NOISE MEASUREMENT OF POWER TRANSFORMERS IN COMPLICATED ACOUSTIC ENVIRONMENT

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This paper deals with the method used to reduce the influence of environmental noise on that of the power transformer in its measurement process. In order to locate the frequency bands of the environmental noise signals including chirps of birds and insects and horns of automobiles, wavelet packet decomposition method is employed. Each decomposed sub-band with noisy signal is de-noised with spectral subtraction. In this process, transformer and environmental noises in time domain are separated. 1/3-octave filters are designed and used to calculate the sound pressure levels of the separated pure noise signals. The proposed method is validated by comparison between calculated sound pressure levels and actual values. Field test results of power transformer noise shows that it can be used to increase the measurement accuracy in complicated acoustic environments.

Keywords: power transformer, audible noise, wavelet packet decomposition, acoustic environment, spectral subtraction

1. Introduction

Audible noise emitted by power transformers in high voltage AC substations constitutes a serious environmental problem to the inhabitants of surrounding community [1]. In order to control the noise and to improve the acoustic environment in the proximity of the substations, it is necessary to make efforts to increase the accuracy of on-site noise test of power transformers.

Recently, noise measurement and its characteristic analysis of power transformers have been the focus of research in China because of the increasing social pressure from the inhabitants around the substations. In many of these researches, sound pressure levels (SPLs), spectrum distributions and noise propagation characteristics of power transformers with voltage up to 1000 kV are measured and corresponding noise control advices are addressed [2-4]. However, researches concerning de-noising method of power transformers are rarely mentioned, which according to field test experience is quite necessary. This is attributed to the reason that environmental noises such as bird chirps and automobile horns have ignorable influences in the transformer noise measurement process.

In addition to the discrepancy of frequency range, it is known that power transformer generates steady-state noise while environmental noises are generally happened in short time. This paper proposes a novel method to increase the noise test accuracy of power transformers, which combines wavelet packet decomposition (WPD) and basic spectral subtraction algorithms. The proposed method is validated and applied in field test of the transformer noise in ultra-high voltage (UHV) AC substations.
2. Description of algorithms

2.1 Principle of the de-noising method

Flow chart of the de-noising method used in the noise measurement process of power transformers is given in Fig. 1. The original noise of power transformers surrounded by complex acoustic environment is measured. The wavelet packet transform method is employed to decompose the noise signal in both time- and frequency-domain. Each sub-band of the noise signal after decomposition is checked to locate the presence of ambient noises generated by birds, insects and automobiles. These sub-bands with noisy signal are processed with the speech enhancement technique of spectral subtraction. After this process, these purified sub-bands are used to reconstruct the new transformer noise signal. In order to calculate the A-weighted SPL, 1/3-octave filters are designed. Finally, the A-weighted SPL of the power transformer noise is obtained.

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Start
Original transformer noise measurement
Wavelet packet decomposition
Spectral subtraction of noisy sub-bands
Reconstruction of transformer noise signal
Design of 1/3-octave filters
A-weighted SPL calculation
End
```

**Figure 1:** Flow chart of the de-noising method.

2.2 Wavelet packet algorithm

WPD is a generalization of wavelet decomposition. In WPD, both the detail and approximation coefficients are decomposed. For \( n \) levels of decomposition, WPD produces \( 2^n \) different sets of coefficients. It divides the frequency space into various narrow bands and allows better time-frequency localization of signals. Hence, frequency components that contain low energy are easier to be identified at different narrow bands [5-6].

The wavelet packet algorithm includes decomposition and reconstruction procedures for the wavelet packet coefficient. The decomposition coefficients are obtained by [7-8]

\[
d_{k}^{j+1,2n} = \sum_{k} h_{k(2l-k)}d_{l}^{j,n} \quad \text{(1)}
\]

\[
d_{k}^{j+1,2n+1} = \sum_{k} h_{l(2l-k)}d_{l}^{j,n} \quad \text{(2)}
\]

where \( h_{k(2l-k)} \) and \( h_{l(2l-k)} \) are respectively the low-pass and high-pass finite impulse filters.

The decomposition coefficients are obtained by [8]

\[
d_{l}^{j,n} = \sum_{k} g_{k(l-2k)}d_{k}^{j+1,2n} + \sum_{k} g_{l(l-2k)}d_{k}^{j+1,2n+1} \quad \text{(3)}
\]

where \( g_{k(l-2k)} \) and \( g_{l(l-2k)} \) are the low-pass and high-pass filters for reconstruction, respectively.

2.3 Spectral subtraction algorithm

Spectral subtraction is an effective algorithm for noise reduction. It is based on the principle that the estimation of the clean signal spectrum can be obtained by subtracting that of the noise spectrum from the noisy speech spectrum. The noise signal is assumed additive, which means its spectrum
does not change with time [9]. The principle diagram of spectral subtraction is shown in figure 5. In this algorithm, the environmental noise is viewed as speech signal and the pure transformer noise is taken as noise signal.

![Principle diagram of spectral subtraction.](image)

Figure 2: Principle diagram of spectral subtraction.

Assuming that \( n(t) \) is the pure transformer noise and \( s(t) \) is the environmental noise, the noisy signal \( \eta(t) \) is the sum of \( n(t) \) and \( s(t) \), \( \eta(t) = n(t) + s(t) \). \( t \) denotes the sampling time. \( s(t) \) and \( n(t) \) are assumed to be independent statistically.

\[
I(\omega) = S(\omega) + N(\omega)
\]

where \( S(\omega) \) and \( N(\omega) \) are the FFT of \( s(t) \) and \( n(t) \), respectively.

As \( s(t) \) and \( n(t) \) are independent, thus the power of noise signals can be computed as [10]

\[
P_{\eta}(\omega) = P_s(\omega) + P_n(\omega) = |S(\omega)|^2 + |N(\omega)|^2
\]

where \( P_{\eta}(\omega) \), \( P_s(\omega) \) and \( P_n(\omega) \) are the power spectra of signals \( \eta(t) \), \( s(t) \) and \( n(t) \), respectively.

The transformer noise keeps stationary before and when the environmental noise occurs. Therefore, the silent part of the transformer noise can be used for power spectral estimation of the environmental noise.

\[
P_s(\omega) = \begin{cases} 
P_{\eta}(\omega) - P_n(\omega), & P_{\eta}(\omega) \geq P_n(\omega) \\
0, & P_{\eta}(\omega) < P_n(\omega) 
\end{cases}
\]

Only the power spectral transform is considered in Eq. (6). As human ear is not sensitive to the phase of noise signal, the phase spectrum of environmental noise is substitute with that of the noisy signal. The environmental noise in time domain can be expressed as

\[
s(t) = \text{IFFT}(\sqrt{P_s(\omega)} \cdot \exp(j\theta(\omega)))
\]

where \( \theta(\omega) \) is the phase spectrum of the noisy signal.

Subtracting environmental noise from the noisy signal, the pure transformer noise is obtained by

\[
n(t) = \eta(t) - s(t)
\]

### 2.4 SPL calculation method

The effective sound pressure \( p_e \) is defined as the root mean square of the sound pressure in the time interval \( T \), which can be expressed as

\[
p_e = \sqrt{\frac{1}{T} \int_0^T p^2 \, dt}
\]

SPL is usually employed to assess the noise level, which is defined by the following equation:

\[
L_p = 20 \log(p_e / p_0)
\]

where \( p_0 = 2 \times 10^{-5} \text{ Pa} \) is the reference pressure.

In the spectral analysis process of transformer noise, obtaining detail spectral distribution in all frequency components is not necessary. The spectrum is usually divided into several connected sections, each section is called octave, in which the sound power is assumed to be uniform. One of the
most used bandwidth of each section is 1/3-octave, in which the relationship of centre frequency $f_0$, upper cut-off frequency $f_h$ and lower cut-off frequency $f_1$ can be written as

$$f_0 = \sqrt{f_h f_1} \tag{11}$$

$$f_h = 2^{1/3} f_1 \tag{12}$$

The 1/3-octave analysis of transformer noise is actually a process using different pass-band filters to deal with its corresponding octave. According to the standard, the 6-order digital Butterworth filter is used to design the 1/3-octave filters. The normalized upper cut-off frequency $w_2$ and lower cut-off frequency $w_1$ is determined, respectively, by the following equations [11]:

$$w_1 = \frac{2f_0}{aF_s}, \quad w_2 = \frac{2af_0}{F_s} \tag{13}$$

$$\alpha = \frac{(1 + \sqrt{1 + 4Q_d^2})}{2Q_d} \tag{14}$$

$$Q_d = \frac{f_0}{f_h - f_1} \frac{\pi}{N \sin(\frac{\pi}{N})} \tag{15}$$

where $F_s$ is the sampling frequency, $N$ is the filter order.

The transfer function of digital Butterworth filter can be written as

$$H(z) = \frac{b_1 + b_2 z^{-1} + \cdots + b_{N+1} z^{-N}}{1 + a_2 z^{-1} + \cdots + a_{N+1} z^{-N}} \tag{16}$$

Considering the weight of each octave, the A-weight SPL of the filtered noise with centre frequency $f_0$ can be calculated with Eq. (9) and (10).

3. Experimental results

Surrounding acoustic environment unavoidably affects the audible noise measurement of power transformers. Measurement accuracy is usually reduced in a large degree due to the noises generated by birds, insects and automobiles. Laboratory and field experiments are carried out. The proposed algorithm is used to deal with these ambient noises.

3.1 Laboratory experiment

Let $s_1$ and $s_2$ denote pure transformer noise and bird noise, respectively. Assuming the pure transformer noise and bird noise are mixed linearly, their time-domain mixed signal $s_m$ given by $s_m = s_1 + 1.2s_2$ in 3s is given in Fig. 1. The sampling frequency is 22.05 kHz. The A-weighted SPL of $s_1$, $s_2$ and $s_m$ are 59.8 dB(A), 60.4 dB(A) and 63.1 dB(A), respectively. The corresponding signal to noise ratio (SNR) is 27.7 dB. Apparently, the measured SPL of transformer has large discrepancy with the pure value.

The measured transformer noise signal $s_m$ is decomposed by wavelet packet algorithm. The db4 wavelet is chosen to be the wavelet base function. The Shannon-entropy is used for 3-layer wavelet packet decomposition. The decomposition result is given in Fig. 4. The bird chirp noise is found in a wide band of S131~S137 with the frequency range above 1 kHz. As bird chirp is absent in the first second, four-frame signals in this range are used for power spectrum estimation. Each frame has 882 data points and 441 data points are overlapped between two sequential frames. After the process of spectral subtraction and IFFT, the pure transformer and bird chirp noise signals ($p_t$ and $p_b$, respectively) are obtained, as shown in Fig. 5. It can be found that the waveform of separated pure signals $p_t$ and $p_b$ are in good agreement with that of the original input pure signals $s_1$ and $s_2$, respec-
tively. The comparison between the spectral distribution of \( p_1 \) and \( s_1 \) is given in Fig. 6. The correlation coefficient of the two spectral signals is almost 1.0, which proves that the proposed algorithm has nearly no influence on the waveform of the original pure signals.

Figure 3: Time-domain waveforms of transformer and bird chirp noises.

Figure 4: Wavelet packet decomposition of the original transformer noise.

Figure 5: Processed pure transformer and bird noise.
The calculated SPLs of the pure transformer noise $p_t$ and bird chirp $p_b$ are respectively 59.5 dB(A) and 60.6 dB(A). Compared with the SPLs of the original pure signals $s_1$ and $s_2$, both the deviations are no more than 0.3 dB(A). It can be concluded from the analysis that the proposed algorithm is effective in improving the noise measurement accuracy of power transformers.

The algorithm is further used to process the transformer noises polluted by the chirps of insects and frogs with the SNRs of 16.5 dB and 15.7 dB. Comparison of the calculated results and actual values are given in Table 1.

<table>
<thead>
<tr>
<th>Ambient Noise</th>
<th>A-weighted SPL of the Pure Transformer Noise, dB(A)</th>
<th>SNR, dB</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Calculated</td>
<td>Actual</td>
</tr>
<tr>
<td>Insect chirp</td>
<td>59.8</td>
<td>59.8</td>
</tr>
<tr>
<td>Frog chirp</td>
<td>59.5</td>
<td>59.8</td>
</tr>
</tbody>
</table>

Figure 6: Spectral comparison of the processed and source transformer noises.

Figure 7: Wavelet packet decomposition of the field transformer noise.

### 3.2 Field experiment

The field audible noise of a 1000 kV UHV power transformer is measured with the sampling frequency of 22 kHz. The bird chirp noise occurs in the time range of 1~2s. After 3-layer wavelet packet decomposition, the time-domain waveform of each sub-band is shown in Fig. 7. It can be observed that bird chirp is present at the sub-bands of $S_{132}$, $S_{133}$, $S_{136}$ and $S_{137}$. The spectral subtrac-
tion method is used to deal with these sub-bands. The noisy signal is divided into 688 frames. Each frame has 256 sampling points and 128 data points are overlapped between two sequential frames. Like the laboratory experiment, sampling points of the first four frames are used to estimate the power spectrum. The time-domain waveform of each sub-band after spectral subtraction is shown in Fig. 8. It can be seen that the bird chirp noise is successfully removed from the original transformer noise.

Figure 8: Wavelet packet decomposition of the field transformer noise after spectral subtraction.

4. Conclusion

A novel algorithm used to increase the measurement accuracy of power transformer noise in complicated acoustic environment is proposed in this paper. It combines the wavelet packet decomposition and spectral subtraction algorithms. The 1/3-octave filters are designed to calculate the A-weighted SPLs of power transformers. Transformer noises including the chirps of birds, insects and frogs are analyzed. The algorithm is verified by comparison between the calculated and actual pure A-weighted SPLs of the power transformer. It is further used in the on-site noise test of a 1000kV UHV power transformer. The influence of bird chirps on the results of transformer noise test is effectively reduced.

REFERENCES


