Measurement of Noise Emission Level at Substation Boundary Based on Coherent Power

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Abstract. According to the Chinese standard of GB 12348-2008, to determine the noise emission level at substation boundary, the noise level of substation boundary and the background should be measured separately. Then correct noise level at substation boundary utilizing measured background noise. However, the measured background noise is inaccurate due to the different acoustic environment. Therefore, the noise emission level at substation boundary applying this method often has a certain error. This paper proposes a method for separating transformer noise to calculate the noise emission level of transformers based on coherent power, which avoids the error caused by the inaccurate measurement of background noise.

1. Introduction

With the increase of electricity consumption and the shortage of urban land, more and more substations are built close to residential areas, which brings about corresponding environmental pollution problems, especially noise pollution problems. In recent years, the noise control technology of substation has become a significant topic.

At present, the measurement method for the noise emission level at substation boundary is based on the Chinese standard of GB 12348-2008. Firstly, the measured noise level at substation boundary and the background noise level are measured, and then the noise emission level at substation boundary is obtained after correction. Since the transformers cannot be stopped, the measurement of background noise needs to be carried out at a measuring point where the acoustic environment is consistent with the measuring point at substation boundary. As a result, there is a certain error between the measured background noise and the actual one, leading to a certain error of the corrected noise emission level. This paper proposes a method for measuring the noise emission level at substation boundary by separating the transformer noise based on coherent power.
Yan and Liu have made research on noise prediction and control of substation [1, 2]. Shu reveals the source of low-frequency noise of diesel engines based on coherent power spectrum analysis [3]. Zhang compares the noise contribution of different parts of diesel engine based on coherent power spectrum analysis [4]. The coherence function has been reported in the analysis of transformer noise [5-6], which can determine the coherence between the noise signal at the measuring point and the sound source, but these reports do not give the quantitative noise emission level. In this paper, the noise emission level at substation boundary is measured accurately via the method based on coherent power.

2. The theory of coherent power

Assume that the vibration acceleration signal on the transformer surface detected by the acceleration sensor is \(x(t)\) which contains the real vibration acceleration signal \(u(t)\) of the transformer and the vibration acceleration signal \(n(t)\) of the instrument.

The noise signal detected by the microphone is \(y(t)\) which contains the noise emission signal \(v(t)\) produced by the transformer and the sum \(z(t)\) of background noise signal and the microphone noise signal.

The transitive relation between the real vibration acceleration signal \(u(t)\) of the transformer and noise emission signal \(v(t)\) at substation boundary is represented by the frequency response function \(H(f)\), where \(t\) and \(f\) represent the time and frequency of the signal respectively.

Compared with the vibration acceleration signal of the transformer, the vibration acceleration signal of the instrument is weaker. The signal-to-noise ratio of acceleration sensor is high, enough to consider \(x(t) = u(t)\). The noise signal detected by the microphone can be represented as \(y(t) = v(t) + z(t)\), where the \(z(t)\) is not related to \(x(t)\) and \(v(t)\). The mean of \(z(t)\) and \(v(t)\) are zero, respectively.

In addition, the Fourier transforms of \(x(t)\), \(v(t)\), \(z(t)\), and \(y(t)\) are expressed as \(X(f)\), \(V(f)\), \(Z(f)\), and \(Y(f)\), respectively, where \(V(f)\) and \(Y(f)\) can be written as

\[
V(f) = H(f) \cdot X(f)
\]

\[
Y(f) = V(f) + Z(f) = H(f) \cdot X(f) + Z(f)
\]

The power spectrums \(S(f)\) of the noise signals and vibration acceleration signals are as follows:

\[
S_n(f) = |H(f)|^2 S_u(f)
\]

\[
S_v(f) = S_v(f) + S_z(f) + S_n(f) + S_v(f)
\]

\[
S_u(f) = H(f) S_u(f)
\]

\[
S_v(f) = H(f) S_u(f) + S_n(f)
\]

When there are enough average times, \(S_u(f)\), \(S_v(f)\) and \(S_v(f)\) are approximately equal to 0. Therefore, \(S_v(f)\) and \(S_v(f)\) can be expressed as

\[
S_{vy}(f) = S_{v}(f) + S_{z}(f)
\]

\[
S_{vy}(f) = H(f) S_{u}(f) = S_{v}(f)
\]

And then \(S_{vy}(f)\), \(S_{u}(f)\) and \(\gamma^2_{vy}\) are given as

\[
S_{vy}(f) = |H(f)|^2 S_{u}(f) = \frac{|S_v(f)|^2}{S_{u}(f)}
\]

\[
S_{zy}(f) = S_{vy}(f) - \frac{|S_v(f)|^2}{S_{u}(f)} = S_{vy}(f) \left(1 - \frac{|S_v(f)|^2}{S_{u}(f) \cdot S_{v}(f)}\right)
\]

\[
\gamma^2_{vy} = \frac{|S_v(f)|^2}{S_{u}(f) S_{v}(f)}
\]
\[ S'_w(f) = \gamma_{xy}^2 S_w(f) \]  

(12)

where \( \gamma_{xy}^2 \) is the coherence function between \( y(t) \) and \( x(t) \).

Furthermore, the power spectrum obtained based on Eq. (9) or Eq. (12) can be calculated by the following Eq. (13) in the entire audible range to obtain the noise emission level generated by transformer.

\[ L_p = 10 \log \left( \frac{\int S_w(f) df}{(2.0 \times 10^{-5})^2} \right) \]  

(13)

3. Coherence analysis of two transformers

A 110kV substation is a semi-indoor substation, with sound barriers installed on the north and east sides of the transformer. Except for the two transformers, the other equipments of the substation are installed indoors. The two transformers are the main noise source that emit noise to the boundary. Therefore, the noise emission level at boundary can be obtained accurately via measuring the noise emitted by the transformer. The coherence function measurement result between the vibration acceleration signals of two transformers is shown in Figure 1. As is shown in Table 1, the coherence coefficients between two transformers at 100Hz and its multiples within 1000Hz are all above 0.95, indicating that the two transformers are coherent strongly. Therefore, the noise emission level of the two transformers at boundary can be obtained via the measurement based on coherent power with one reference signal.

![Figure 1. The coherence coefficients between the vibration acceleration signals of two transformers.](image)

**Table 1.** The coherence coefficients between the vibration acceleration signals of two transformers at different frequencies.

| Frequency/ Hz | 100 | 200 | 300 | 400 | 500 | 600 | 700 | 800 | 900 | 1000 |
|---------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|------|
| Coherence coefficients | 0.99 | 0.99 | 0.99 | 0.99 | 0.99 | 0.95 | 0.98 | 0.99 | 0.97 | 0.97 |

The method based on coherent power is used to measure the noise emission level at boundary. The distribution of the measuring points is shown in Figure 2. The acceleration sensor is attached to the surface of one of the transformers, and the microphone is placed 1m outside the wall and 0.5m above the wall.
4. The measurement results based on coherence power

The coherence function spectrum between the noise signal and the vibration acceleration signal of the transformer, the auto-spectrum of noise signal, and the coherent power spectrum at measuring points 3–4 are shown in Figure 3-4. The coherent power spectrum is the spectrum of noise emitted by the transformer after the background noise is separated. The measured noise level at boundary, noise level calculated based on coherent power, and coherence coefficients at 100Hz and its multiples within 600Hz are shown in Table 2. The noise emission level at boundary generated by transformer at different frequencies is the noise level calculated based on coherent power.

For measuring point 1, the coherence coefficients between the noise signal and vibration acceleration signal at 100Hz and 200Hz are 0.84 and 0.93, respectively, and the noise level of auto-spectrum are 29.6dB(A) and 35.7 dB(A) respectively. However, the noise level of coherent power spectrum is 28.8dB(A) and 35.4dB(A) at 100Hz and 200Hz, respectively, indicating that the transformer noise has a great contribution to measuring point 1 at 100Hz and 200Hz.

For measuring point 2, the frequencies with a coherence coefficient above 0.8 are 100Hz, 200Hz, 300 Hz, 400 Hz. The noise level of auto-spectrum is 33.4 dB(A), 30.1 dB(A), 29.6 dB(A), 30.2 dB(A), and the contribution of the transformer noise is 33.2 dB(A), 29.3 dB(A), 29.2 dB(A), 29.8 dB(A), respectively.

For measuring point 3, the frequencies with a coherence coefficient above 0.8 are 100Hz, 200Hz, 300 Hz, 600 Hz. The noise level of auto-spectrum is 41.0dB(A), 32.0 dB(A), 32.1 dB(A), 41.3 dB(A), and the contribution of the transformer noise is 41.0dB(A), 31.8 dB(A), 31.6 dB(A), 40.6 dB(A), respectively.

For measuring point 4, the coherence coefficients at 100Hz and its multiples within 600Hz are all above 0.9. The noise level of auto-spectrum is 30.6 dB(A), 34.3dB(A), 33.1dB(A), 30.5dB(A), 35.0 dB(A), 40.3dB(A), and the contribution of the transformer noise is 30.4 dB(A), 34.0 dB(A), 33.0 dB(A), 30.2 dB(A), 34.6dB(A), 39.8dB(A) at 100Hz and its multiples within 600Hz, respectively.

For measuring point 5, the frequencies with a coherence coefficient above 0.8 are 100Hz, 400Hz, 500 Hz, 600 Hz. The noise level of auto-spectrum is 36.7dB(A), 24.1dB(A), 32.2dB(A), 38.4dB(A), and the contribution of the transformer noise is 36.6dB(A), 23.5dB(A), 32.1dB(A), 37.8dB(A), respectively.

For measuring point 6, the frequencies with a coherence coefficient above 0.8 are 100Hz, 200Hz, 300 Hz. The noise level of auto-spectrum is 35.5dB(A), 28.3dB(A), 27.6dB(A), and the contribution of the transformer noise is 35.5dB(A), 27.8dB(A), 26.7dB(A), respectively.

For measuring point 7, the frequencies with a coherence coefficient above 0.8 are 100Hz, 200Hz, 600 Hz. The noise level of auto-spectrum is 32.9dB (A), 29.5dB(A), 35.7dB(A), and the contribution of the transformer noise is 32.6dB(A), 29.4dB(A), 35.2dB(A), respectively.
Table 2. Coherence function and Coherent power measurement.

| Frequency/Hz | 100 | 200 | 300 | 400 | 500 | 600 |
|--------------|-----|-----|-----|-----|-----|-----|
| Coherent power spectrum | 29.6 | 35.7 | 25.2 | 24.0 | 25.2 | 31.1 |
| Coherence coefficient | 0.84 | 0.93 | 0.41 | 0.23 | 0.40 | 0.52 |
| Coherent power spectrum | 33.4 | 30.1 | 29.6 | 30.2 | 22.3 | 32.7 |
| Coherence coefficient | 0.97 | 0.82 | 0.92 | 0.91 | 0.12 | 0.71 |
| Coherent power spectrum | 41.0 | 32.0 | 32.1 | 21.8 | 31.1 | 41.3 |
| Coherence coefficient | 0.99 | 0.96 | 0.88 | 0.52 | 0.64 | 0.84 |
| Coherent power spectrum | 30.6 | 34.3 | 33.1 | 30.5 | 35.0 | 40.3 |
| Coherence coefficient | 0.96 | 0.94 | 0.98 | 0.93 | 0.92 | 0.90 |
| Coherent power spectrum | 36.7 | 17.7 | 24.5 | 24.1 | 32.2 | 38.4 |
| Coherence coefficient | 0.97 | 0.25 | 0.71 | 0.88 | 0.97 | 0.87 |
| Coherent power spectrum | 35.5 | 28.3 | 27.6 | 22.6 | 27.5 | 39.6 |
| Coherence coefficient | 0.99 | 0.89 | 0.82 | 0.24 | 0.74 | 0.78 |
| Coherent power spectrum | 32.9 | 29.5 | 22.9 | 19.3 | 29.0 | 35.7 |
| Coherence coefficient | 0.94 | 0.97 | 0.37 | 0.34 | 0.50 | 0.89 |
5. Comparison of the measurement results of different methods based on Chinese standard and coherent power

According to Chinese standard of GB 12348-2008, the first step of measuring the noise emission level at boundary is to measure the total noise level at boundary; the second step is to measure the background noise; and finally the noise emission level is obtained by correcting the total value using background noise. Since the transformer cannot be stopped, compared with the measurement of background noise, the measurement of the noise at boundary under standard of GB 12348-2008 is not at the same time and same measuring point. The measured background noise is not the actual background noise when the noise at boundary is measured, resulting in the noise emission level after correction has a certain error. However, the method based on coherent power is to separate the spectrum of the noise emitted by transformers at boundary, and then the noise emission level is calculated. The noise emission level at boundary based on the standard of GB 12348-2008 and coherent power is shown in Table 3. The measurement result based on the standard of GB 12348-2008 is significantly affected by the background noise. It can be seen from Table 3 that the measuring point 7 is far away from the transformer, but the noise emission level in daytime is greater than the measuring points 3–6 which are closer to the transformer, indicating that this method has a certain inaccuracy. Due to the difference of background noise between daytime and night-time, the noise emission level at boundary is different evidently based on the standard of GB 12348-2008. However, the result based on coherent power is not affected by the background noise, and the noise emission level is similar between daytime and night-time at the same measuring point. The difference of noise emission level between these two methods in the night-time at measuring point 3–4 is within ±0.4 dB(A), indicating that the noise emission level via these two methods is similar when the background noise level is significantly less than the noise emission level. More importantly, the noise emission level at boundary based on coherent power can be measured accurately in a complex noise environment.

Table 3. The noise emission level at boundary of two methods.

| Measuring point | Daytime/dB(A) | Night-time/dB(A) |
|-----------------|---------------|------------------|
|                 | GB 12348-2008 | Coherent power   |
| 1               | 45.8          | 38.7             |
| 2               | 48.9          | 37.6             |
| 3               | 46.3          | 43.7             |
| 4               | 45.0          | 42.2             |
| 5               | 45.2          | 42.4             |
| 6               | 45.8          | 42.1             |
| 7               | 48.5          | 37.3             |

|                 | GB 12348-2008 | Coherent power   |
|-----------------|---------------|------------------|
| 1               | 44.1          | 38.2             |
| 2               | 44.5          | 38.9             |
| 3               | 44.5          | 44.7             |
| 4               | 43.4          | 43.0             |
| 5               | 43.6          | 41.7             |
| 6               | 43.2          | 41.7             |
| 7               | 43.1          | 38.9             |

[a] According to Chinese standard of GB 12348-2008. [b] According to the method based on coherent power.

6. Conclusion

This paper proposes a method for measuring the noise emission level at substation boundary based on coherent power and draws the following conclusions.

The coherence coefficients between the vibration acceleration signals of different transformers are higher than 0.95 at 100 Hz and its multiples within 1000 Hz. Therefore, the method based on coherent power with one reference signal can accurately measure noise emission level of two transformers at boundary.

The spectrum of the noise emitted by the transformer at boundary can be separated via coherent power. It is found that the noise signal at 100Hz and its multiples within 600Hz at boundary is highly coherent with the vibration acceleration signal of the transformer in a 110kV substation, and the noise emission level is quantitatively calculated at different frequencies.

Through above method, the measurement of the noise emission level at substation boundary is not affected by background noise based on the coherent power, so it can avoid the error caused by the inaccurate measurement of background noise based on the standard of GB 12348-2008.
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