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Audible Noise Performance of Conductor Bundles Based on Cage Test Results and Comparison with Long Term Data

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Abstract: A reasonable acoustic power formula is vital to precisely evaluate the audible noise (AN) level of ultra-high-voltage (UHV) AC power lines. This study derived a formula by taking several AN measurements under heavy rain conditions, using multiple conductor bundles in a UHV corona cage, and then subjecting these measured values to least squares fitting. The validity of the proposed formula was subsequently verified with statistical data obtained from two long-term stations at Henan and Hubei Province, which are located under the Jindongnan-Nanyang-Jingmen UHV AC transmission lines operating at 1000 kV. The deviation between the prediction and the long-term (L50) value was 0.76 dB for the Henan station and 0.17 dB for the Hubei station. It shows that the acoustic power formula derived in this paper is more accurate than the widely used Bonneville Power Administration formula, in which the corresponding deviations are much larger (3.07 and 2.53 dB).

Keywords: UHV AC power lines; corona performance; audible noise; acoustic power

1. Introduction

Ultra-high-voltage (UHV) AC transmission lines are indispensable to the development of electric power transmission in China [1]. However, with the increase in applied voltage, the corona discharge around the conductor bundles becomes more severe and can engender audible noise (AN), which is more serious and irritating in high-voltage transmission lines [2–5]. Therefore, AN level is an important limiting factor for the design of overhead line conductors. Whether the AN predicting method is accurate or not has a direct influence on project investment due to the costly solutions to meet the environmental limits, such as using larger conductors, lifting the lines height and the associated cost of additional strength needed in towers [6,7]. Therefore, a method for precisely estimating the AN level of UHV AC transmission lines is in demand for Chinese UHV AC construction projects.

To investigate the corona characteristics of UHV AC transmission lines, the State Grid Corporation of China built a corona cage at the Wuhan UHV AC Test Base. The cage is a two-layer wire-mesh enclosure, with a cross-section of 8×8 m^2 and an effective length of 35 m [8]. The general view and structure of the corona cage are shown in Figure 1.

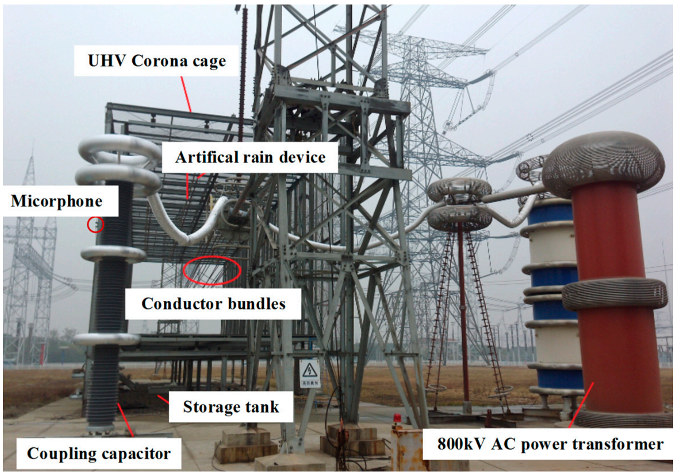


Figure 1. UHV AC corona cage.

The corona cage is an important piece of apparatus for research on the AN level of transmission lines; and it is generally recognized that AN level from AC transmission lines is serious in foul weather, especially in rain [9]. Therefore, numerous earlier studies of AN characteristics had utilized a corona cage under artificial rain conditions. Between 1967 and 1971, many tests were performed by the American Electric Power Company to evaluate the corona effects of high-voltage lines, including a single-span overhead test line and test cage; then the AN method was derived to predict the L_5 value of AN level (L_5 value is the value exceeding 5% of the all-time value in rainy weather) [10]. Trinh and Maruvada from the Institut de Recherche d'Hydro-Québec (IREQ) had measured the AN level of several conductor bundles by using a corona cage in heavy rain conditions, and they had established a semi-theoretical method for predicting AN levels [11,12]. In addition, Electricité de France (EdF) in France [13], Ente Nazionale per L'Energia Elettrica (ENEL) in Italy [14] and the Central Research Institute of Electric Power Industry (CRIEPI) in Japan [15] had also proposed their AN formulas which all derived from heavy rain conditions. Chartier and Stearns from the Bonneville Power Administration (BPA) made a statistical analysis of AN levels on some full-scale lines and operating transmission lines, and they developed a general formula for predicting the A-weighted L_{50} level (the value exceeding 50% of the all-time value in rainy weather) for AC lines [16]. Then all these formulas were evaluated in an IEEE Committee paper [9] in 1982 by comparing them with experimental results obtained on several operating lines, and it is turned out that the BPA formula is more accordant with the practical line. Therefore, the BPA formula had become the most widely used formula to predict the L_{50} value of AN level for transmission line in the last decades. In 2010, Tang has discussed in detail the effects of conductor bundles on AN levels given different weather conditions, surface gradients of the conductor, diameters of the subconductor, split space, and split number [17]. Lu and Chen discussed the consistency analysis between the electric field and AN caused by UHV test lines and transmission lines [18,19]. Li and Cui investigated the time-domain characteristics of AN produced by corona from DC conductors, then the correlation between audible noise and corona current was discussed in detail [20–22]. Yi and Zhang proposed an acoustic source model to simulate the sound pressure pulse of positive DC corona discharge [23]. The references [20–23] mainly discussed the mechanism of audible noise, and it is difficult to predict the AN level of practical transmission lines by using the obtained conclusions due to the complexities of wide area calculation.

Currently, the BPA formula is used as the standard method in China to predict the AN level of long lines. However, because of differences in productive principles and conductor processes, the values predicted by the BPA formula are greater than the actual AN levels in China. This was confirmed by comparing the AN performance between BPA calculations and the long-term statistical data of two stations in China under the Jindongnan-Nanyang-Jingmen UHV transmission lines operating at 1000 kV [24,25]. In this study, to obtain a more accurate description of the AN level caused by transmission lines, AN cage measurements were taken for a high number of conductor bundles; these were summarized, and used to derive a relevant AN formula. The predicted values calculated by this function were compared with the long-term data, and the results showed a good match.

2. Experimental Method

2.1. Test Conductors

In this study, several bundled conductors were used to measure the sound pressure level (SPL) under the heavy rain condition in the cage. The types of bundled conductors are presented in Table 1. These conductors have different sizes, with subconductor diameters varying from 24.2 to 39.9 mm and the number of conductors in the bundle ranging from 6 to 12. The relationship between the conductor type and subconductor diameter is shown in Table 2.

Table 1. Types of bundle conductors.

Bundle Number	Bundle Types	
6	6 × LGJ400 6 × LGJ630	6 × LGJ500 6 × LGJ900
8	8 × LGJ300 8 × LGJ500 8 × LGJ720	8 × LGJ400 8 × LGJ630 8 × LGJ900
9	9 × LGJ400	9 × LGJ720
10	10 × LGJ400	10 × LGJ630
12	12 × LGJ400 12 × LGJ720	12 × LGJ630 -

Table 2. Relationship between conductor type and subconductor diameter (Unit: mm).

Conductor Type	LGJ300	LGJ400	LGJ500	LGJ630	LGJ720	LGJ900
Subconductor Diameter (mm)	24.20	26.80	30.00	33.60	36.24	39.90

2.2. Setup and Measurement

The measurement system consisted of a microphone, amplifier, data acquisition system, and computer. The microphone was the half-inch Type 4189 (Brüel & Kjær, Copenhagen, Denmark) with a frequency range of 6.3 Hz to 20 kHz and a normal sensibility of 50 mV/pa. The amplifier supplied the polarized voltage to the microphone, providing 20 dB amplification to the microphone's output signal. The data acquisition module was the Type 3050 (also by Brüel & Kjær), offering 4–6 high-precision input channels with an input range from DC to 51.2 kHz [26]. The SPL signal could be measured by the microphone and converted to an electrical signal, which could then be transmitted to the data acquisition module and processed. Subsequently, the measurement data could be displayed by the pulse measurement and analysis software (pulse Labshop by Brüel & Kjær) on a PC.

In the experimental arrangement (Figure 2), the microphone was placed close to the shield cage at the same height as the bundled conductors. The vertical distance of the microphone was at the center of the entire corona cage. AC high voltage was applied to the conductors, supplied by a single-phase transformer with a voltage rating of 800 kV and a rated capacity of 400 kVA.

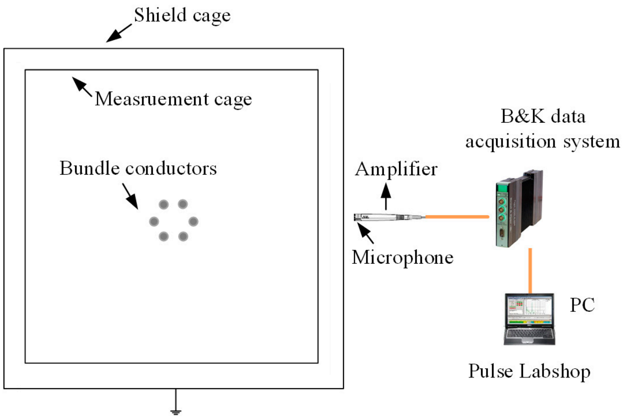


Figure 2. Measurement system for the AN.

2.3. Method of Gaining Acoustic Power Density and Sound Pressure Level

Due to the complexity of the corona discharge process, determining the AN entirely from theoretical considerations is difficult. Therefore, the A-weighted acoustic power density was used as the generation quantity of AN to describe the AN performance of transmission lines [14]. The A-weighted acoustic power level (PWL) can be derived from the experimental data obtained in the corona cage according to the following procedure:

(1) Assuming the corona is distributed uniformly along the test line, the AN source of the element length dx can be described as an independent point source and the acoustic propagation as a spherical sound wave. The acoustic power energy from a test line can be calculated as (1), which accounts for the reflection properties of the ground:

$$J = \int_{-L/2}^{L/2} \frac{A_0}{4\pi(D^2 + x^2)} \mathrm{d}x + k \int_{-L/2}^{L/2} \frac{A_0}{4\pi({D_\mathrm{i}}^2 + x^2)} \mathrm{d}x = \frac{A_0}{2\pi}\left[\frac{1}{D}\arctan(L/2D) + \frac{k}{D_\mathrm{i}}\arctan(L/2D_i)\right] \quad (1)$$

where J is the acoustic power energy, A_0 is the acoustic power generated per unit length of conductor (PWL), L is the conductor length, D is the radial distance from the measuring point to the conductor, X is the variable distance along the conductor, D_i is the distance from the measuring point to image of the line, and k is the reflection coefficient of ground.

(2) The SPL measured from the corona cage experiment can be defined as follows:

$$P = \sqrt{\delta c J} \quad (2)$$

where P is the SPL, δ is the air density, δ = 1.205 kg/m^3, and c is the velocity of the sound wave propagation in air, c = 344 m/s.

(3) From Equations (1) and (2), the relationship between P and A_0 is:

$$A_0 = \frac{P^2 H}{\delta c} \quad (3)$$

where:

$$H = 2\pi \Big/ \left[\frac{1}{D}\arctan(\frac{L}{2D}) + \frac{k}{D_\mathrm{i}}\arctan(\frac{L}{2D_\mathrm{i}})\right] \quad (4)$$

(4) Combining the measured SPL from the cage test and (7), the acoustic power density of the different bundled conductors can be obtained.

For an infinite line (i.e., transmission lines), $L/2D \to \infty$, and $\arctan(\infty) = \pi/2$, k is considered as 0 when the ground is assumed to be a good sound absorbing medium for high frequency noise [16]. Then H is:

$$H = 2\pi \Big/ \left[\frac{1}{D} \cdot \frac{\pi}{2}\right] = 4 \cdot D \quad (5)$$

The SPL of infinite lines is:

$$P = \left(\frac{A_0 \delta c}{4D}\right)^{1/2} \tag{6}$$

Converting Equation (6) in terms of $\mathrm{dB}_{20\mu\mathrm{Pa}}$, δ = 1.205 kg/m^3 and c = 344 m/s, Equation (6) becomes:

$$P_{\mathrm{dB}} = 10\lg\left(\frac{P}{20\mu\mathrm{Pa}}\right)^2 = A_{\mathrm{dB}} - 10\lg D + 10\lg\left(\frac{\delta c}{4}\right) - 10\lg(400) = A_{\mathrm{dB}} - 10\lg D - 5.8 \tag{7}$$

From [12,16], the term 11.4lg$D$ is recommended to replace the term 10lg$D$ in considering the atmosphere absorption of audible noise, then the SPL for each phase of transmission lines is:

$$P_{\mathrm{dB}} = A_{\mathrm{dB}} - 11.4\lg D - 5.8 \tag{8}$$

3. AN Performance of Bundled Conductors

In this study, the SPLs of 17 distinct bundled conductors were measured using the corona cage, and the influence of multiple variables on acoustic power density are discussed as follows, including the average maximum bundle gradient $g_{\max}$, the bundle size n, and the subconductor diameter d.

As presented in Figure 3, the applied voltage of the conductors was 1 kV, and the electric-field strength at the surface of the bundled conductors was nonuniform. Owing to the shielding effect, the electric-field strength of the inner parts of the bundled conductors was less than the outer parts.

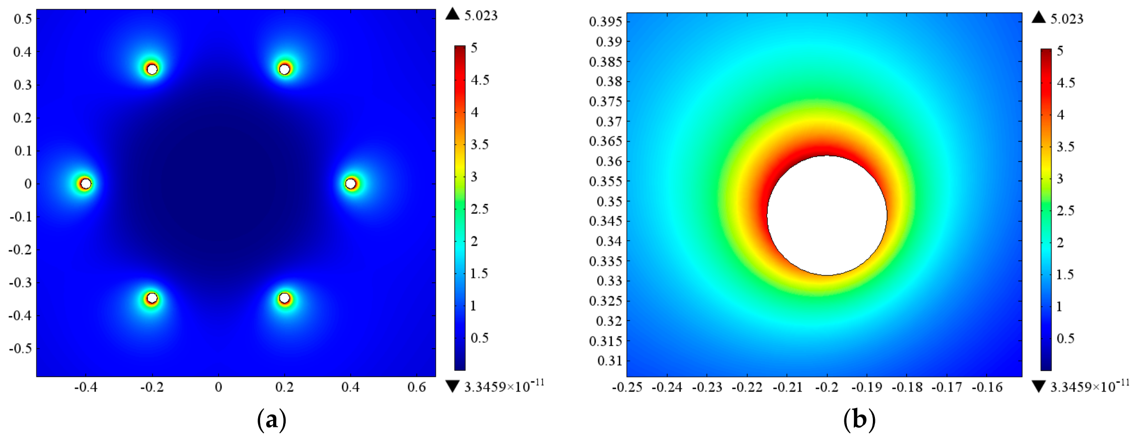


Figure 3. E-field distribution of conductor bundles in a corona cage: (**a**) Contour surface of electric field (kV/m); (**b**) Enlarged contour surface of electric field (kV/m) (upper-left conductor).

Because of the nonuniformity of the bundled conductors' surface electric-field strength, the maximum gradient of each subconductor was selected, and the average of these gradients was calculated as a variable to derive the acoustic PWL from the corona cage.

Some typical relation diagrams are illustrated in Figures 4–9. Figure 4 describes the relationship between the PWL and the average maximum bundle gradient; the change in the PWL in the eight-bundle conductor with different subconductor diameters tended to be the same, increasing as $g_{\max}$ increased.

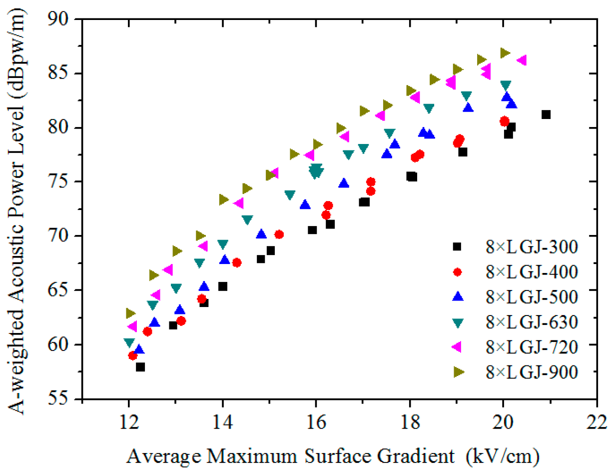


Figure 4. PWL at different average-maximum surface gradients of the 8-bundled conductor.

Figures 5 and 6 describe the influence of bundle size on the PWL, indicating the same subconductor type (LGJ400 in Figure 5 and LGJ630 in Figure 6) with varying bundle size from six to 12 conductors. When g_{max} was constant, the PWL increased with the bundle size. Figures 7 and 8 describe the influence of the subconductor diameter on the PWL; the subconductor diameter changed from 24.2 to 39.9 mm, but the bundle size remained constant (six conductors in Figure 7 and eight conductors in Figure 8). When g_{max} was constant, the PWL increased with the subconductor diameter.

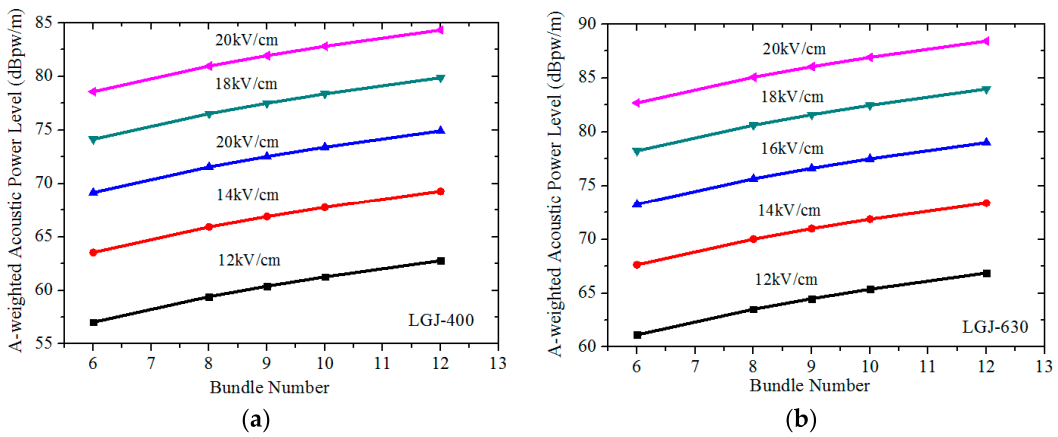


Figure 5. PWL for different bundle sizes with the same subconductor diameter. (**a**) LGJ400; (**b**) LGJ630.

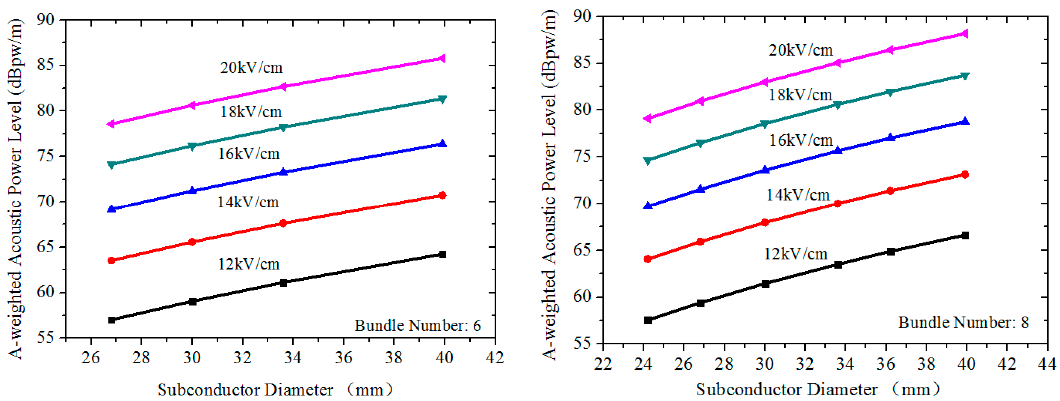


Figure 6. PWL for different subconductor diameters with the same bundle size.

The results reveal that the PWL increased with the average maximum bundle gradient, and that it was positively correlated with the bundle size and subconductor diameter for the same average maximum bundle gradient. These results can be explained by the corona discharge performance. When g_{max} is constant, the number of corona discharge points in bundle conductor surface becomes larger with the increase of bundle size or subconductor diameter. Therefore, the noise source increases and the PWL of the conductor increases. According to Peek's formula [27], the corona onset electric field decreases with an increase in the subconductor diameter and the corona discharge level of a larger diameter conductor should therefore be intensified with the same g_{max}. However, in practical transmission projects, engineers usually reduce the AN level by increasing the bundle size. This is mainly because the surface gradient decreases with increased bundle size if the applied voltage is constant. Consider, for example, LGJ400; the g_{max} value of 4 × LGJ400 was 0.0683 kV/cm and 12 × LGJ400 was 0.0404 kV/cm when the applied voltage was 1 kV in the corona cage, signifying a reduction of approximately 41%. Therefore, the noise performance can be improved by increasing the bundle size in practical projects where the operating voltage is almost constant.

4. Derivation of the PWL Formula

According to the IREQ and BPA [11,16], the PWL can be presented in an approximated linear relationship with lg(g_{max}), lg(n) and lg(d) as:

$$\mathrm{PWL} = \beta_0 + \beta_1 \cdot \lg g_{max} + \beta_2 \cdot \lg n + \beta_3 \cdot \lg d \tag{9}$$

where β_0 is a constant term, β_1, β_2, and β_3 are variable coefficients, n is the number of subconductors, and d is the subconductor diameter.

Based on test data from the corona cage, the PWL formula can be fitted by using the least mean squared error method as:

$$\mathrm{PWL} = -123.0 + 97.2\lg g_{max} + 19.1\lg n + 41.7\lg d \tag{10}$$

where g_{max} is in the range of 12–20 kV/cm, n is 6–12, and d is 24–40 mm.

The fitted formula and its coefficients could then be estimated using statistical methods [28], as shown in Table 3.

Table 3. Analysis results of regression coefficient and significance of the acoustic power.

Test Type	Statistics	Value	Significance Level *p*
R test	R^2	0.98	
F test	F	3385.18	<0.001
T test	β_0 β_1 β_2 β_3	97.16 −123.00 19.08 41.73	<0.001

For the R test, which is a goodness of fit test, the R^2 value was 0.98, meaning that this formula presents a very good fit. The F test is the significance level test for this formula; $p < 0.001$ would mean this regression formula is generally significant. The T test is a test of significance for each variable; each variable for which $p < 0.001$ has a significant influence on PWL. Therefore, according to these tests, this formula is valid and can represent the test data.

5. Predicted Values and Measured Data

5.1. SPL Prediction by PWL Formula

(1) According to the applied voltage, line structure and conductor parameter of operating transmission lines, the voltage gradient at the surface of each subconductor can be calculated by using the finite element method based on the Gauss' theorem. Then the average maximum gradient of each phase is obtained by calculating the mean of each subconductor's maximum gradient in the same phase.

(2) The PWL value of each phase can be calculated by using PWL formula with three variables, including the average maximum gradient $g_{\max}$, the bundle number n and the subconductor diameter d.

(3) From Equation (8), the SPL of practical transmission lines in heavy rain condition can be calculated as:

$$\mathrm{SPL}_5 = 10\lg\sum_{i=1}^{z}\lg^{-1}\left[\frac{\mathrm{PWL}(i) - 11.4\lg R_i - 5.8}{10}\right] \tag{11}$$

where SPL_5 level indicates the value exceeding 5% of the all-time value in rainy weather. PWL(i) is the PWL value of i-th phase in heavy rain conditions, R_i is the radial distance from the i-th phase to the point of observation in m, which has the same meaning with D in (8) and i is the number of phases.

(4) The L_{50} level of SPL in rainy weather is:

$$\mathrm{SPL}_{50} = 10\lg\sum_{i=1}^{z}\lg^{-1}\left[\frac{\mathrm{PWL}(i) - 11.4\lg R_i - 5.8}{10}\right] - 3.5 \tag{12}$$

where SPL_{50} indicates the value exceeding 50% of the all-time value in rainy weather. From [29], $\mathrm{L}_5 - \mathrm{L}_{50}$ = 3.5 dB, therefore the predicted SPL_{50} value is SPL_5 minus 3.5.

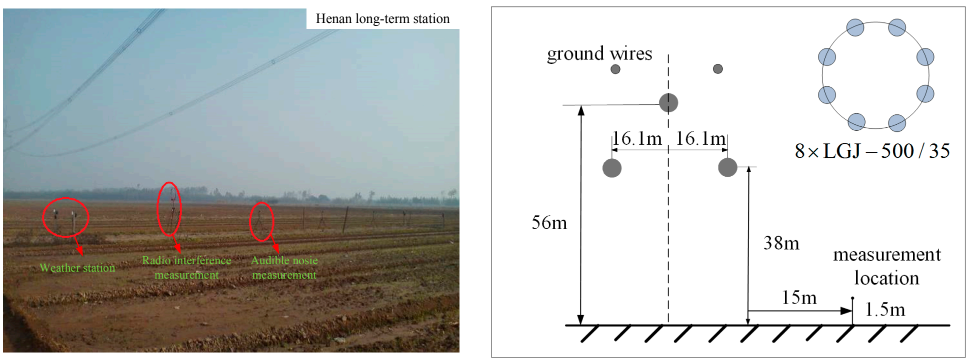
For comparison, the PWL formula proposed by BPA in L_{50} rainy weather is:

$$\mathrm{PWL}_{BPA} = -164.6 + 120\lg g_{\max} + 55\lg d_{\mathrm{eq}} \tag{13}$$

$$d_{\mathrm{eq}} = 0.58n^{0.48}d \tag{14}$$

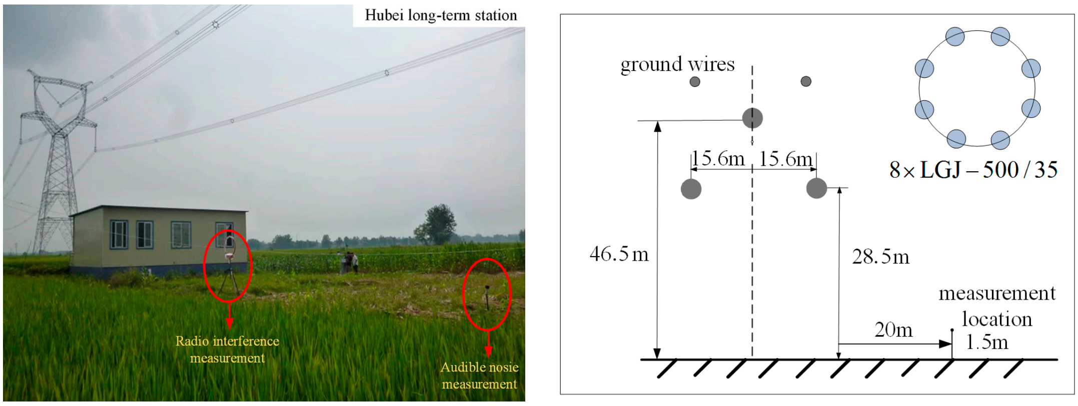
5.2. Predicted Values Versus Long-Term Data

To further research the AN level of the UHV AC transmission lines, the Henan and Hubei long term stations were built under the 1000 kV Jindongnan-Nanyang-Jingmen power lines by the China Electric Power Research Institute. A large quantity of data was obtained from Henan in 2011 and Hubei in 2013 [25]. A general view of the long-term stations and a diagram of the structure of their power lines are shown in Figures 7 and 8, respectively. The altitude of the Henan station is 85 m and that of the Hubei station is 30 m.



(**a**) (**b**)

Figure 7. Henan long-term station. (**a**) General view; (**b**) Structure diagram.



(**a**) (**b**)

Figure 8. Hubei long-term station. (**a**) General view; (**b**) Structure diagram.

The schematic of the measuring system is shown in Figure 9. A model HOBO U30 weather station (Onset Computer Corporation, Bourne, MA, USA) was used to measure meteorological parameters at the test site, including precipitation, air temperature, relative humidity, wind speed, wind direction, and barometric pressure. This station consists of meteorological sensors and a data logging system.

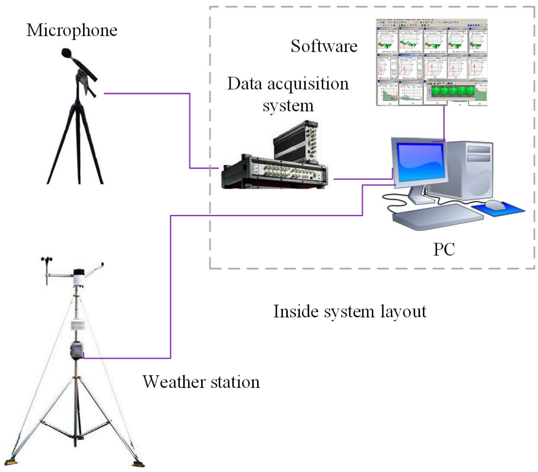


Figure 9. Schematic of measuring system.

Precipitation is highly important in long-term AN measurement, and it was measured by the HOBO rain gauge smart sensor, which involves a tipping bucket. The sensor produces one tip for every 0.2 mm of accumulated water. The measured precipitation over 1 min is translated into rainfall rate (mm/h). The resolution of this sensor is 0.2 mm, with a measurement range of 100 mm/h and calibration accuracy of ±1.0%.

The steady A-weighted SPL of the 1000-kV Jindongnan-Nanyang-Jingmen power lines, measured outside 15 m from the outer phase was obtained at the Henan station. From a data set of 1351 samples, the total rainfall time was approximately 22.5 h, the average rainfall 1.2 mm/h, and the maximum rainfall 12 mm/h. According to the statistical analysis of these data, the A-weighted SPLs of the power lines near the Henan station exhibited an approximately normal distribution. The statistical values are presented in Table 4.

Table 4. A-weighted SPL value measured outdoors in rainy weather 15 m from the outer phase in the henan station (Unit: dB).

Sample Statistics	Mean	Median	Standard Deviation	SPL Value			
				L_{95}	L_{90}	L_{50}	L_{10}
1351	44.78	45.23	2.72	39.68	41.00	45.23	47.90

The AN level at the measurement point near the Henan long term station was then calculated by Equation (6) with the parameters of the power lines. The calculated values were subsequently compared with the statistical data and the AN level calculated by the BPA formula (Table 5). In the calculation, the applied voltage was 1050 kV, which coincided with the operating voltage of the 1000-kV project most of the time. The conductor bundle was 8 × LGJ500 with a bundle spacing of 400 mm.

Table 5. Comparison of L_{50} level between calculated values and values measured outside in rainy weather.

PWL Formula Type	L_{50} Value in Rainy Weather/dB		
	Calculated Value	Measured Value	Difference
BPA formula	48.30	45.23	3.07
Formula (6)	45.99		0.76

From Table 6, the L_{50} level of statistical data from the Hubei station was 45.23 dB, which is 3.07 dB lower than the BPA-calculated value but only 0.76 dB lower than that calculated from (6).

Table 6. A-weighted SPL value in rainy weather 20 m from the outer phase in the hubei station (Unit: dB).

Sample Statistics	Mean	Median	Standard Deviation	SPL Value			
				L_{95}	L_{90}	L_{50}	L_{10}
7348	46.80	46.74	2.72	39.52	41.06	46.74	52.60

The steady A-weighted SPL of the 1000 kV Jindongnan-Nanyang-Jingmen power lines, measured outside, 20 m from the outer phase was obtained from the Hubei station. From a data set of 7438 measurements in 2013, the total rainfall time was approximately 124 h and the average rainfall was 2.3 mm/h. The A-weighted SPLs of the power lines near the Hubei station are shown in Table 6, and a comparison of the calculated values with the statistical data is presented in Table 7.

Table 7. Comparison of L_{50} level between calculated values and measured values outside in rainy weather.

PWL Formula Type	L_{50} Value in Rainy Weather/dB		
	Calculated Value	Measured Value	Difference
BPA formula	49.27	46.74	2.53
Formula (6)	46.91		0.17

As indicated in Table 7, the L_{50} level of statistical data from the Hubei station was 46.74 dB, which is 2.53 dB lower than the BPA calculated value, yet only 0.17 dB lower than the value calculated from (6). This results reveal that (6) can make a more accurate assessment of AN levels from the L_{50} value under rainy weather conditions than the BPA formula.

6. Conclusions

In this paper, the AN performances of 17 bundle conductors has been investigated by using a corona cage under heavy rain conditions. The influence of different variables on AN levels are analyzed, such as voltage gradient, bundle number and subconductor diameter. The results show that all these variables have a positive correlation with AN performance. Then based on the experimental results, a useful PWL formula for heavy rain conditions is derived:

$$\mathrm{PWL} = -123.0 + 97.2\lg g_{\max} + 19.1\lg n + 41.7\lg d$$

Two long term stations have been built under the 1000 kV Jindongnan-Nanyang-Jingmen power lines, and large quantity of AN data were obtained and statistically analyzed. It is shown that L_{50} values of the SPL from the Henan and Hubei stations are 45.23 and 46.74 dB, respectively. The predicted AN value which is calculated by PWL formula derived in this paper are compared with long-term data from the Henan and Hubei stations, and the results show strong agreement.

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