Research on audible noise of ultra-high voltage direct current (UHV DC) transmission lines with a digital twin [version 1; peer review: awaiting peer review]

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Abstract
Much attention has been paid to audible noise in the design of ultra-high voltage (UHV) direct current (DC) transmission lines because of its negative impact on residents' lives. In order to analyze audible noise, shorten the research period, and reduce experimental costs, firstly, a digital twin model for audible noise of UHV DC transmission lines is proposed. Then, the model's structure and related principles are explained in detail. Finally, an application, as a research paradigm, uses digital twin to study the source distribution on transmission lines and influencing factors of audible noise. The A-weighted sound level of audible noise on the ground is calculated and compared with the data obtained by the BPA empirical formula. The results show that the position of the sound source tends to have uniform distribution and the intensity tends to have Gaussian distribution, while temperature and relative humidity exert obvious effects on audible noise, illustrating the great value of digital twin technology in the study of audible noise. This paper not only provides a new method for audible noise research, but also provides a reference for the design of UHV DC transmission lines.

Keywords
UHV DC transmission lines; audible noise; digital twin; source distribution; influencing factors
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**Introduction**

Electricity has become the most important energy source in global social and economic development due to its convenience and practicality. In order to transport electricity across distance and space, and ensure power supply, ultra-high voltage (UHV) direct current (DC) transmission technology has been widely used. However, the electromagnetic environment problems caused by corona discharge, such as corona current, electric field effect, audible noise, and radio interference, are becoming more and more serious with the increasing line voltage. Among these problems, audible noise can be perceived by residents and exerts a significant impact on human production and life. Statistical research shows that when audible noise of transmission lines is below 52 dB, there will be almost no complaints from residents. However, there will be a few complaints when the noise is between 52.5 dB to 59 dB, and more complaints when the noise exceeds 59 dB. Hence, audible noise is one of the most important factors to be considered in the design and construction of UHV transmission lines.

For achieving accurate prediction and control of audible noise from UHV transmission lines, scholars have carried out a series of experimental studies on the generation mechanism, influencing factors, and prediction methods of audible noise since the 1960s. Due to the complexity of audible noise, researchers used to analyze the statistical characteristics of audible noise using actual transmission lines. For example, long-term measurements of audible noise and meteorological variables were carried out using an operating 400 kV transmission line in Sweden. American Electric Power Service Corporation measured and analyzed audible noise and corona loss data under a variety of weather conditions and different voltages. However, long-term observation is required in the research because it is difficult to control a variety of environmental factors, which affect audible noise seriously.

In a corona cage, influencing factors such as wire type, spacing, voltage, humidity, and temperature can be flexibly changed, and electromagnetic environments could be detected conveniently. Therefore, a corona cage applied to audible noise study becomes a solution, which is much more efficient than the actual transmission lines. Literature measured audible noise and corona current simultaneously in the world’s largest corona cage to obtain the statistical law of their frequency spectrums, and then explained the statistical law by electro-acoustic conversion theory. Using corona cages usually helps to study the impact of a single factor on UHV audible noise productively. Several audible noise measurements under heavy rain conditions were taken and a formula was derived based on the cage test. The effect of temperature and humidity on audible noise was studied in a mini corona cage which was constructed and put in a manual environment room. However, construction and maintenance costs of corona cages are high, which limits its promotion and application.

In recent years, reduced-scale platforms with artificial defeat conductors were also built up in an anechoic chamber to study audible noise characteristics of a single corona source or multiple sound sources. The platform can exclude natural influencing factors when studying the characteristics of audible noise in the time and frequency domains. However, lacking systematic and comprehensive analysis, this method is hard to apply to the prediction and evaluation of audible noise in complex outdoor environments.

The long research period, high investment costs, and the lack of systematic analysis have limited the progress of study into audible noise to some extent, while the digital twin technology emerging in recent years has potential to solve these problems well. Using digital and virtual technology to explore and predict the operation state of physical reality in a virtual environment, the digital twin could complete the model’s establishment, simulation, and verification. Digital twin has been applied to shop floor environments, effectively shortening the development cycle, reducing the development cost, and realizing digital recordings and predictions. At present, the research on digital twin is mainly focused on the production process, and the research applying digital twin in audible noise analysis and prediction is rare.

In order to explore an effective research paradigm to support a systematic analysis of audible noise, shorten the long research period, and reduce the high investment costs, this paper applies digital twin technology to audible noise and introduces the composition and related principles of the digital twin model. On this basis, an application of digital twin has been discussed to study the distribution of sound sources and influencing factors, which is an example to validate the feasibility of audible noise research based on digital twin technology.

**The digital twin model of audible noise**

Before applying digital twin technology to audible noise research, we firstly expound the generation process and influencing factors of UHV audible noise. After that, a digital twin model is proposed and its structure is illustrated. The relevant physical parameters during sound generation and propagation are digitized and virtualized, and some principles, such as source characteristics and calculation methods of UHV audible noise, are used in the digital twin model.

**Formation mechanism of audible noise**

A synthetic electric field could be generated around UHV DC transmission lines, and free electrons in the air move directionally under the action of the electric field force. When the electric field exceeds a critical value, the kinetic energy of electrons increases and hits the air molecules to create new free electrons and ions, resulting in a large number of electrons and ions in the area. For positive polarity conductors, electrons would rapidly surge into the wires, while positive ions flow to the ground, which causes corona discharge. Since the mass of ions and air molecules is similar, inelastic collisions occur during this movement, causing increased intramolecular energy and enhanced Brownian motion. This phenomenon manifests macroscopically as air vibrations and produces broadband audible noise.
Audible noise produced by corona discharge from UHV DC transmission lines is affected by many factors, which can be divided into two categories. The first can be controlled by human designation, including wire arrangement, wire diameter, phase spacing, wire-to-ground height, single/double loop, and the number of splits. After the transmission line has been in operation for several months, the effect of these factors on audible noise tends to stabilize. The second is related to natural conditions, including relative humidity, air pressure, temperature, wind speed, ultraviolet radiation, rainfall, and snowfall, which cannot be controlled by humans and requires more focus and research.

The structure of the digital twin model

The digital twin model should reflect environmental data from various aspects such as geometry, physics, and rules. Therefore, the establishment of the model consists of the following three steps, as shown in Figure 1.

Firstly, the main objects in the actual environment should be extracted, including transmission lines, ground, buildings, roads, vehicles and vegetation, while the dimensions, geometry, and location of these objects should be determined. Secondly, various parameters such as temperature, atmospheric pressure, humidity, and wind speed in multiple physics fields are collected through different sensors. These physical fields are generally closely coupled, interact and influence each other, making some parameters difficult to measure directly. So, we use virtual sensors instead of physical sensors to calculate, simulate and analyze environmental fields. Thirdly, the related principles and theories, including the sound source characteristics and calculation methods, are used to deal with the parameters and give the audible noise results.

According to the above steps, the digital twin virtual model of UHV audible noise would be built by the existing theory and knowledge. Then we can set different environmental parameters and adopt virtual simulation technology to discuss and predict UHV audible noise, which can conduct systematic research on audible noise, while reducing experimental costs and shortening experimental time.

Data acquisition of digital twin model. The digital twin is the virtualized mirroring of physical reality and a variety of data in the physical environment needs to be collected. The 3D structure and geometry of UHV DC transmission lines and their surroundings are required to be reproduced in the digital twin model. Besides, to realize the communication and interaction between the physical reality and digital model, it is necessary to determine the multi-domain physics around audible noise and to acquire the environmental information. Audible noise of UHV DC transmission lines involves temperature field, pressure field, electric field, velocity field, ion current field, magnetic field, and humidity field. In order to measure these physical parameters, different sensors should be set up, as shown in Figure 2.

In these physical fields, environmental information such as temperature, atmospheric pressure, humidity, wind speed, and air density are easily obtained, and we can directly measure...
them using physical sensors. However, the electric field, magnetic field, and ion current are difficult to measure directly, and instead could be calculated by the finite element method.

It is worth mentioning that environmental parameters could be manually changed to study and predict the characteristics and laws of audible noise under different conditions. Therefore, physical sensors are replaced by virtual sensors to collect parameters in the digital twin model.

Source characteristics of audible noise. UHV audible noise is generated from the sound source around the transmission lines and propagates to the ground after passing through a medium (like air). So, it is important to determine source characteristics in the digital twin model. According to previous studies\(^{13,24}\), the characteristics of audible noise produced by single corona discharge are similar to point sound sources. Therefore, audible noise of UHV DC transmission lines is regarded as the simultaneous emission of multiple point sources. Consider a single sound source of audible noise as a point vibrating in the unconstrained space, which satisfies the wave Equation (1) in the frequency domain.

\[
\nabla \left( \frac{1}{\rho_0} \nabla p - q \right) - \frac{\rho_0^2 \omega^2 p}{\rho_0 c_s^2} = Q \quad \text{#(1)}
\]

where \(\nabla\) is the Hamiltonian operator; \(\rho_0\) is the air density; \(p\) is the sound pressure; \(q\) is the dipole source; \(\omega\) is the angular frequency; \(c_s\) is the sound velocity; \(Q\) is the monopole source.

The sound source of audible noise can be regarded as a monopole source, and the sound pressure to the ground can be expressed as

\[
p(r) = \frac{Q e^{-kr}}{4\pi r} \quad \text{#(2)}
\]

where \(r\) is the distance from the sound source to the measurement point; \(k = \omega c_s\) is the wavenumber.

According to experimental results from UHV DC transmission lines, corona discharges are independent random events\(^{25,26}\). The position of audible noise sources in a period may satisfy the uniform distribution, and the intensity of sound sources may satisfy the uniform distribution or the Gaussian distribution. In addition, audible noise usually occurs at wire defects, resulting in a fixed sound source. If these positions emit audible noise independently at a constant average rate, then it can be considered that the sound intensity of a fixed sound source point satisfies a negative exponential distribution per unit time according to the formula of equivalent continuous sound level\(^{27}\). Therefore, for a transmission line with length \(L\) and
source number \( X \), the distribution of source position \( P \) and intensity \( Q \) is set to the following three types:

(a) The sound source position and intensity are both uniform distributions.
\[
\begin{align*}
  P_i & \sim U(0, L) \\
  Q_i & \sim U(Q_{\text{min}}, Q_{\text{max}})
\end{align*}
\]
\( i = 1, 2, 3, \ldots, X \)

(b) The sound source position is uniform distribution and the intensity is Gaussian distribution.
\[
\begin{align*}
  P_i & \sim U(0, L) \\
  Q_i & \sim N(\mu, \sigma^2)
\end{align*}
\]
\( i = 1, 2, 3, \ldots, X \)

(c) The sound source is fixed and the intensity is exponential distribution.
\[
\begin{align*}
  P_i & \sim M_i \\
  Q_i & \sim E(\lambda)
\end{align*}
\]
\( i = 1, 2, 3, \ldots, X \)

where \( P_i \) and \( Q_i \) are the position and intensity of the \( i \)-th source point, \( U(Q_{\text{min}}, Q_{\text{max}}) \) represents a uniform distribution ranging from \( Q_{\text{min}} \) to \( Q_{\text{max}} \), \( N(\mu, \sigma^2) \) represents a Gaussian distribution with mean \( \mu \) and variance \( \sigma^2 \), \( M_i \) is a constant and \( 0 < M_i < L \), \( E(\lambda) \) represents an exponential distribution with rate parameter \( \lambda \).

The position and intensity distribution of audible noise sources of UHV DC transmission lines may satisfy any of the above three types, and needs to be analyzed according to the actual wire conditions.

The calculation method of audible noise. In the digital twin model, the sound pressure level (SPL) is calculated to describe the strength of the sound on the ground. According to the superposition principle of waves, the ground sound pressure can be obtained by summing up sound sources. The wave generated by the sound source is a linear sound wave, this allows the sound pressure in the time domain to be calculated by the Fourier transform superposition at multiple different frequencies.

The human ear is more sensitive to high-frequency sounds, but not to low-frequency sounds. Audible noise with the same sound pressure level but different frequencies exerts different subjective effects on the human body. A-weighted is valid scale used to represent the sensitivity of the human ear as a function of the frequency of pure tones\(^2\), so we use A-weighted SPL to describe audible noise in our model.

If the audible noise ranged from 20Hz to 20kHz is divided into 30 frequency bands, and the highest frequency of each frequency band is \( \sqrt{2} \) times the lowest frequency, the spectral information of audible noise can be completely reflected, which is called 1/3 octave of audible noise. The frequency of the sound source is set as the center frequency of each frequency band, and corrected with an A-weighted filter. A-weighted SPL at the receiving point can be obtained by superimposing the SPL of each frequency band with the following formula.
\[
L_{\text{eq}} = 10 \log \left[ \sum 10^{\frac{-L_{\text{eq}} + L_{\text{eq}}}{10}} \right]
\]  
(#3)

where \( L_{\text{eq}} \) is A-weighted SPL; \( L_{\text{eq}} \) is the SPL at each centre frequency; \( A_i \) is A-weighted correction value at each centre frequency.

An application for audible noise research with digital twin

Applying the composition and principles of digital twin, a model of audible noise is built to simulate and discuss the position and intensity distribution of sound sources from UHV DC transmission lines, as well as the influencing factors of audible noise.

The model adopts the world’s largest outdoor corona cage, located in the UHV DC experiment base in Beijing, China. The double corona cages, shown in Figure 3(a), consist of two parts of positive and negative polarity. In this instance, we only study audible noise generated by positive corona discharge. The size of the single cage is 10mx10m, and a 6-bundled conductor JL/GIA-720/50-45/7 (Beijing Jianghaiyang Cable Co., Ltd) is hung in the centre of the cage, as seen in Figure 3(b). The sub-line diameter, bundle spacing, and the height to the ground are respectively 36.2mm, 0.45m, and 5m. An 800kV supply is applied to the 6-bundled conductor.

Simulation condition settings

A simulation model is created with digital twin technology according to the corona cage structure in Figure 3 using COMSOL Multiphysics (COMSOL inc., 2021)(RRID:SCR_014767). The temperature, relative humidity, and atmospheric pressure in the digital twin model are set at 10°C, 50%, and 101.325kPa, respectively. The length of transmission line was set to 40m, the air density is 1.15kg/m\(^3\) and the sound speed in the air is 340m/s\(^2\).

The geometric distance between the split wire and the ground is much larger than the size of the split conductor when calculating the sound field around the wire. Therefore, the 6-bundled conductor can be equivalent to a single conductor and the equivalent radius can be calculated by the following formula\(^2\).
\[
r_{eq} = R \left( \frac{nr}{R} \right) \frac{1}{n}
\]  
(#4)

where \( r_{eq} \) is the equivalent radius of split conductor, \( R \) is the radius of split circle, \( n \) is the number of sub-lines, \( r \) is the radius of sub-lines.

When the geometric size far exceeds the wavelength, we can ignore the wave properties of the sound source and approximate it as the propagation of rays from a point. Therefore, we use the pressure acoustic model in the low-frequency band of 20-600Hz to observe the fluctuation. The ray acoustic model is used in the high-frequency band of 600-20000Hz to improve the calculation efficiency. The fluid is defined as the atmospheric attenuation module and the wall condition of the ground is set to diffuse scattering, and the wall condition of other faces is set to pass through. The sound absorption and reflection coefficient of grassland are 0.8 and 0.2 respectively. We use tetrahedron to generate meshes and the maximum length of the grid is...
0.2m. The maximum number of iterations for mesh generation is 25, and the iteration error is 1%. To simplify the operation and ensure accurate simulation results, we put forward the following approximations.

(a) Ignore the sag of transmission wires and treat them as line segments parallel to the ground.

(b) Audible noise from transmission lines is stable for a period.

(c) Only still air is considered, and the effect of wind speed is not considered.

(d) Only flat ground is considered, and complex ground conditions such as slopes and standing water are not considered.

Simulation for source distribution

We discuss the position and intensity distribution of audible noise sources from corona cage transmission lines. The source position $P_i$ and intensity $Q_i$ are random numbers, generated by the three distribution types discussed in "Source characteristics of audible noise". The relevant parameter values are set as follows.

\[ X = 30 \]
\[ Q_{\min} = 0, Q_{\max} = 0.01 \]
\[ \mu = 0.005, \sigma^2 = 0.001 \]
\[ \lambda = 200 \]

Then we set the source position and intensity on the transmission line, as shown in Figure 4, and use the digital twin model to simulate the A-weighted SPL at receiving points on the ground.

In order to determine which type of source distributions of UHV audible noise in the corona cage belongs, the simulation results are compared with the BPA prediction \textit{Formula (5)}. It is summarized through long-term experimental observations and data accumulation from full-scale lines and presented by Bonneville Power Administration\textsuperscript{30}. Therefore, this formula is widely used to predict UHV audible noise with high accuracy. The sound sources on the transmission line tend to be more consistent with the distribution whose simulation result is closest to that calculated by the prediction formula.

\[ L_{AN} = 80\lg g + k\lg n + 40\lg d - 11.4\lg D + L_{AN0} \quad \#(5) \]

\[ k = \begin{cases} 25.6 & n \geq 3 \\ 0 & n < 3 \end{cases} \]
\[ L_{AN0} = \begin{cases} -100.6 & n \geq 3 \\ -93.4 & n < 3 \end{cases} \]

where $L_{AN}$ is A-weighted sound level $L_0$ on sunny days; $g$ is the surface gradient of the conductor; $k$ is the adjustment factor depending on the value of specific parameters; $n$ is the number of sub-lines; $d$ is the sub-line diameter; $D$ is the radial distance from the conductor; $L_{AN0}$ is a reference A-weighted SPL.

The A-weighted SPL on the ground and the radial distance from receivers to the conductors in the model are indicated by black dots in Figure 5. As a comparison, the A-weighted SPL calculated by the BPA prediction formula is represented by the red dots in Figure 5\textsuperscript{31}.

From scatters in Figure 5, it can be found that the A-weighted sound level continues to decrease as propagation distance increases. With the further increase of the propagation distance, the reduction of the noise level gradually slows down and becomes stable.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{image}
\caption{(a) The structure of the corona cage, (b) arrangement of the 6-bundled conductor.}
\end{figure}
Figure 4. Schematic diagram of sound sources and receivers in the model.

Figure 5. Comparison between simulation results and formula prediction. (a) source position and intensity are both uniform distributions, (b) source position is uniform distribution and intensity is Gaussian distribution, (c) source position is fixed and intensity is exponential distribution.
When the sound source position and intensity are both uniform
distributions, the noise obtained by the simulation is slightly
larger than the empirical prediction formula overall. Several
scatters deviate more from the empirical formula, showing
that the simulation error becomes larger as the distance increases.
When the position is uniform distribution and the intensity is
distributed with a Gaussian pattern, the simulation results are
consistent with the empirical formula and the data are concen-
trated near the empirical formula, indicating the distribution
is closest to reality. When the intensity is exponential distri-
bution, the noise value at the ground has a large deviation com-
pared with the prediction formula, and the model effect is
poor.

Therefore, it can be considered that the position of noise
sources from actual transmission lines is closer to the uniform
distribution and the intensity of noise sources is closer to the
Gaussian distribution. This may be because the sound source
points of audible noise are mostly caused by wire defects and
accumulation of contamination, which occur randomly in the
natural environment. The probability of sound sources gener-
ated at each position of wires is roughly equal, showing a uni-
form distribution. Long-distance wires will continuously generate
audible noise, and the intensity of the sound source is affected
by various environmental factors. The noise intensity will
satisfy the Gaussian distribution for a long time.

Simulation for influencing factors
There are many influencing factors of UHV audible noise.
We select two major factors, including temperature, and rela-
tive humidity, and then calculate, simulate and analyze audi-
able noise in the model. The radial distance is set at 10 m and
other parameters are kept constant.

In the process of audible noise generation and propagation, the
vibration and directional motion of air molecules are affected
by the ambient temperature, which changes the air resistance
and absorption, resulting in sound attenuation. We study the
A-weighted sound level of ground audible noise when the
temperature is set at -10, 0, 10, 20 and 30°C. Figure 6 shows
the variation of audible noise with the temperature at differ-
ent frequencies. It can be found that as the air temperature
increases, the ground A-weighted noise continues to decrease.
The smaller decrease is because the air viscosity and absorption
resistance increase slowly when the temperature increases.

Water molecules in the air also have an important influ-
ence on corona discharge. We set the relative humidity at 0%,
20%, 40%, 60% and 80% and calculate the audible noise, as
shown in Figure 7. When the relative humidity is 0%, the audi-
ble noise is the highest. And when the relative humidity is 20%,
the audible noise is the lowest. With the increase of ambient
relative humidity, audible noise at 15000 Hz decreases rapidly
from 77.5 dB to 61.5 dB at first but increasing humidity
beyond 20% sees a slow increase to 69.5 dB. This is because
when the relative humidity is low, water molecules will
absorb free electrons to form negative ions. The movement
speed of negative ions is greatly reduced compared with free elec-
trons, causing low-frequency collision ionization. Then corona
discharge is suppressed and audible noise continues to diminish.
When the relative humidity is higher, a large volume of water
molecules is gradually formed in the air and adheres to the sur-
face of the wire. The large curvature radius of the water drop-
let generates a distorted electric field. It leads to the electric
field strength increasing, which accelerates the ionization and
gradually enhances the audible noise.

In addition, from Figure 6 and Figure 7 we can know that the
higher the frequency, the more drastically the audible noise is
affected by temperature and humidity. Under the same conditions,
the ground A-weighted SPL in the high-frequency band is
lower, indicating that high-frequency noise is more prone to be attenuated and absorbed in propagation.

Conclusions
In this paper, digital twin is applied to research audible noise of UHV DC transmission lines. The following conclusions are obtained:

(1) The introduction of digital twin technology into audible noise solves the problems of long test periods and huge test costs in outdoor experiments, providing a systematic and effective method for both theoretical studies of audible noise and the design of transmission lines.

(2) A digital twin model of audible noise is proposed, while the structure and related principles including the sound source characteristics and calculation method in the model are explained.

(3) We discuss the distribution of sound sources and influencing factors of audible noise, as a paradigm that digital twin technology is applied to audible noise. It is found that the position of UHV audible noise tends to the uniform distribution and the intensity tends to the Gaussian distribution. Temperature and relative humidity also exert obvious effects on audible noise.

Data availability

This project contains the following underlying data:
- source_distribution_a.csv This file includes simulation results when source position and intensity are both uniform distributions, as shown in Figure 5(a).
- source_distribution_b.csv This file includes simulation results when source position is uniform distribution and intensity is Gaussian distribution, as shown in Figure 5(b).
- source_distribution_c.csv This file includes simulation results when source position is fixed and intensity is exponential distribution, as shown in Figure 5(c).
- source_distribution_formula.csv This file includes prediction results by BPA formula, as shown in Figure 5.
- temperature.csv This file includes audible noise at different temperature, as shown in Figure 6.
- relative_humidity.csv This file includes audible noise at different relative humidity, as shown in Figure 7.

Data are available under the terms of the Creative Commons Attribution 4.0 International license (CC-BY 4.0).

Software availability
We create a simulation model to study audible noise by COMSOL Multiphysics (version 5.6). The files have been uploaded to Zenodo. Alternative open access software that could be used include Elmer and KRATOS Multiphysics.

Repository: The simulation model of source distribution and influencing factors.

This project contains the following files:
- source_distribution_a.mph (This file includes the simulation model when source position and intensity are both uniform distributions.)
- source_distribution_b.mph (This file includes the simulation model when source position is uniform distribution and intensity is Gaussian distribution.)
- source_distribution_c.mph (This file includes the simulation model when source position is fixed and intensity is exponential distribution.)
- temperature.mph (This file includes the simulation model at different temperature.)
- relative_humidity.mph (This file includes the simulation model at different relative humidity.)
- The instructions of simulation programs.pdf (This file introduces the function and usage of the programs.)

Software are available under the terms of the Open Software License 3.0 (OSL-3.0).

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