A Preliminary Study on Emission Limits of Substation Noise Based on Equivalent Annoyance

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Abstract. Substation noise disturbs residents despite satisfying emission standards because the impact of its low-frequency components is underestimated by the commonly used A-weighted equivalent continuous sound pressure level (L_{Aeq}). To optimize the control indicators and emission limits of substation noise, this study conducted listening tests of noise perceived annoyance (Am) according to GB/T 42473-2023 of China. Based on the annoyance ratings of 148 noise samples from 110 kV–1000 kV substations self-reported by 280subjects, fitting curves between L_{Aeq} and A_m for substations noise of different voltage levels were established. Results indicated the necessity of formulating noise emission limits for 500 kV–1000 kV substations and 110 kV–220 kV substations respectively because of the significant difference of Am at the same L_{Aeq}. On the basis of different control targets of Am, a new limit of L_{Aeq} for two groups of substations above was derived, and corresponding limits of sound pressure level at each 1/1 octave band within 31.5 Hz–500 Hz were proposed based on noise criteria curves (NC curves). Results showed that under the control target of Am≤6, the limit of L_{Aeq} for boundary noise from 110 kV–220 kV substations was 5.9 dBA higher than that from 500 kV–1000 kV substations, and the limits of sound pressure level at five 1/1 octave bands from the former were 4.6 dBA higher than those from the latter on average. Among 500 kV–1000 kV substations boundary noise samples satisfying the suggested limit of L_{Aeq}, 4.7% of samples didn't simultaneously satisfy the limits of sound pressure levels at five 1/1 octave bands. To evaluate the influence of low-frequency noise from substations effectively, it is recommended to use L_{Aeq} and sound pressure levels at each 1/1 octave band within 31.5 Hz–500 Hz, corresponding to the condition when Am=6, as emission limits for noise at the boundaries of substations.

Keywords: substation noise; sound pressure level in octave bands; emission limits; mean perceived annoyance; noise criteria curves.

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1 Introduction

With the development of China's power grid project, the number of substations being in the vicinity of residential areas is increasing. The impact of low-frequency noise from substations is gradually becoming prominent[1]. A-weighted equivalent continuous sound pressure level (L_{Aeq}) is the main evaluation index of environmental noise, but it underestimates the impact of low-frequency noise to some extent[2]. Currently, China only specifies the limit of L_{Aeq} for noise emissions from industrial enterprises, such as substations. However, despite satisfying these limits, the substation noises are often complained by residents. The standards pertaining to the control of low-frequency noise in China are currently incomplete and require further refinement[3]. Noise annoyance is an important basis for determining the acceptability of environmental noise exposure and formulating environmental noise emission standards. Therefore, it is necessary to optimize the control indicators and the limit of noise emission of substations based on noise annoyance.

Considering the shortcomings of L_{Aeq} in evaluating the impact of noise, many countries have proposed different noise evaluation curves, mainly including NC curve[4], NR curve[5], and RC curve[6]. These curves can quantify the maximum acceptable sound pressure level for each octave band. Among them, NC curves are widely used to evaluate the acceptability of noise in environment. The American National Standards Institute (ANSI) provided the latest NC curve with an evaluation range as low as 16 Hz in ANSI S12.2-2008. In China, "Emission Standard for Industrial Enterprises Noise at Boundary" (GB 12348-2008) and "Emission Standard for Community Noise" (GB 22337-2008) specify limits of sound pressure levels at five 1/1 octave bands within 31.5 Hz–500 Hz for indoor noise through structure propagation in buildings [7,8]. However, these standards are not applicable to the evaluation and control of low-frequency from outdoor substations through air propagation. In addition, indicators such θ_{low} and L_{Ceq}-L_{Aeq} have been introduced to evaluate the low-frequency noise at the boundaries of substations in China, but there are certain shortcomings[9].

2 Listening Tests of Perceived Annoyance

Listening tests in laboratory are an important method for determining noise annoyance. Noise annoyance obtained from listening tests is called perceived annoyance.

2.1 Noise Samples

Five substations in China, with voltage levels of 110 kV, 220 kV, 500 kV, 750 kV, and 1000 kV respectively, were selected. In these substations, on-site noise samples for listening tests of perceived annoyance were collected. Along two sampling lines perpendicular to the main transformer (Fig. 1), sampling points were arranged at different distances from the transformer, starting from 0.5 meters and progressing incrementally to 50 meters and beyond. The interval between sampling points increased with the distance from the transformer. Notably, the noise level recorded at the outermost sampling point from transformers approximated that of the ambient background noise. The height of sampling points was 1.5 meters above the ground and the data collection lasted between 15 and 30 seconds per point. During sampling, the main transformer was operating normally.

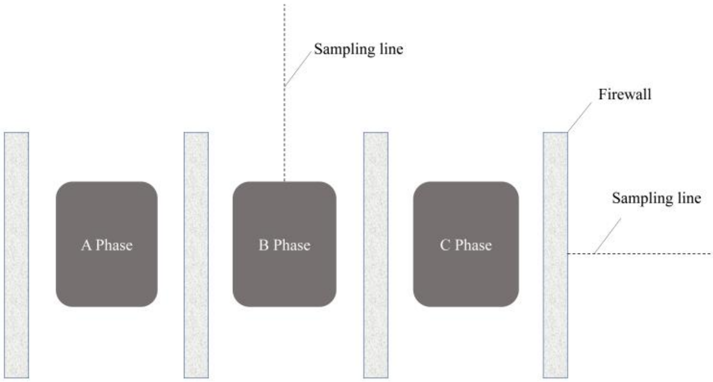


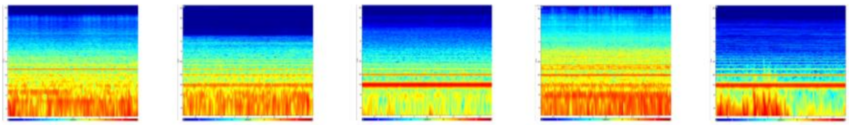
Fig. 1. The layout diagram of sampling lines for on-site noise samples.

A total of 148 **on-site noise samples** (see Table 1) were collected through a digital artificial head measurement system (HMS IV.0, HEAD Acoustics GmbH, Germany). These samples encompassed an L_{Aeq} range of 25.5 dBA–80.0 dBA. A 5-second segment with less interference from other noises was extracted as an **experimental sound sample** from each original noise sample through an acoustic analysis software (ArtemiS 10.0, HEAD Acoustics GmbH, Germany). Additionally, a total of 120 noise samples (see Table 1) were randomly collected at boundaries of 500 kV–1000 kV substations. These 120 samples were used to analyze the rationality of the noise emission limits for substations. The specific arrangement of sampling points refers to GB 12348-2008[7].

Table 1. The Number of noise samples from substations of different voltage levels.

Substation voltage level	On-site noise samples	Noise samples at the boundary of substations
110kV	31	/
220kV	29	/
500kV	25	50
750kV	30	20
1000kV	33	50
Total	148	120

Figure 2 shows the time-frequency maps of noise samples collected at 10 meters away from the main transformers in 110 kV–1000 kV substations. It can be seen that for substation noise, obvious peaks occur at 100 Hz and its harmonic frequencies, and noises from substations of different voltage levels have different characteristics from.



(a) 110kV substation (b) 220kV substation (c) 500kV substation (d) 750kV substation (e) 1000kV substation

Fig. 2. Time-frequency maps of noise samples in 110 kV–1000 kV substations.

2.2 Experimental Site and Equipment

Listening tests were conducted in a soundproof room (3m×2m×2m) with background noise below 25 dBA. The audio playback system comprised a digital equalizer (PEQ V, HEAD acoustics GmbH, Germany), a computer (Core i7-2600, Intel, US) installing ArtemiS 10.0, a headphone signal distribution amplifier (HDA IV.1, HEAD acoustics GmbH, Germany), and four pairs of high-quality headphones (HD-600, Sennheiser electronic GmbH & Co. KG, Germany). A 40-inch LCD screen was used to simultaneously present the visual information of the actual scene where the sound sample was recorded.

2.3 Experimental Procedures

A total of 280 college students (137 males, 143 females, 23 ± 2 years old) from Zhejiang University with normal hearing were recruited randomly as subjects for listening tests. The experimental procedure was carried out strictly in accordance with GB/T 42473-2023 "Acoustics—Procedures for Assessment and Prediction of Noise Annoyance"10. According to the standard, each experimental sound sample was evaluated three times by the same subject in a random order. During the formal listening tests, four subjects were simultaneously exposed to a sequence of sound samples and were asked to independently choose an integer between 0 and 10 to rate the perceived annoyance of each sample.

2.4 Calculating Annoyance of Sound Samples

If the difference between any two ratings from a same subject for a same sample exceeds 2, the sound sample will be regarded as a misjudged sound sample from this subject and the data of misjudged sound samples will be eliminated. If the ratio of misjudged sound samples to the total sound samples evaluated by a subject is higher than 30%, this subject will be regarded as an invalid subject and all data from invalid subjects will be eliminated[10]. The arithmetic mean of three ratings for a certain sound sample from subject i, A_i, was first obtained according to formula (1). Then, the average annoyance (A_m) of each sound sample was determined based on the ratings from all subjects, as shown in formula (2)[11].

$$A_i = \frac{A_{i,1}+A_{i,2}+A_{i,3}}{3} \tag{1}$$

$$A_i = \frac{1}{n}\sum_{i=1}^{n} A_i \tag{2}$$

where n is the number of valid subjects in the sound sample, and A_i is the annoyance of the i-th participant on the sound sample.

3 Emission Limits for Substation Noise based on Perceived Annoyance

3.1 Limits of L_{Aeq} under Different Perceived Annoyance Control Targets

Based on formula (3), fitting curves between L_{Aeq} and A_m of noises from substations with five different voltage levels were established[11], as shown in Figure 3.

$$A_m = \frac{10}{1+e^{-k(L_{Aeq}-z)}} \tag{3}$$

where k and z are undetermined constants.

As shown in Figure 3, there was a significant difference in A_m for noises with an equal L_{Aeq} from substations with different voltage levels. Thus, it is necessary to divide 110kV–1000kV substations into distinct groups and formulate noise emission limits respectively for different groups. According to the range of the 11-level numerical scale, if the difference of noise annoyance between two groups with equal L_{Aeq} is less than 1, the relative discrepancy of annoyance between the two groups is less than 10%. Consequently, two groups of substation noise can be consolidated to establish an L_{Aeq}–A_m curve.

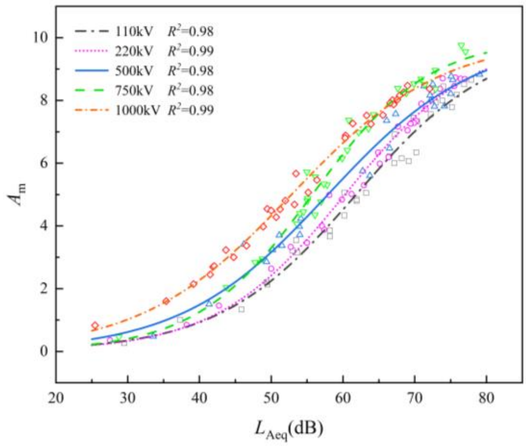


Fig. 3. The L_{Aeq}-A_m fitting curves of noises from five substations with different voltage levels

According to formula (4), the absolute difference of the mean annoyance between noise samples with an equal L_{Aeq} in any two substation noise groups, $|\Delta A_m|$, can be calculated. The maximum value of $|\Delta A_m|$ within the range of 25 dBA–80 dBA is denoted as $|\Delta A_{\mathrm{m}}|_{\max}$. Table 2 shows the $|\Delta A_{\mathrm{m}}|_{\max}$ between every two different groups of substations.

$$|\Delta A_{\mathrm{m}}| = |A_{\mathrm{m},1} - A_{\mathrm{m},2}| \tag{4}$$

where $A_{\mathrm{m},1}$, $A_{\mathrm{m},2}$ are the annoyance on two L_{Aeq}-A_{m} fitting curves with an equal L_{Aeq}.

Table 2. $|\Delta A_{\mathrm{m}}|_{\max}$ between two substation groups of different voltage levels

Substation noise grouping	110kV vs. 220kV	110kV vs. 500kV	110kV vs. 750kV	110kV vs. 1000kV	220kV vs. 500kV	220kV vs. 750kV	220kV vs. 1000kV	500kV vs. 750kV	500kV vs. 1000kV	750kV vs. 1000kV	110kV–220kV vs. 500kV–1000kV
$\|\Delta A_{\mathrm{m}}\|_{\max}$	0.51	**1.08**	**1.76**	**2.21**	0.7	**1.33**	**1.95**	0.82	0.98	0.86	**1.62**

Therefore, the five groups of substations can be divided into 110 kV–220 kV group and 500 kV–1000 kV group. The fitting results of L_{Aeq}-A_{m} for two groups of substations are shown in Figure 4.

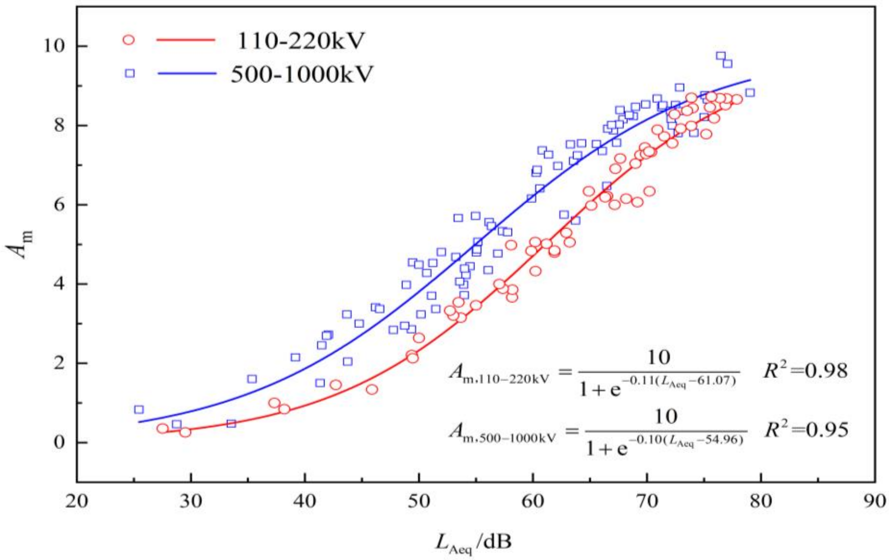


Fig. 4. Fitting curves of L_{Aeq}-A_{m} of two groups of substations.

According to Figure 4, the day-time emission limits of L_{Aeq} for boundary noise can be obtained according to different control targets of A_{m}. Referring to GB 12348-2008 in China, the night-time emission limits of L_{Aeq} for noise at the boundary were set 10 dBA lower than the day-time limits, as shown in Table 3.

Table 3. The limits of L_{Aeq} for two substation groups under different control targets of A_m.

Perceived annoyance control target	Limits of L_{Aeq}			
	110kV–220kV		500kV–1000kV	
	Day-time	Night-time	Day-time	Night-time
$A_m \leq 4$	57	47	51	41
$A_m \leq 5$	61	51	55	45
$A_m \leq 6$	65	55	59	49
$A_m \leq 7$	69	59	64	54

Under different control targets of A_m, the limits of L_{Aeq} for noise emission at the boundary of 500kV–1000kV substations were 5 to 6 dBA lower than those at the boundary of 110kV–220kV substation.

3.2 Limits of Sound Pressure Levels at 1/1 Octave Bands under Different Perceived Annoyance Control Targets

By the formula (5), the noise criteria number corresponding to the j-th octave band sound pressure level (N_{NCj}) from 31.5 Hz to 8000 Hz of each sound sample was calculated, and the maximum N_{NCj} of a sound sample was regarded as the noise criteria number of the sound sample (N_{NC}) [5].

$$L_{pj} = A + B \times N_{NCj} \tag{5}$$

where L_{pj} is the sound pressure level of the j-th 1/1 octave band, j=1, 2..., 9, A and B are coefficients, and their values are shown in Table 4.

Based on the N_{NC} of 148 substation noise samples, L_{Aeq}-N_{NC} fitting curves for two groups of substations were established, as shown in formulas (6) and (7).

$$N_{NC,110kV-220kV} = 1.22L_{Aeq} - 14.3 \tag{6}$$

$$N_{NC,500kV-1000kV} = 1.21L_{Aeq} - 12.8 \tag{7}$$

Table 4. Coefficients A and B.

1/1 octave band center frequency /Hz	31.5	63	125	250	500	1000	2000	4000	8000
A	52	36.9	24.6	15.7	7.8	3.0	-0.9	-3.1	-4.0
B	0.5	0.7	0.8	0.8	0.9	1.0	1.0	1.0	1.0

Based on the L_{Aeq}-N_{NC} curve, the limits of N_{NC} for substation noise under different perceived annoyance control targets were calculated. Through the formula (5), the limits of sound pressure level at each 1/1 octave band from 31.5Hz to 500Hz for substation noise were further calculated. The results are shown in Table 5.

Table 5. Limits of N_{NC} and sound pressure levels at different octave bands of substation noise under different control targets of A_m.

			N_{NC}	31.5Hz	63Hz	125Hz	250Hz	500Hz
110 kV–220kV	Day-time	$A_m \le 4$	55	80	76	69	60	58
		$A_m \le 5$	59	82	79	73	64	62
		$A_m \le 6$	63	84	82	76	68	66
		$A_m \le 7$	68	87	86	80	72	71
	Night-time	$A_m \le 4$	44	74	67	59	50	47
		$A_m \le 5$	48	76	71	63	54	51
		$A_m \le 6$	52	78	74	67	58	55
		$A_m \le 7$	57	81	77	71	62	60
500 kV–1000kV	Day-time	$A_m \le 4$	49	76	71	64	55	52
		$A_m \le 5$	54	79	75	68	59	56
		$A_m \le 6$	59	81	78	72	63	61
		$A_m \le 7$	64	84	82	76	67	66
	Night-time	$A_m \le 4$	37	70	62	54	45	41
		$A_m \le 5$	42	73	66	58	49	45
		$A_m \le 6$	47	75	70	62	53	50
		$A_m \le 7$	52	78	73	66	57	55

4 Analysis and Discussion

As listed in Table 5, the difference between the day-time limit of N_{NC} and the night-time limit of N_{NC} is 11-12. The range of difference between day-time and night-time limits of different 1/1 octave band sound pressure levels is 6-11 dBA. Under the conditions that $A_m \le 6$, the limit of L_{Aeq} for noises at 110 kV–220 kV substation boundaries is 5.9 dBA higher than that at 500 kV–1000 kV substationboundaries, and the limits of sound pressure levels at different 1/1 octave bands of the former is on average 4.6 dB higher than that of the latter.

In GB 12348-2008, there are four functional areas of sound environment named Classes 0–4 with different limits of L_{Aeq}(see Table 6), respectively. For 110 kV–220 kV substations, the noise emission limit of L_{Aeq} under the conditions that $A_m \le 4$, $A_m \le 5$, $A_m \le 6$, and $A_m \le 7$ is close to the emission limit for Classes 1–4 functional areas of sound environment, respectively. For 500kV–1000kV substations, the limit of L_{Aeq} under the conditions that $A_m \le 5$, $A_m \le 6$, and $A_m \le 7$ is close to that for Classes 1–3 functional areas of sound environment, respectively. Therefore, the noise emission limit for the boundary of 500kV–1000kV substations is significantly higher than that of 110kV– 220kV substations.

Table 6. The limit of L_{Aeq} in Classes 1–4 functional areas of sound environment.

	Class 0	Class 1	Class 2	Class 3	Class 4a	Class 4b
Day-time	50	55	60	65	70	70
Night-time	40	45	50	55	55	60

For the noise samples at 500 kV–1000 kV substation boundaries, the **ratio of** the number of samples not simultaneously satisfying the limits of sound pressure levels at five 1/1 octave bands **to** the number of samples satisfying the suggested limit of L_{Aeq}, i.e., the limit-exceeding ratio (η), was calculated. Under the conditions that $A_m \leq 5$, $A_m \leq 6$, and $A_m \leq 7$, the values of η are 3.7%, 5.7%, 1.7%, and 4.7%, respectively. It means that substation noises with the L_{Aeq} satisfying the standard may still disturb the public. According to the limit of sound pressure level at 1/1 octave band from 31.5Hz to 500Hz and the limit of L_{Aeq} proposed in this study, the influence of low-frequency noise in substations can be better evaluated.

When formulating noise emission standards for substations in different countries, perceived annoyance control targets and corresponding control limits should be determined in accordance with basic national conditions, such as the level of social and economic development and the current noise control capabilities of substations[12]. Considering the economic feasibility of low-frequency noise control in substations, it is recommended to use the L_{Aeq} and sound pressure levels at 1/1 octave bands within 31.5 Hz–500 Hz corresponding to the condition that A_m =6 in China.

5 Conclusion

The influence of low-frequency noise from substations was underestimated by L_{Aeq}, which leads to that substation noise satisfying the limits of L_{Aeq} still disturbs the public. This study conducted listening tests of perceived annoyance for substation noise from 110 kV–1000 kV substations and established the curves of L_{Aeq}-A_m and L_{Aeq}-N_{NC} for groups of 110 kV–220 kV and 500 kV–1000 kV substations, respectively. If different perceived annoyance is regarded as the control target, corresponding limits of sound pressure level of substation boundary noise were proposed at each 1/1 octave band within 31.5 Hz–500 Hz on the basis of two curves above. Results showed that if A_m takes 6 as the control target, the limits of L_{Aeq} for boundary noise from 110 kV–220 kV substations are 5.9 dBA higher than that from 500 kV–1000 kV substations. Among noise samples satisfying the suggested limit of L_{Aeq} for 500 kV–1000 kV substation boundaries, 4.7% did not simultaneously satisfy the limits of sound pressure levels at the five 1/1 octave bands. To evaluate the influence of low-frequency noise from substations effectively, it is recommended to use L_{Aeq} and sound pressure levels at each 1/1 octave band within 31.5 Hz–500 Hz, corresponding to the case when A_m=6, as emission limits for noise at substation boundaries in China.

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