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*Review*

# Research Progress on Audible Noise Emitted from HVDC Transmission Lines

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**Abstract:** The audible noise (AN) of DC transmission lines is a crucial factor affecting environmental assessment and electromagnetic design. In recent years, the public has paid increasing attention to the audible noise after the emergence of the HVDC technique. This paper emphatically reviewed the work investigating audible noise characteristics in both time and frequency domains, especially the correlation between sound and discharge. The proposed mechanisms of DC audible noise and the mitigating techniques are summarized, including the noise generation process, the physical models, the measurement method, and the mitigating technologies. It is found that the existing literature mainly focused on the prediction and characteristics of AN, the environmental factors which influence AN, and the methods to minimize AN emission. However, existing achievements still need to be improved to fully understand the mechanism of AN generation and solve the adaptability problem of AN prediction methods. The following aspects are valuable in future research: The correlation between audible noise and other corona effects will help solve the problem of difficulty in measuring audible noise in field condition; The corona discharge mechanism and weather resistance anti-corona coating when raindrops are attached to the surface of the transmission line, which will help guide the development and application of anti-corona coatings for the transmission line. Future research should also understand the mechanism of sound wave generation when considering the space charge effect.

**Keywords:** DC transmission line; audible noise; corona discharge; overview



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## 1. Introduction

HVDC transmission lines are emerging with the development of renewable power generation, crucial to achieving Net-zero in future power systems. With the increased demand for overhead lines (OHL) and reduced availability of corridors, more and more electricity transmission corridors are inevitably crossing densely populated areas [1–3]. The complaint raised from increased levels of AN which affects residents is gradually becoming the main reason preventing the construction of new OHLs. The electromagnetic interference impacts of power grids mainly come from substations [4–7] and transmission lines [7]. Corona discharge is a primary source within transmission lines. Research on audible noise began in the late 1960s [8–11]. With the operation of AC ultra-high voltage lines in North America, residents around the line corridor began complaining about the corona noise. In the United States, the power company replaced several 500 kV and 765 kV AC lines in the early stage of reconstruction due to audible noise. After 2005, National Grid (U.K.) completed expanding and upgrading its 400 kV transmission network, and in some cases, it led to unsatisfactory noise performance. Italian State Grid Corporation, Swedish State Grid Corporation, Brazilian State Grid Corporation, Electric Power Corporation of Japan, New Zealand Electric Power Corporation, and other companies have all experienced excessive audible noise from transmission lines. In China, audible noise has become the control factor of the electromagnetic environment assessment of transmission lines with voltage levels above 500 kV [12–17]. Summarizing the international research progress on corona audible noise, and clarifying the difficulties in existing research and engineering applications, is of great significance for guiding the research direction of DC corona discharge environmental effects and assisting in the efficient and economical design and construction of DC transmission lines.

For the issue of audible noise in transmission lines, researchers usually conduct research from the following aspects: the characteristics and influencing factors of audible noise in transmission lines, the mechanism of audible noise generation, and the control technology in transmission lines. Regarding the characteristics and influencing factors of audible noise in transmission lines, existing studies have shown that corona noise in transmission lines is mainly affected by voltage level, altitude, and climate conditions. As the voltage level increases the corona noise gradually increases. At the same voltage, the higher the altitude, the greater the audible noise, with a growth rate of approximately A/300, where A is the altitude in meters [18]. Weather conditions also have a significant impact on transmission lines. Rain, snow, fog, frost, and ice on the surface of lines can enhance the irregularity, increasing field strength and leading to corona discharge. Among them, the increase in noise is most apparent in light rain weather. The impact of rain on DC lines is opposite to that of AC, where raindrops on the surface become a single-point corona source, causing a sharp increase in space charges near the line, which in turn limits the electric field intensity, making the noise level of DC lines smaller than good weather [18]. However, recent research results have shown that the audible noise level of DC transmission lines can reach its maximum when there are water droplets attached after rain and condensation appears on the surface of lines during high humidity. In addition, after the rainfall, the audible noise of the DC lines first increases and then decreases over time, until the water droplets evaporate entirely [19].

Research on the mechanism of corona audible noise began in electroacoustic. The research results show that the mechanisms of gas discharge generating sound waves can be divided into two categories: "cold" and "hot" [20,21]. Hot sound waves are generated by high-frequency corona and plasma sources, and the basic process is the collision between positive and negative ions caused by air ionization and the collision between charged ions and air molecules; these collisions cause changes in gas temperature, resulting in changes in gas pressure and the generation of sound waves. Cold sound waves mainly refer to sound waves with frequencies less than 10 kHz, and their generation mechanism is air vibration driven by electric field forces [22]. The mechanism of gas discharge generating sound waves can be divided into two situations: weakly ionized gas and strongly ionized gas [23]. Corona belongs to weakly ionized gas, and the process of generating sound waves can be summarized as follows: charged particles accelerate under the action of electric field force, and their temperature increases, reaching $10^4$ K to $10^5$ K. Due to the energy transfer speed from the electric field being much faster than the heat conduction speed of the gas, the neutral gas temperature remains at room temperature. This temperature difference generates a continuous energy flow from electrons to neutral gas molecules, and a portion of this energy is transmitted to the surroundings through sound waves. Based on this fundamental process, researchers have conducted continuous research. Early studies include: the time of sound propagation in weakly ionized gases [24], the principles of generating sound waves in different discharge forms [22], and different methods to generate sound waves in gas discharge [25]. In recent years, Kiichiro [26], Ph Bequin [27,28], M.K. LIM [29], Michael S. Mazzola [30], Maxim Chizhov [31], P M. Scholars, such as Gomez [32] and Li Zhen [33], have conducted research on the acoustic mechanism of corona discharge from various aspects, such as the characteristics of DC corona sound sources, sound source models, electro-acoustic conversion efficiency, and corona acoustic frequency response, making essential contributions to revealing the mechanism of corona sound generation.

The research methods of audible noise control technology include actual transmission line measurement, test section, and corona cage test [34]. Compared with actual lines, the test section and corona cage test have the characteristics of a short cycle and low cost. The Central Research Institute of Electric Power Industry (CRIEPI), Russian Research Institute for Pulse Technology (NIIPT), Korea Electric Power Corporation (KEPCO), China State Grid, and China Southern Power Grid have established their high voltage and ultra-high voltage test sections for research. The current idea for controlling audible noise is to first evaluate the noise based on the operating conditions of the transmission line and then design the line parameters according to the requirements of acoustic environment limitations. This method relies on empirical formulas. Currently, the main empirical formulas for audible noise in DC lines include the formula proposed by the China Electric Power Research Institute (CEPRI) for calculating the audible noise of four to eight split conductors on good weather. The calculation formula for audible noise proposed by Bonneville Power Administration (BPA) is applicable to good weather, with line splitting number $4 \leq n \leq 8$, and sub-line radius $r \leq 2.5$ cm. The research association for Power Transmission and Distribution Equipment and Systems (FGH) proposed a formula for calculating audible noise suitable for good weather, with a number of line splits $2 \leq n \leq 5$, and a sub-line radius of $1$ cm $\leq r \leq 2$ cm. The audible noise calculation formula proposed by IREQ is suitable for good weather, line splitting number $4 \leq n \leq 8$, and sub line radius $r \leq 2.5$ cm. The audible noise formula proposed by CRIEPI is suitable for good weather, with line splitting numbers $1 \leq n \leq 4$, sub-line radius $1.12$ cm $\leq r \leq 2.47$ cm, and interstate distance $S \geq 8.44$ m.

In recent years, researchers have summarized the progress of audible noise in transmission lines and proposed suggestions for the DC transmission lines in the past decade. Tan et al. [35] reviewed the two major influencing factors of audible noise in AC/DC transmission lines in 2009: the influence of line structure, design and construction, and the influence of external conditions such as atmosphere and environment. It was found that the most feasible noise reduction methods in engineering are increasing the diameter and number of split wires, and changing the spacing. R. Shuttleworth et al. [36] summarized the corona cage test devices in Switzerland, Japan, China, and the United Kingdom in 2013, and proposed the necessity of using anechoic chambers to study the audible noise of corona. Che et al. [37] summarized the issue of audible noise in the construction and operation of ultra-high voltage transmission lines in 2015, analyzed the differences in audible noise from positive and negative corona, then pointed out the promising prospects of improving the surface structure of lines and applying new audible noise suppression technologies, such as hydrophilic anti-corona coatings. Xiao et al. [38] summarized the mechanism, influencing factors, measurement methods, and noise reduction methods of positive and negative corona in 2017; they found that the energy conversion of air molecules during the noise generation process requires quantitative standards, and the universality of the evaluation and prediction models for audible noise is insufficient. Hu et al. [34] summarized the limit standards, test methods, and prediction methods for audible noise, and proposed that attention should also be paid to the audible noise generated by line fittings. In 2023, Meng et al. [39] focused on analyzing the main differences and research difficulties between DC lines and AC lines. They believed that the main reason for the significant differences in corona effects between AC and DC lines was the influence of ion fields in DC lines. They proposed that the key to using corona cages to study the corona effects of DC lines was to establish a correlation between corona cages and actual lines in the synthetic electric field.

There has been many progress in the research and engineering application of audible noise in DC transmission lines. By reviewing the research achievements on audible noise, future research directions that need to be paid attention to have been summarized. However, existing review articles have not noticed that the research on the audible noise has progressed from the frequency domain to the time domain, and there has been no in-depth analysis of the mechanism and the difficulties encountered in the time domain computational models.

Therefore, this article focuses on summarizing the latest progress in the time domain characteristics and correlation characteristics between corona and audible noise, and sorting out the experimental measurement and control methods. Then, the research results of time domain physical models of audible noise are summarized. Finally, the characteristics of audible noise, physical models, and research directions for new noise control technologies were analyzed. The literatures involved in the paper are searched in the web of Science, IEEE Xplore, MDPI, SpringerLink, IOP Publishing, Elsevier and Engineering village.

## 2. Audible Noise Characteristics of DC Transmission Line

### *2.1. Frequency Domain Characteristics of DC Line Audible Noise*

The audible noise spectrum of HVDC transmission lines can be divided into the unipolar operation (positive and negative) and bipolar operation. Corona cages are usually used for experimental research on audible noise. Through statistical analysis of the laboratory test data, the noise characteristics of positive and negative conductors and the noise frequency spectrum characteristics of positive and negative conductors have been obtained [40–43]. Figure 1 shows the frequency spectrum characteristic of audible noise from the unipolar experiment in the corona cage (positive and negative polarity). Figure 2 shows the frequency spectrum characteristic of the audible noise at the positive and negative sides during the bipolar operation [44], and the measurement setup in the corona cage.

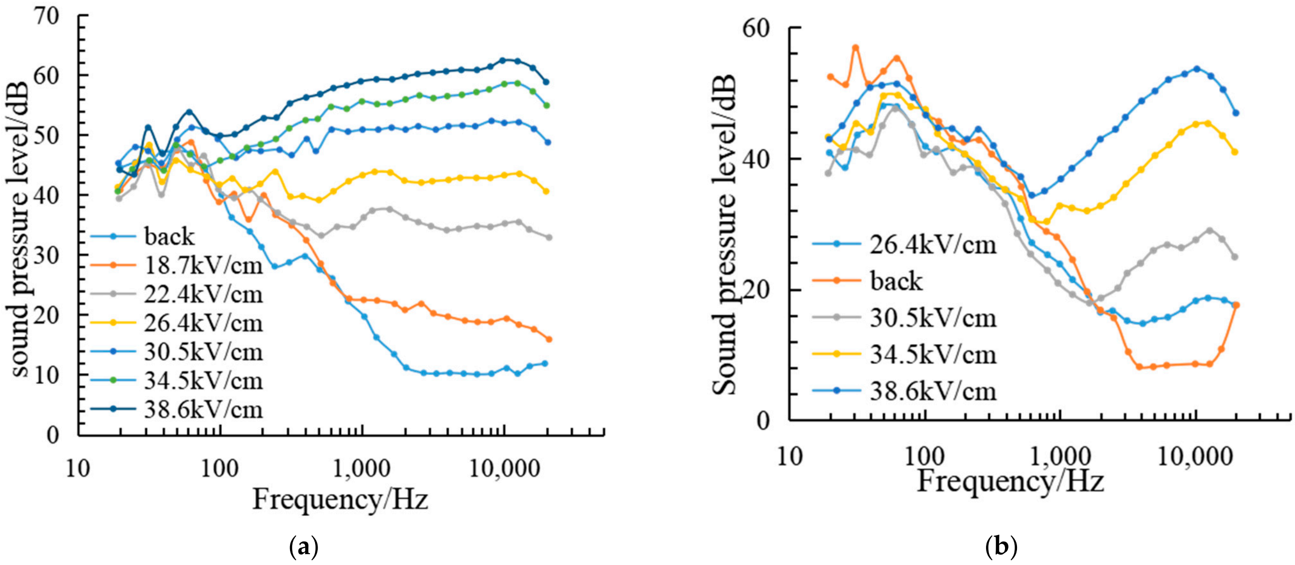


**Figure 1.** Corona audible noise spectrum characteristic curve of positive (**a**) and negative (**b**) conductors [44].

As shown in Figures 1 and 2, the sound probe measures the noise from both the negative and positive line under the bipolar experiment; the audible noise in the frequency domain of HVDC transmission lines has the following characteristics [40–46]:

(1) The frequency characteristics of positive conductor noise can be divided into three parts: (1) The low-frequency band (less than 125 Hz) has little relationship with the corona discharge. (2) The noise in the middle-frequency band (125 Hz~10 kHz) is relatively stable; the curve's regularity is better than the low-frequency band. With the increased frequency, the corona noise is more distinguished from the background noise. With the conductor surface electrical field increase, the audible noise increases more obviously. The frequency band after 1 kHz is exceptionally stable, which can be used as the characteristic frequency band of corona noise. (3) In the high-frequency

band (>10 kHz), the corona noise attenuates with an increase in frequency, but remains much larger than the background noise.

(2) The noise-frequency characteristics of the negative line are quite different from that of the positive line. The audible noise is gradually distinguished from the background noise after 630 Hz~2 kHz, and the frequency above which the emissions increase with frequency decreases with the increase in applied field. The noise frequency characteristics of the positive line are relatively flat, whereas the noise level of the negative line displays a field-dependent minimum between 600 and 5000 Hz, reaching the maximum value near 10 kHz.

(3) When the same voltage level is applied to the positive and negative bipolar wires, the frequency characteristics of the audible noise measured at the positive and negative sides are similar to the positive line, which is relatively flat. The noise level of the negative wire is relatively small, buried in the positive line's noise curve. As the corona discharge degree increases, the measured audible noise also increases.

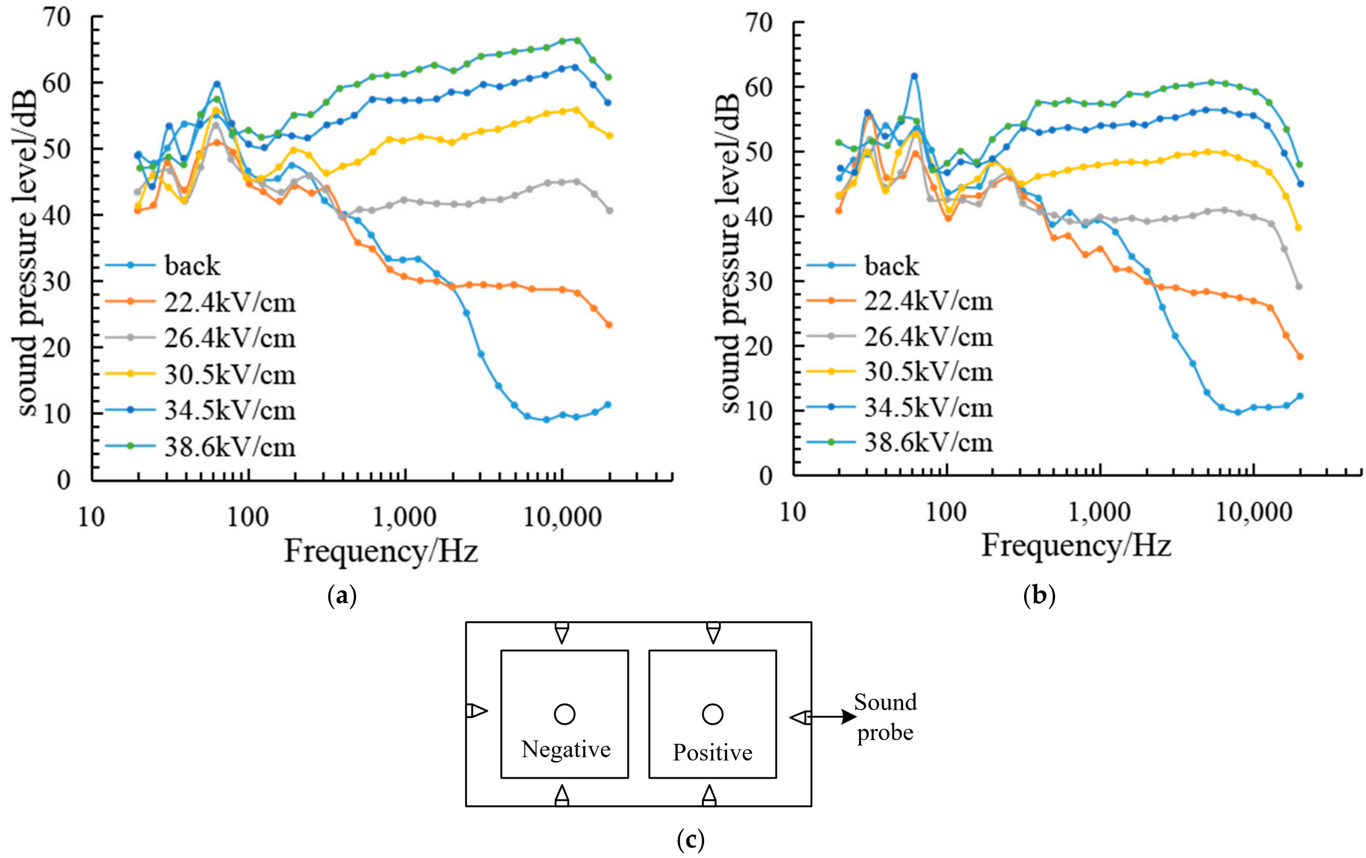


**Figure 2.** Corona audible noise spectrum at different sides of bipolar conductor [44]. (**a**) Measurement result at the positive side, (**b**) Measurement result at the negative side, (**c**) Measurement setup in the corona cage.

### *2.2. Time Domain Characteristics of DC Corona Audible Noise and Corona Noise Correlation Characteristics*

In recent years, researchers have gradually focused on the time domain characteristics of the corona discharge, further revealing the process of corona discharge generated audible noise. North China Electric Power University and Tsinghua University have studied the time domain characteristics of DC corona audible noise and obtained the single noise-pulse waveform generated by positive and negative corona discharge [47–50], as shown in Figure 3.

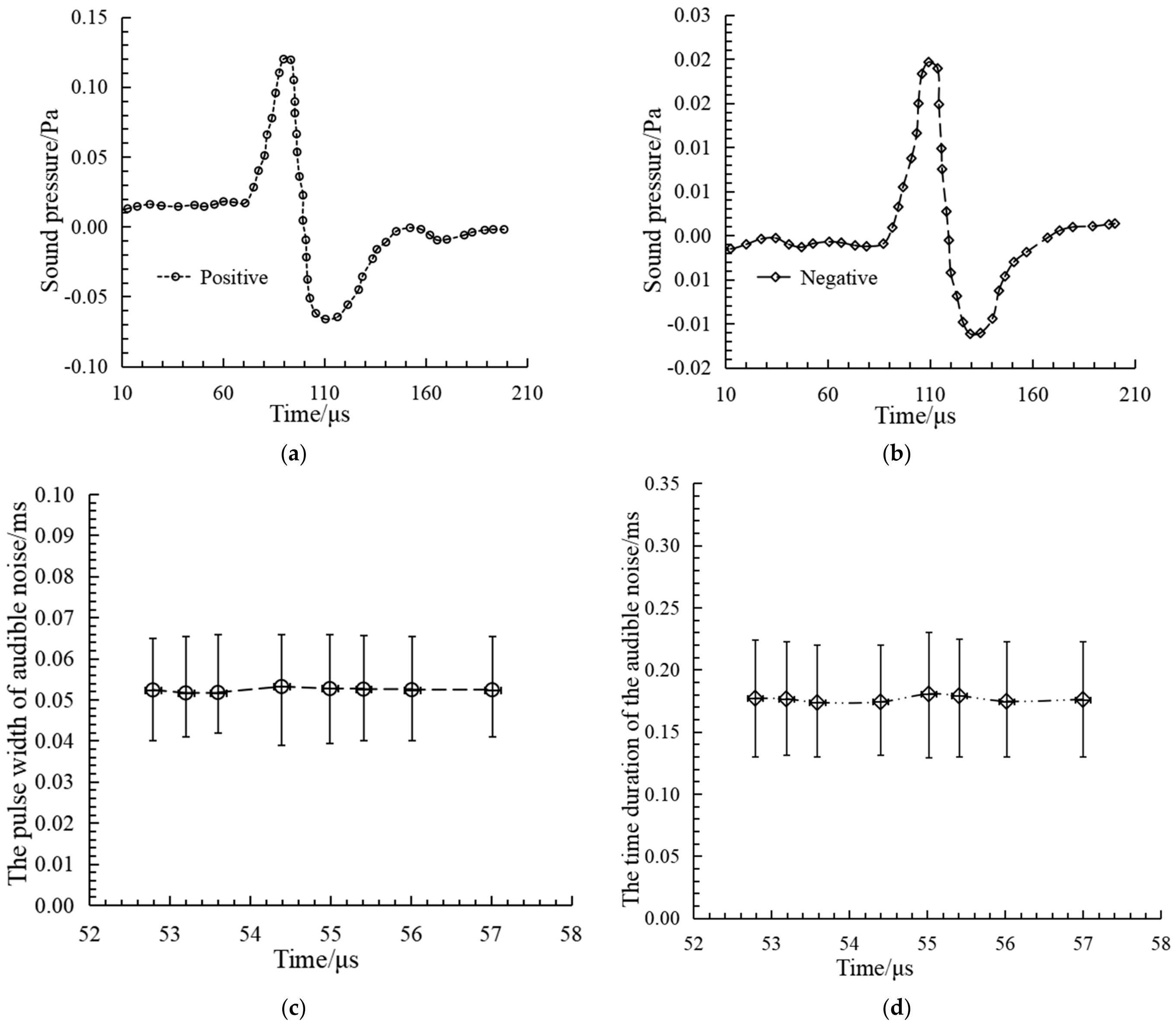


**Figure 3.** Single audible noise pulse waveform generated by positive and negative corona discharge [45,47–50]. (**a**) Positive corona audible noise, (**b**) Negative corona audible noise, (**c**) The pulse width of audible noise, (**d**) The time duration of the audible noise.

North China Electric Power University studied the sound wave that generates from corona discharge and the typical waveform, as shown in Figure 3 [45]. The experimental results show that the audible noise pulse generated by positive and negative corona has randomness, but both have the following statistical rules:

(1) The average amplitude of audible noise pulse generated by positive corona discharge is about five times bigger than that generated by negative corona discharge;
(2) With the voltage increase, the average time between audible events gradually decreases in both negative and positive corona, and the repetition rate of negative corona audible noise is greater than that of positive corona audible noise.

The statistical results of the pulse repetition frequency, pulse amplitude, duration time, and pulse width of the audible noise pulse show that the temporal statistical characteristics of the DC corona audible noise have the following characteristics [45,49]:

(1) Audible noise's average pulse repetition frequency increases with voltage. When the voltage rises to a specific value, the pulse repetition frequency tends to remain

unchanged and reaches a stable state. When the pulse repetition rate is at growth and steady state, the time interval distribution follows the exponential and normal distribution.

(2) The amplitude of positive and negative half waves of audible noise decreases and tends to remain unchanged with the voltage increase. The positive and negative peaks ratio is more significant than one and does not change significantly with voltage. The distribution of positive and negative half-wave amplitude follows lognormal distribution;

(3) The time duration of the audible noise pulse under different voltages is relatively random, but its average value does not change with the voltage and remains at 0.17 ms~0.185 ms (Figure 3d);

(4) The pulse width of audible noise has randomness but does not change with the voltage. The pulse width is maintained at 0.052 ms under different voltages (Figure 3c).

Research on the correlation of DC corona and audible noise are based on the time domain waveforms. The figure shows the time domain waveform of positive DC corona and audible noise.

In Figure 4, the red waveform, black waveform and blue arrows are the noise, current and the indicator arrows, respectively. The existing research results show that DC corona current and audible noise have the following correlation characteristics [47,48], as shown in Figure 4:

(1) Corona current waveform and audible noise waveform have a one-to-one correspondence in the time domain, in which the audible noise pulse lags behind the corona current, and the lag time is the propagation time of the sound wave.

(2) Corona current amplitude and audible noise amplitude have the same change rule with voltage and have the same fitting function form. The amplitude of audible noise increases linearly with the increase of corona current amplitude.

(3) The peak value of audible noise and corona current is linear with the number of space charges generated by a single discharge. The space charges determine the correlation between audible noise and corona current.

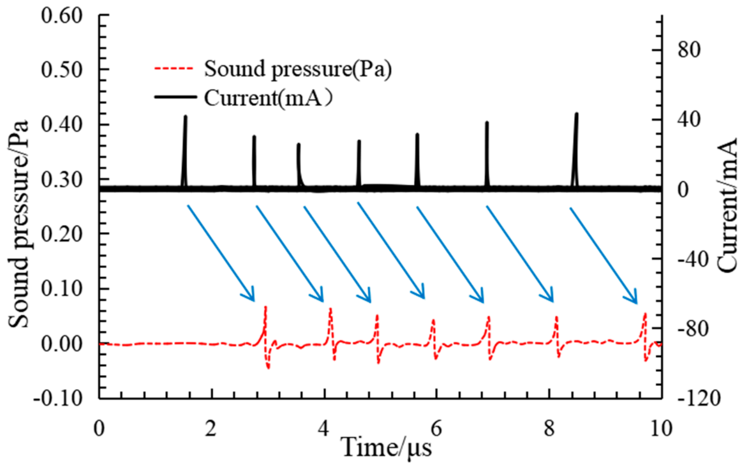


**Figure 4.** Audible noise pulse waveform generated by positive corona discharge [47,48].

### 2.3. Influence of Complex Environment on DC Audible Noise Characteristics

At present, the research on the influence of DC corona audible noise in a complex environment mainly involves pollution, high altitude (low atmospheric pressure), rainfall, fog (high humidity), wind, and icing [42,43,51–57]:

(1) Influence of pollution on corona audible noise: When the conductor surface is polluted, its audible noise is greater than that of the dry and clean conductor. At the same time, the different frequency bands of the audible noise are affected by the pollution

differently. Under the same voltage, the frequency component of the audible noise of the dirty conductor is greater than that of the clean conductor, and the amplitude in the spectrum of the audible noise less than 1 kHz is less than that of the clean conductor. When the surface is polluted, the audible noise of the positive conductor is significantly greater than that of the negative conductor, and the frequency characteristics of the audible noise are affected by the pollution type, as shown in Figure 5 [51,53].

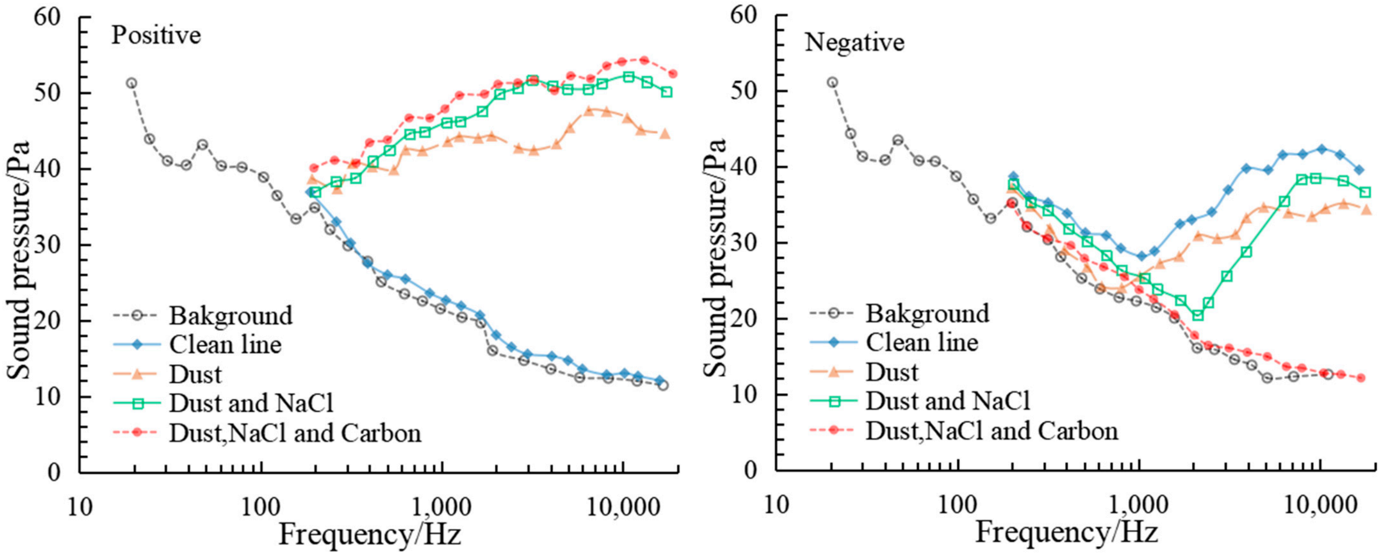


**Figure 5.** Influence of pollution on the spectrum characteristics of audible noise of positive and negative conductors [51,53].

(2) The influence of altitude: In the range of 50 m~4300 m, th-e audible noise increased with the increase above sea level. With the increase in the surface field strength, the calibration curve of the audible noise shows an "n" shape that increases first and then decreases.

(3) The effect of fog (high humidity): Presently, research on the corona characteristics in fog (high humidity) environments mainly focuses on the conductor. Results show that the small fog droplets formed on the conductor will seriously distort the electric field around the conductor. The ionization degree around the conductor will increase with the increase in the fog water conductivity, which will reduce the corona inception voltage. The DC corona inception voltage of the conductor will increase slowly with the relative humidity. When droplets are attached to the line surface, the greater the conductivity of the fog water, the lower the DC corona inception voltage of the line.

(4) Impact of rainfall. The characteristics of DC conductor audible noise under rainfall conditions differ from that of AC [56]. The current research results show that DC corona audible noise is larger before and after rainfall, and the noise during rainfall is smaller than that in good weather. The relevant test data show that the audible noise produced by the conductor increases gradually with time after the conductor is exposed to rain. The stronger the corona discharge of the conductor, the shorter the time required for the audible noise to stabilize. When the corona discharge under a high-electric field is stable, the audible noise generated by corona discharge is stable.

(5) Impact of wind. The study of DC audible noise in windy weather focuses on the A-weighted characteristics of noise (the A-weighted simulates the noise response of the human ear) [52]. The audible noise in the 2.5 m/s~10 m/s is 5 dB greater than that in the range of 1.5 m/s~5 m/s. The test data measured by China Southern Power Grid in the National Engineering Laboratory of the UHV (Kunming) shows that when the wind speed is less than 2 m/s, the audible noise generated by the bipolar DC conductor is relatively stable. When the wind speed is 2 m/s~5 m/s, the audible noise

of the conductor increases rapidly. When the wind speed exceeds 6 m/s, the audible noise value tends to be saturated. However, the wind itself produces noise so that the controversy still exists relative to the impact of wind.

(6) Impact of icing. The Chongqing University has studied the corona audible noise of DC conductors under artificial rime, rime icing, and natural icing conditions in the artificial climate laboratory and Xuefeng Mountain Natural Test Basement. The conductor test layout and icing conditions are shown in Figure 6 [54,55,57].

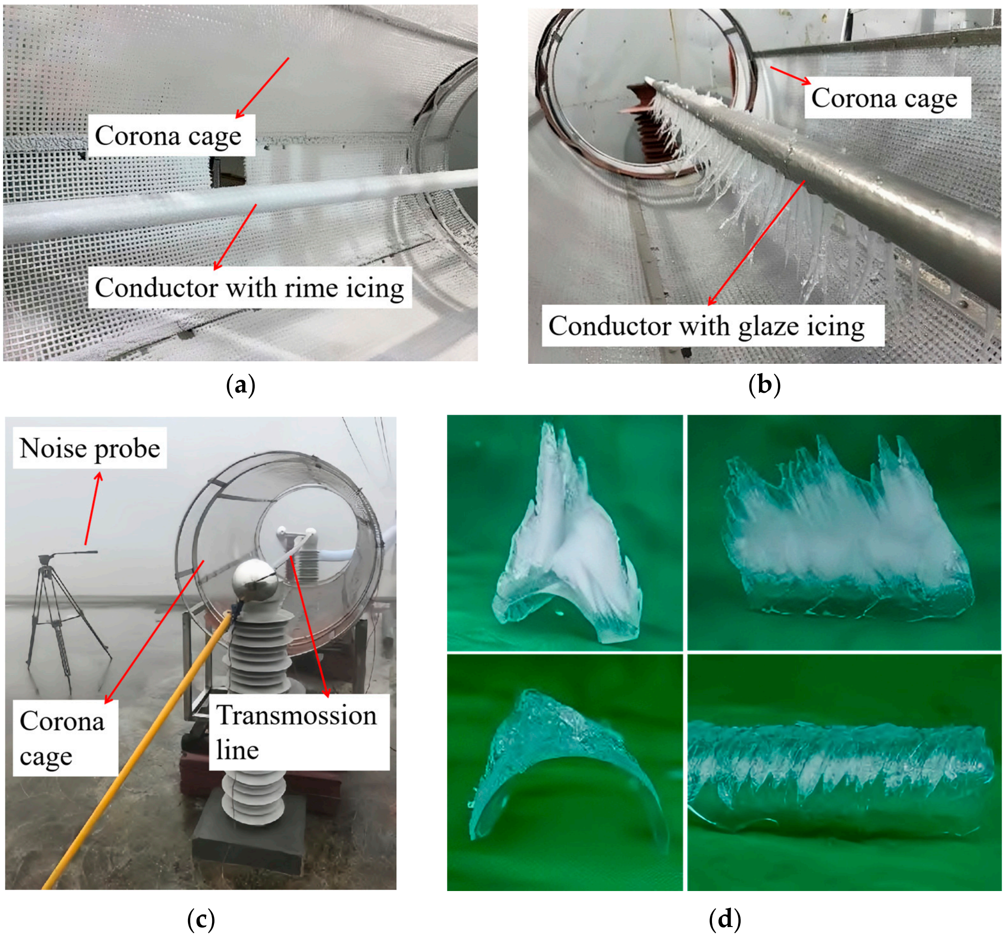


**Figure 6.** Audible noise test arrangement of conductor under artificial and natural icing conditions [54,55,57]. (**a**) Artificial rime icing, (**b**) Artificial glaze icing, (**c**) Natural icing test, (**d**) Natural icing type.

The research shows that the corona audible noise of positive and negative polarity conductors under icing conditions has the following characteristics:

(1) The audible noise of positive and frosted conductors is greater than that of negative conductors, and the audible noise of glazed conductors is greater than that of conductors with rime icing. Icing is the worst case of audible noise of DC lines. The audible noise of positive and negative glazed conductors is 5.0~16.2 dB (A), higher than that of good weather conditions. The audible noise of positive rime icing conductors is 7.1~15.5 dB (A) higher than that of good weather conditions.

(2) The higher the conductivity of the water, the higher the intensity of the electric field, and the more serious the icing, the greater the corona audible noise. Among them, the influence of icing degree is largest, the influence of electric field strength during icing is the second, and the influence of icing water conductivity is the least. The audible noise of the conductor with glaze icing increases with the increase of the water

conductivity and the strength of the electric field. It has no significant relationship with the degree of icing.

(3) The DC corona audible noise of the conductor with glaze and rime icing is a broadband noise with an "n" shape. The increase of the electric field only increases the amplitude of the noise without changing the spectrum shape. The increase of the water conductivity, the decrease of the electric field, and the increase of the icing degree may distort the 1/3 octave–frequency spectrum of the audible noise.

## 3. Generation Mechanism of Audible Noise in DC Transmission Line

### *3.1. Generation Process of DC Corona Audible Noise*

There are few studies on the generation process of DC corona audible noise, since the physical mechanism of corona discharge has yet to be understood entirely. The physical process of corona discharge producing audible noise is limited to the qualitative explanation, which includes two aspects: the generation of DC corona audible noise and the reasons for the difference in positive and negative noise amplitude [47,49,58–60]:

(1) The generation process of DC corona audible noise: Researchers proposed that the generation process of DC corona audible noise can be summarized into several stages, as shown in Figure 7 [57].

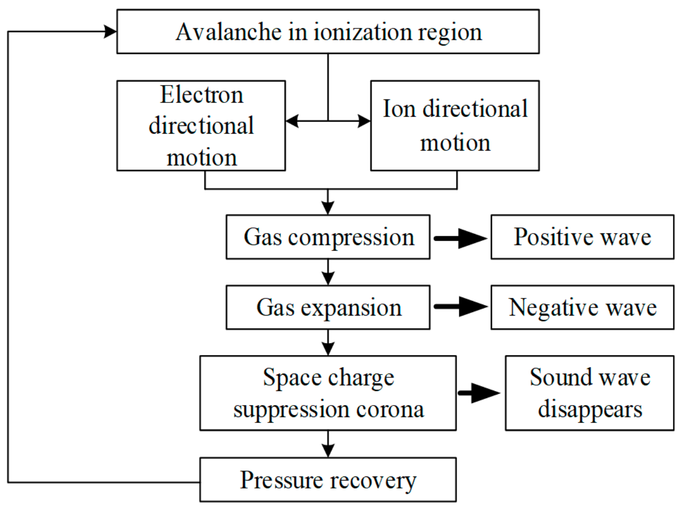


**Figure 7.** Generation process of DC corona audible noise.

Figure 7 shows a general process for the audible noise in the corona discharge. The electron avalanche in the corona ionization region produces a large number of electrons and ions. These charged particles move in the direction and collide with neutral molecules under the electric field, transferring their energy to the molecules, compressing the gas, and producing the positive half-wave of the sound wave. With the absorption and disappearance of the electron avalanche, the energy obtained by the gas in the ionized region decreases and expands, and the negative half wave of the acoustic wave is generated. Finally, the corona discharge stops under the suppression of space charge. The gas in the ionization region returns to its original state, which makes the sound wave disappear until the next corona appears.

(2) Differences between positive and negative corona noise amplitude: Existing research results show that the noise amplitude of the DC corona has a one-to-one relationship with the amplitude of the corona current. Thus, the difference between the amplitude of positive and negative corona noise directly comes from the difference between the corona current. From the point of the fundamental physical process of corona discharge, the difference in the development scale of electron avalanche in the positive

and negative corona directly results in the amplitude of positive noise being more significant than negative noise.

*3.2. Physical Model of DC Corona Audible Noise*

At present, few physical models can be used to calculate the time domain characteristics of DC corona audible noise. Based on the statistical law of DC corona audible noise, North China Electric Power University proposed a mathematical-physical model in the time domain. This model starts from the statistical characteristics of the audible noise of single-point corona discharge and calculates the audible noise of the conductor through the method of sound-source superposition. The main steps are as follows [47,49]:

(1) The probability distribution functions of repetition frequency, positive and negative half-wave amplitude, duration, and width of audible noise sound waves are obtained experimentally.
(2) The fitting function is used to construct the standard positive and negative half-wave waveform of audible noise. The probability-density-distribution function is used to establish the random model of the single-point noise source.
(3) The audible noise of single-point corona discharge at the noise-measuring point is calculated according to the acoustic wave propagation model.
(4) Assume the number and distribution of noise sources on the conductor surface according to the conductor layout and length.
(5) The corona audible noise of the conductor at the noise measuring point is calculated according to the superposition principle.

According to the above steps, the relationship between the sound pressure level and the noise amplitude, the pulse-time interval, the conductor diameter, the nominal electric field on the conductor surface, and the propagation distance can be calculated.

Tsinghua University established a physical model of audible noise generated by single-point DC corona discharge. The model is based on the process by which electrons in weakly ionized gas transfer energy to neutral molecules through collision, and calculated the time-domain waveform of DC corona audible noise through numerical calculation [33–35], as shown in Figure 8.

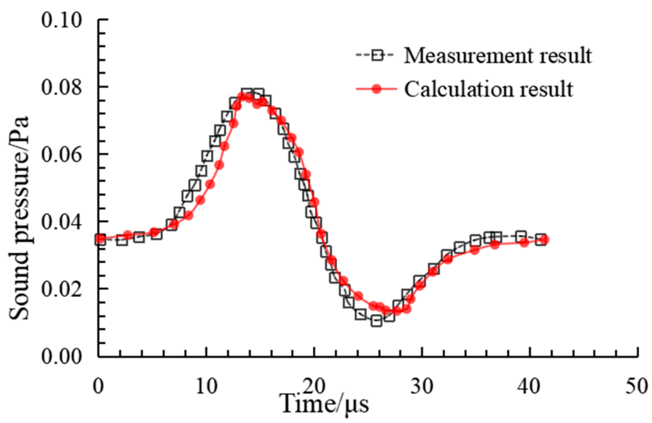


**Figure 8.** Comparison between the calculated and measured results of DC corona audible noise [47,49].

It can be seen from the results in the figure that this model can well simulate the sound-pressure waveform of DC corona audible noise.

## 4. Control of Audible Noise of DC Transmission Line

*4.1. Research Methods and Devices of Wire Audible Noise*

Since the 1960s, many countries have gradually begun systematically researching the audible noise of AC high-voltage transmission lines. The research methods are based on the corona cage's artificial corona audible noise test. The main research institutions include

Westinghouse Electric Corporation, Bonneville Power Administration, General Electric, the Soviet Union Institute of Electrical Engineering, the Institute of Higher Education Hydro-Quebec Research Institute of Canada, and ENEL. Since the 1990s, China has built AC and DC outdoor corona cage test platforms in Wuhan and Beijing and the Tibet high-altitude corona cage test platforms. Tables 1 and 2 show the outdoor corona cage test platform and audible noise measurement performance parameters [61–69].

**Table 1.** Statistics of outdoor corona effect test platform and its main parameters [70–77].

| Parameter \ Organization | EPRI (China) | UHV AC Test Base (Wuhan) | UHV DC Test Base (Beijing) | Qinghai Corona Test Platform (China) | IREQ (Canada) |
|---|---|---|---|---|---|
| Length | 10 m (Overall) | 35 m (Overall)<br>25 m (Test length) | 70 m (Overall)<br>60 m (Test length) | 35 m (Overall)<br>10 m (Test length) | 67 m (Overall)<br>61 m (Test length) |
| Cross-sectional area | Square; 6 × 6 $m^2$ | Double-layer cage; square; 8 × 8 $m^2$ | positive and negative boxes, with sections of 10 × 10 $m^2$; total area 22 × 20 $m^2$ | Section area 9.6 × 9.6 $m^2$; test area: 8 × $m^2$ | 5.5 × 5.5 $m^2$, Squre |
| Voltage | 600 kV | 800 kV | 1200 kV | 800 kV | 550 kV |
| Surface field stress | No data | 30 kV/cm | 30 kV/cm | No data | No data |
| Audible noise condition | Outdoor cage, movable | Outdoor cage with background noise measurement | Outdoor cage with background noise measurement | Outdoor cage | Outdoor cage |
| Load design | No data | 12 Bundled conductor | Traction insulator meets 1000 kV design requirements | No data | No data |
| Electrical measurement | PD, RIV | PD, RIV, Corona loss | PD, RIV, Corona loss | PD, RIV | PD, RIV, Corona loss |
| Noise measurement | Pressure sensor | Sound level meter | Sound level meter | Pressure sensor | Brüel & Kjær Pressure sensor |
| Environmental condition simulation | Rainfall, Sand, Dust | Rainfall | No data | High altitude, rainfall | Rainfall |

**Table 2.** Statistics of outdoor corona effect test platform and its main parameters [78–82].

| Parameter \ Organization | CRIEPI (Japan) | CRIEPI (Japan) | SAHVEC (South Africa) | ETH (Switzerland) | ESKOM (South Africa) | JPS (Japan) |
|---|---|---|---|---|---|---|
| Length | 24 m (Overall)<br>14.4 m (Test length) | 55 m (Overall) | 40 m (Overall)<br>30 m (Test length) | 6 m (Overall) | No data | 7.5 m (Overall) |
| Cross-sectional area | 8 × 8 $m^2$, Square | Radius: 2.1 m | Radius: 3.5 m | Radius: 1.5 m, 12-sided | No data | Radius: 1 m |
| Voltage | 800 kV | 350 kV | 170 kV | 166.6 kV | No data | 150 kV |
| Surface field stress | 18 kV/cm~30 kV/cm | 18 kV/cm~30 kV/cm | 40 kV/cm | 17.6 kV/cm | 14~22 kV/cm | 10~17 kV/cm |
| Audible noise condition | Outdoor cage | Outdoor cage | Outdoor cage | Outdoor cage, ground noise correction | Outdoor cage | Outdoor cage |
| Load design | No data | No data | No data | No tension load | No data | Tension load |
| Electrical measurement | PD | PD | PD, RIV, Corona loss | Leakage current | No data | No data |
| Noise measurement | Pressure sensor | Pressure sensor | No data | Sound level meter | No data | Pressure sensor |
| Environmental condition simulation | No | No | No | No | No | No |

In addition to the outdoor corona test platform, the indoor corona cage has also been widely used. The indoor corona cage is often used to study the generation mechanism of the transmission line corona effect. The indoor corona cage can be flexibly combined with other equipment to measure the corona effect under various ideal environmental conditions. Various institutions have built their indoor corona cage, as shown in Table 3 below.

**Table 3.** Statistics of indoor corona effect test platform and its main parameters [17,83–86].

| Parameter \ Organization | Tsinghua University (China) | North China Electric Power University (China) | University of Manchester (UK) | UKZN (South Africa) | WITS (South Africa) | Chongqing University (China) |
|---|---|---|---|---|---|---|
| Length | 4 m (Overall) 3 m (Test length) | 1.8 m (Overall) | 4 m (Overall) | 2 m (Overall) 1.5 m (Test length) | 4.7 m (Overall) 3.5 m (Test length) | 2.5 m (Overall) 1.5 m (Test length) |
| Cross-sectional area | Square; $1.7 \times 1.7$ m$^2$ | Radius: 0.4 m | Radius: 0.75 m | Ellipse, short shaft diameter: 0.88 m, long shaft diameter: 1.5 m | Radius: 0.75 m | Radius: 1 m |
| Voltage | 90~130 kV | 80 kV | 90~150 kV | 500 kV | 270 kV | 452.88 kV |
| Surface field stress | 23~32 kV/cm | No data | 16~25 kV/cm | 10~40 kV/cm | 10~40 kV/cm | 15~25 kV/cm |
| Audible noise condition | Indoor cage | Indoor cage | Anechoic chamber (22.5 dBA attenuation at 100 Hz) | Indoor cage | Indoor cage | Indoor cage |
| Load design | Maximum 2 tons | Insulator support | Maximum 1 ton | No data | No data | No data |
| Electrical measurement | PD, RIV | PD | PD, RIV, leakage current | PD, corona loss | PD, corona loss | PD, |
| Noise measurement | Sound level meter | Pressure sensor and Noise analyzer | Brüel & Kjær sound measurement platform | No data | No data | No data |
| Environmental condition simulation | No data | Humidity simulation | Rainfall | No | Water mist, temperature, wind speed | Humidity, high altitude |

It can be seen from Tables 1–3 that the corona effect of DC lines in various countries is usually studied by using test line segments or corona cages. Some corona cages with a sizeable sectional area can simulate DC single-pole or bipolar operation by separating them inside the cage. The various external insulation conditions can be realized by adding additional environmental simulation equipment. The methods for simulating the external insulation environment are as follows:

(1) installing a nozzle to simulate the rainfall condition
(2) installing a wind-sand feeding device to simulate the sand and dust condition
(3) applying the corona cage in high-altitude areas with different altitudes

The outdoor corona cage is large and challenging to sound insulation when measuring the audible noise. Usually, adding a background noise measuring device and filtering is used to eliminate the background noise interference. The indoor corona cage has certain advantages in manually controlling the environmental parameters. It can simulate various adverse weather conditions by combining with the artificial climate chamber and achieve more accurate measurements by installing a muffler to simulate the free-sound field. In addition to the indoor corona cage shown in the table, there are also smaller corona cages. By adding a Plexiglas bin, the humidity can be accurately controlled, and the condensation and corona discharge on the line surface can be simulated.

Various corona cage test platforms currently simulate the corona effect of single-phase lines under different external insulation environments. However, the main shortcomings of existing research methods and devices are as follows:

(1) In the environmental simulation, it is difficult to simulate the actual operating conditions due to the structural characteristics of the corona cage. In terms of electric field distribution, the ion-flow field of DC transmission lines varies significantly with the tower structure. When a corona cage is used to study the audible noise of DC lines, it

is difficult to directly support the actual lines by defining the sound–power–density independent of the test structure.

(2) The audible noise measurement of outdoor large corona test platform usually adopts the method of background noise filtering, and the accuracy of eliminating background noise interference needs to be improved. Manchester University has conducted an indoor anechoic chamber corona cage test, and the relevant test technology needs further improvement.

(3) The environmental parameters measured by the existing outdoor large corona test platform are not accurate enough, which cannot meet the requirements of finding the internal relationship between the corona effect and the environmental parameters, and establishing the corresponding theoretical model.

*4.2. Control Technology of Transmission Line Audible Noise*

There are two aspects to controlling audible noise. One is to predict and evaluate the audible noise to guide the design and construction of the line. The second is to reduce the surface field strength of the transmission line to control the level of corona discharge and then suppress the audible noise. Currently, the evaluation and prediction method of the DC audible noise follows the AC transmission lines. The primary method is to obtain the prediction formula of the sound-pressure level through many tests and data statistics, analysis, and fitting. Then, use the elevation, rainfall, conductor type, split number, split spacing, and other factors to correct the prediction formula. Finally, make the prediction formula suitable for specific engineering needs.

The EPRI formula from the United States generally calculates the audible noise of HVDC lines. However, this formula only applies to conductors with less than six strands, and the prediction error is significant when the conductor section is greater than 900 mm$^2$. For ±800 kV and ±1100 kV UHV DC transmission lines, it is necessary to use a larger cross-section and multi-bundle conductors, whose sub-conductor cross-section and splits number have exceeded the applicable range of the existing DC prediction formula. For this reason, the State Grid Corporation of China has studied the audible noise prediction of ±800 kV and ±1100 kV DC lines with large cross-sections and multi-bundle conductors using a corona cage and test section of UHV DC. More than 20 kinds of sub-conductors with bundle numbers four, six, and eight, and sections of 630 mm$^2$~1600 mm$^2$ have been tested, and the audible noise level under different field strengths has been obtained. The applicable range of the formula is: the number of conductor splits is eight or less, the sub-conductor section is 630–1600 mm$^2$, and the conductor surface-field strength is 18 kV/cm~32 kV/cm [70–72].

Currently, the corona effect assessment methods developed by scientific research institutions are based on the statistical analysis of their test data. Due to the different climatic conditions, geographical locations, and test conditions in different countries, the assessment results obtained by various research institutions differ significantly. Figure 9 shows the audible noise distribution of the same transmission line calculated using the empirical formula obtained by different organizations. It can be seen from the figure that the maximum and minimum difference between the evaluation results is up to 8 dB (A), which causes great uncertainty in the evaluation of the corona effect.

In addition to the prediction and evaluation of audible noise, the conductor field-strength control technologies are as follows [74–78]:

(1) Apply the split conductors. When the split conductor adopts the sub-conductor with symmetrical distribution, it can reduce the surface-field strength and reduce the audible noise level by increasing the number of split conductors, increasing the conductor section, and controlling the split-spacing. The current research results show that the audible noise decreases with the increase in the line diameter and the number of strands. When the number of sub-wire strands increases from six to eight, the noise can be reduced from 4 to 5 dB (A); take an eight-bundle conductor as an example. When the diameter of the sub-conductor increases from 30 mm to 40 mm, the audible noise of the conductor can decrease by 6 dB (A) or more. The split

conductor adopts the sub-conductor asymmetric split-mode, which can increase the charging uniformity of sub-conductors in each phase, and thus reduce the audible noise. The corresponding audible noise level can reach 12 dB (A) lower than the ordinary symmetrical bundle conductor.

(2) Change the strand structure of the wire and use the trapezoidal or Z-shaped outer structure with a smoother surface to reduce corona discharge, and thus reduce audible noise. The commonly used wire is made of round aluminum. The surface roughness coefficient of the conductor is generally about 0.8. When the outer trapezoidal or Z-shaped structure is used, the surface roughness coefficient is above 0.95, which improves the critical electric-field strength of the corona.

(3) Apply the hydrophilic and hydrophobic anti-corona coating. Spraying hydrophilic or hydrophobic coating on the conductor so that the water droplets attached to the conductor surface are absorbed between the strands and are not easy to form water droplets to reduce the corona discharge. However, considering the safety and reliability of the transmission line, the actual application of the conductor coating is relatively limited.

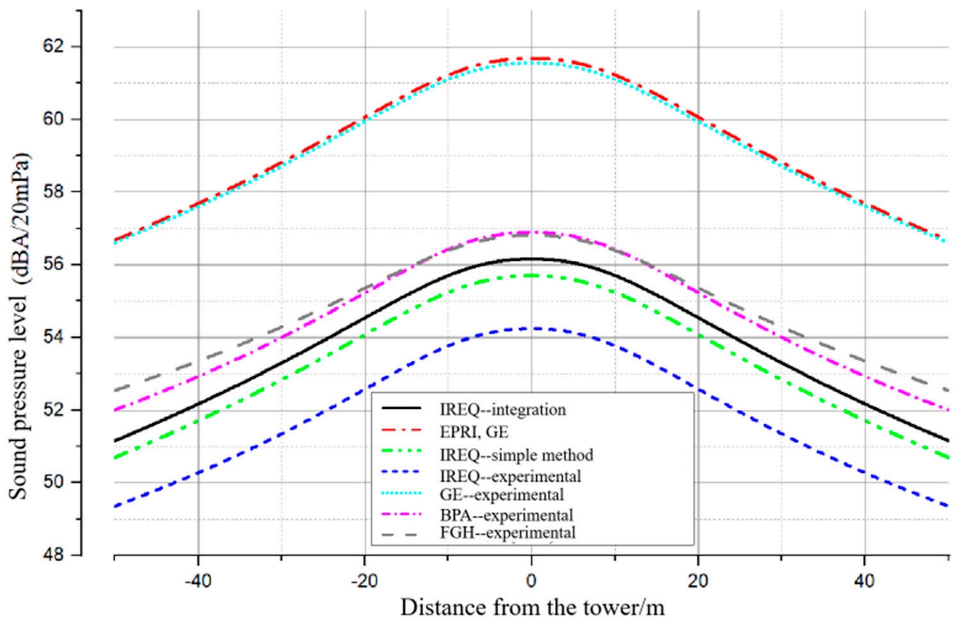


**Figure 9.** Evaluation example of audible noise in corona effect of actual overhead transmission line.

## 5. Discussion on the Research Progress

### *5.1. The Audible Noise Characteristic of DC Transmission Lines*

Progress in audible noise has been made in the A-weighted sound level and frequency domain characteristics of the DC transmission line, and relevant research results have supported this engineering design. The research on the temporal characteristics of DC corona audible noise and the correlation between corona and noise is still in the initial stage. The correlation between the acoustic and corona characteristics has been obtained. However, the correlation between the micro-discharge process of the corona and the audible noise is still lacking. Some progress has been made in the influence of the external insulation environment on the DC audible noise of conductors. Still, the relevant research focuses on macroscopic characteristics and qualitative discussion. Quantitative and rational studies are necessary for revealing the audible noise-generation mechanism.

Due to the characteristics of the transmission line, such as the high distance between the conductor and the ground and the complex natural environment, it is difficult to measure the audible noise in actual lines. Therefore, the understanding of the audible noise characteristics of the line is usually from laboratory data or test lines; the operating line still needs to be improved. In response to this issue, audible noise can be indirectly measured in the future through other corona effect parameters, such as radio interference and corona loss. Some specific ideas are as follows:

(1) By conducting systematic experimental research, the time-domain characteristics of corona current, corona loss, radio interference, and audible noise were obtained;
(2) Analyze the correlation between corona loss, radio interference, and audible noise, respectively;
(3) For operating lines, the audible noise characteristics are indirectly reflected by measuring the line's radio interference or corona loss.

### *5.2. The Mechanism of DC Corona Audible Noise*

Existing studies focus on the characteristics of DC audible noise, and there needs to be more research on the mechanism. The reason is that the corona discharge process is relatively complex, and its microphysical mechanism has yet to be fully understood. Further in-depth research and breakthroughs are needed for the new technology supporting the measurement of DC corona audible noise and numerical simulation. Finally, promote the engineering design of audible noise from statistical analysis and data fitting to quantitative calculation and numerical simulation.

Regarding the mechanism of audible noise generated by corona discharge, existing research has preliminarily established relevant physical models from the perspective of the gas ionization process and gas molecular motion propagation, achieving time-domain waveform calculation of AC and DC corona noise. However, existing models are usually based on ideal state analysis and calculation, which is different from the actual operating environment. In the future, in-depth research is needed in the following aspects:

(1) The audible noise mechanism of the line during the rainfall. The high-humidity environment before rainfall will lead to condensation on the line surface. During the rainfall process, raindrops will fall and break on the line surface, and there will be residual raindrops after rainfall. Under these conditions, raindrops will directly be charged, causing corona discharge. Due to the difference in corona characteristics between liquid surfaces and solids, there will be differences in the mechanism and characteristics of audible noise.
(2) The deformation and electric field distribution mechanism of droplets under the action of an electric field. The wettability of the transmission line surface will vary with different operating times, and the modified line will have super-hydrophilicity or super-hydrophobicity. At this time, the attachment conditions of raindrops on the line surface will change, leading to changes in its deformation and electric field distortion law under the electric field, thereby affecting the generation of audible noise;
(3) The propagation mechanism of corona noise. There is a specific understanding of the amplitude-frequency characteristics of noise generated by corona discharge. However, with the application of AC/DC hybrid transmission lines and AC/DC parallel lines, the superposition and propagation of corona noise have become more complex.
(4) The influence of space charge around the DC transmission line on the audible noise.

### *5.3. The DC Line Audible Noise Control Technology*

The primary methods to study the audible noise of DC transmission lines are experimental research in artificial corona cages. They have certain advantages in noise control, complex external-insulation environments, and bipolar operation simulation, but the cage's space-charge distribution differs from the transmission lines. The noise control, space charge, and environmental simulation should be comprehensively considered in the design of the new corona cage. The standard methods to control the transmission lines' noise are based on evaluating audible noise and controlling the conductor surface-field strength. They have yet to be closely combined with the research results on audible noise's time-domain characteristics and mechanism. At present, several aspects need further research on noise control technology for transmission lines:

(1) Anti-corona coatings. Presently, preliminary research and exploration have been conducted on anti-corona coatings. However, there is still controversy over whether the coatings should be hydrophilic or hydrophobic. Systematic theoretical simulation and experimental research are needed to determine the optimal coating wettability under different line parameters and operating environments.
(2) The roughness of the coating. The contact angle of the coatings usually needs to be controlled by micro/nano solid particles, such as silica. Adding these micro/nano solid particles will change the roughness of the coating surface, which may lead to an increase in discharge points and an intensification of corona noise. Therefore, it is necessary to compare the roughness of the operating line to design the coating;
(3) Durable anti-corona coating. The biggest challenge in the engineering application of anti-corona coatings is their poor durability. After spraying, the mechanical properties of the coatings deteriorate rapidly under sunlight exposure, the temperature difference between day and night, and outdoor wind blowing, resulting in difficulties in actual line operation and maintenance. Improving the durability of anti-corona coatings will significantly enhance their engineering application value.

## 6. Conclusions

This paper reviewed the research progress in the characteristics, mechanism, and mitigating techniques of AN from the HVDC transmission lines. In particular, it is focused on the latest research outcomes in the frequency and time-domain characteristics of AN, the correlation between corona discharge and sound generation, noise generation process, physical model, measurement methods and devices, and mitigating techniques. The following conclusions are obtained:

(1) Research on AN characteristic within time and frequency domain for DC corona discharge has made notable progress. However, the existing work focused on the macroscopic characteristics of the AN, which is the sound-pressure level only. The relationship between the intrinsic characteristic of corona discharge (space-charge density, distribution, channel pressure) and audible noise needs to be further studied to understand the mechanism of the AN generation from corona discharge. At the same time, the relationship between the audible noise and other corona effect parameters needs to be further studied to help the noise measurement on the operating lines.
(2) The process and related physical models of AN enable the single AN waveform to be calculated through self-consistent equations, but the mechanism of the time-domain characteristics of AN has yet to be revealed. A further study of the AN mechanism under rainfall environment, and the relationship between space charge and audible noise is essential for calculating the physical process in the time domain quantitatively; this will be helpful to apply the physical model on the actual operating lines rather than the ideal condition.
(3) The existing prediction methods for HVDC AN, established from the AC line measurement results, is based on empirical equations. It is not correlated with the mechanism of noise generation, which limited the effectiveness of the relevant mitigating techniques. To overcome this, the physical model and numerical simulation, which explains the mechanisms of AN generation, is suggested to be considered when developing empirical equations for AN prediction. This not only improves the accuracy of the prediction of AN but also helps in identifying effective techniques for AN mitigation. In addition, the anti-corona coating is a valuable noise-control method after overcoming the weather resistance and roughness problem.

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