$ is the sound velocity in the air.

According to the relationship between the particle velocity and the sound pressure, the radial particle vibration velocity can be calculated as:

$$u(r, t) = \left(\frac{jk}{r} + \frac{1}{r^2}\right) p_a e^{j(\omega t - kr)}.$$  \hspace{1cm} (15)

Substituting equation (14) and equation (15) into equation (1), the sound intensity of point O is calculated as:

$$I_c(\omega) = \frac{\rho_0 \omega^2 p_a^2}{2 c_0 \omega r^2}.$$  \hspace{1cm} (16)

According to equation (2) and equation (14), the simulated value of sound intensity in each direction can be obtained. For example, the sound intensity of side BC can be obtained as:

$$I_{BC}(\omega) = \frac{\rho_0 \omega p_a^2 \sin[k(r_c - r_p)]}{2d r_p r_c}.$$  \hspace{1cm} (17)
Similarly, the sound intensity in other directions can be simulated. Assuming that the microphone spacing is 0.02m and the monopole sound source is at (−1, −0.8, −0.6), the device is used to measure the sound intensity level (SIL) in the three-dimensional sound field. The results of the model are shown in figure 5.

![Figure 5. (a) Calculation and Simulation of sound intensity level. (b) The error distribution of sound intensity level.](image)

6. Conclusion
Audible noise in existing researches is detected far away from UHV transmission lines. This paper proposes a method for detecting sound intensity vector of audible noise at sound sources. Through theoretical analysis and simulation, the structure model, the adaptability of electric field and error of the sound intensity detection device are studied, the following conclusions can be obtained:

- A spherical sound intensity detection device is designed, which can simultaneously collect 14-channel sound pressure signals. The sound intensity vector calculation method for the device is deduced, and the optimal solution of the sound intensity vector is obtained.
- The proposed spherical wire mesh can reduce the electric field intensity around the device. The simulation results show that the maximum electric field intensity on the surface of the spherical wire mesh is related to its radius. For the UHVDC transmission line with 1000kV, the optimal radius is 280mm.
- We use a monopole sound source to analyse the theoretical error of the measuring device. The core frequency range of audible noise is 100–5000Hz. Within this range, the calculation error of total sound intensity level does not exceed 2dB.

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