A novel de-noising method based on coherence average for ultrasonic signal of partial discharge in transformer

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Abstract
Ultrasonic method is widely used for the detection and location of partial discharge (PD) in transformer, however, the measured ultrasonic signal is usually corrupted by noise, and sometimes is even buried by noise entirely. Therefore, the de-noising of the measured signal is essential. Conventional de-noising methods, such as wavelet method and singular value decomposition (SVD) method, generally require empirical parameter selection or estimation, and the best parameters for de-noising vary with the PD source and noise condition, which will bring some limitation to their applicability. More importantly, conventional de-noising methods usually have poor performance for the low signal-to-noise-ratio (SNR) signals. To improve this problem, the paper proposes a de-noising method based on coherence average for the ultrasonic signal. The de-noising performance of the proposed method is evaluated based on a comparison with conventional methods, the results indicate that the proposed method has great de-noising effect for the ultrasonic signals, even for the low-SNR signals. Besides, the proposed method is free from empirical parameter selection or estimation, which can make its applicability more extensive. The proposed method can offer a practical and effective solution to the de-noising of ultrasonic signal of PD in transformer.

1 | INTRODUCTION

Partial discharge (PD) is an important threat for the safe functioning of power transformers [1, 2]. Therefore, it is significant to detect and locate PD accurately [3–5].

The UHF method is an effective PD detection method because of its high detection sensitivity and good anti-interference capacity [6–9]. However, the accurate PD source location conventionally requires four or more sensors [10, 11], but the UHF sensors are usually fixed in the dielectric window on transformer shell or oil valves [12, 13], the position and the numbers of UHF sensors are restricted, therefore, the UHF method may face some limitation to the PD location in some cases.

The ultrasonic method is another widely used PD detection method [14, 15]. The ultrasonic sensors can be stuck to the transformer shell, and the position and the number of sensors are free, therefore, the ultrasonic method is a major PD location method for transformer, and many PD location algorithms based on ultrasonic detection are proposed [16, 17]. However, the most problem is that the ultrasonic signal will be largely attenuated before it is captured by the sensors. For the PD that is not strong enough, the ultrasonic signal detected by sensors will be very weak and may be quite buried by noise. Therefore, de-noising or extraction of ultrasonic signal must be made before location algorithm is applied.

Several de-noising methods for PD ultrasonic signal have been proposed and have obtained some successful application in practice [18–21], such as filtering method, wavelet de-noising, singular value decomposition (SVD) based method. However, none of the methods can meet all the de-noising requirement of PD ultrasonic signal in field. Filtering method has good performance just to narrow band interference [22], while the noise in field is usually complex and wide-band. The de-noising performance of wavelet method is closely related to the mother wavelet selection and threshold setting, however, the selection...
of the parameters depends on practical experience partly and varies with samples [23–26], and the SVD method faces the similar problem [27, 28]. In practice, PD types in transformer are various and previously unknown, and the noise is usually random and wide-band [29], which will make it difficult to determine the proper parameters and the parameter adjustment will cost a lot of effort. Of course, these problems can still be overcome and solved, but the most problem is that these conventional methods show poor performance to the extremely low-SNR signals, the PD ultrasonic signal in field will be largely attenuated, and the measured signal usually has low SNR and will even be buried by noise [30]. Therefore, conventional methods can’t meet all the de-noising requirements of PD ultrasonic signals in field.

In the paper, we propose a novel de-noising method based on coherence average for ultrasonic signal of PD in transformer. The effectiveness of proposed method and comparisons with other de-noising methods are presented based on an experiment. Compared to conventional methods, the proposed method is simpler and more effective, and the algorithm is free from empirical parameter selection, which makes its applicability more extensive. More importantly, the method has good performance for signals with low SNR, it can offer a practical and effective solution to the de-noising of ultrasonic signal of PD in transformer.

2 COHERENCE AVERAGE BASED DE-NOISING METHOD

Generally, the physical states of PD in transformer will not change a lot in a short time, therefore, the original noise-free ultrasonic signals motivated by PD are strongly correlated in a short time, which means the main difference of different times of ultrasonic signal is amplitude. For the convenience of analysis, each original ultrasonic signal can be presented as

\[ s_i(n) = a_is(n) \]  

where \(a_i\) is the amplitude coefficient of the ultrasonic signal, \(s(n)\) is the original ultrasonic signal with amplitude of 1 V.

The measured ultrasonic signal usually contains wide-sense stationary (WSS) random noise \(X(n)\), and the expectation of it is usually zero and the variance is \(\sigma^2\).

\[ \mu(n) = E\{X(n)\} = 0 \]  

\[ \sigma^2(n) = E\{|X(n) - \mu|^2\} = \sigma^2 \]  

Then, each measured ultrasonic signal can be presented as

\[ x_i(n) = a_is(n) + \delta_i(n), n = 1, 2 \cdots N \]  

where \(x_i(n)\) is actual measured ultrasonic signal with noise, \(a_is(n)\) is original noise-free ultrasonic signal, \(\delta_i(n)\) is a sample of random signal \(X(n)\). \(N\) is the number of points of each measured signal. Assuming the mean of \(\delta_i(n)\) is \(\bar{\delta}\) and the variance of \(\delta_i(n)\) is \(\sigma^2\). Usually, the \(X(n)\) is ergodic, which means

\[ \lim_{N \to \infty} N^{-1} \sum_{i=1}^{N} \delta_i(n) = E\{X(n)\} = 0 \]  

\[ \lim_{N \to \infty} \frac{1}{N} \sum_{i=1}^{N} (\delta_i(n) - \bar{\delta})^2 = Var\{X(n)\} = \sigma^2 \]  

Therefore, when the length of \(\delta_i(n)\) is large enough, the mean and variance of each \(\delta_i(n)\) is approximately equal to 0 and \(\sigma^2\). Furthermore, the energy of each \(\delta_i(n)\) can be calculated as

\[ P(\delta_i) = \sum_{n=1}^{N} \delta_i(n)^2 \approx N \cdot \sigma^2 \]  

Supposing the power of signal \(s(n)\) is \(P\), then the power of each original ultrasonic signal is \(a_i^2P\). Therefore, the SNR of each measured ultrasonic signal can be calculated by

\[ SNR_i = \frac{a_i^2P}{N\sigma^2} \]  

Averaging the measured signals, it can be obtained as

\[ \frac{1}{M} \sum_{i=1}^{M} x_i(n) = \frac{1}{M} \sum_{i=1}^{M} a_is(n) + \frac{1}{M} \sum_{i=1}^{M} \delta_i(n) \]  

\[ = a_s(n) + \frac{1}{M} \sum_{i=1}^{M} \delta_i(n) \]  

where \(M\) is the number of the measured signals. Generally, the random noise \(\delta_i(n)\) are mutually uncorrelated, therefore, the power of the noise item \(\frac{1}{M} \sum_{i=1}^{M} \delta_i(n)\) can be calculated as

\[ P\left(\frac{1}{M} \sum_{i=1}^{M} \delta_i(n)\right) = \frac{1}{M^2} \sum_{i=1}^{M} P(\delta_i) = \frac{1}{M^2} \cdot MN\sigma^2 = \frac{N\sigma^2}{M} \]  

Then the SNR of de-noised signal can be represented as

\[ SNR' = M\frac{\sigma^2P}{N\sigma^2} \]  

It can be concluded that the SNR of de-noised signal has been improved by \(M\) times compared to that of each measured signal. Generally, the de-noising effect improves with the increasing of \(M\), therefore, the \(M\) should be large enough to obtain a good de-noising effect. Of course, the larger \(M\) means the longer sampling time and larger computation, in practice, we usually set an initial value of \(M\) and then increase the value of \(M\) gradually until an expected de-noising effect is obtained.
The key of coherence average method is to ensure the alignment of phase of each original signal \( a_i(n) \) when averaging, in other words, to ensure the alignment of start points of original signals, otherwise, the de-noised signal will have distortion. However, in practice, the original signal is usually corrupted by noise, it’s difficult to find the exact start point of original signal. To solve this problem, we propose to use the UHF pulse of the PD as the synchronization signal to help to align the start point of ultrasonic signal.

When PD occurs, the UHF pulse and ultrasonic signal will be motivated simultaneously, the time difference \( \Delta t \) between the each measured UHF pulse and its corresponding ultrasonic signal will be constant if the locations of UHF sensor and ultrasonic sensor are fixed, just as illustrated in Figure 1(a). Therefore, the start point of ultrasonic signal can be aligned by aligning the peak point of the UHF pulse of each PD, just as showed in Figure 1(b). The UHF sensor in transformer is usually placed into transformer through dielectric window or oil valve, therefore, the UHF signal usually has a good SNR and the peak point of it can be easily picked up. Furthermore, even if some pick-up errors of the peak point may occur due to the noise in UHF pulse, however, the duration of UHF pulse is in ns scale, it is far smaller than that of ultrasonic signal, which is usually in ms scale, the pick-up errors have little influence on the alignment of ultrasonic signals. Therefore, the ultrasonic signals can be aligned effectively by the synchronization of UHF pulse. The flow chart of proposed method is given in Figure 2.

The principle and structure of the proposed the method is simpler compared to conventional methods, and the implementation of the method is free from empirical parameter selection or estimation. What’s most important, in principle, the method can be used for extraction of weak ultrasonic signal as long as the number of average times \( M \) is large enough, even if the ultrasonic signals are quite buried by random noise. Of course, the method also has some limitation. It must depend on the UHF pulse as synchronization signal, besides, the de-noised signal by the method is just an average of original ultrasonic signals, the method can’t be used for single measured signal.

### 3 SIMULATIVE CASE STUDY

In this section, the de-noising effect of coherence average method is studied based on the simulative signals. As the start point of simulative signal can be easily obtained, we don’t use the synchronization signal in this section. The PD signal is simulated with damped oscillatory pulse (DOP) signal, the expression is shown as follows:

\[
s(t) = A(e^{-\alpha_1 t} \cos(\omega_d t - \varphi) - e^{-\alpha_2 t} \cos(\varphi))
\]

where \( A \) is the magnitude coefficient assumed to be 1, \( \alpha_1 = 1 \times 10^6 \text{ s}^{-1} \), \( \alpha_2 = 1 \times 10^7 \text{ s}^{-1} \), \( \omega_d = 2\pi f_d \), \( f_d = 1 \text{ MHz} \), \( \varphi = \tan^{-1}(\alpha_1 / \alpha_2) \). The waveform of DOP signal is shown in Figure 3.

The Gaussian white noise \( \delta(t) \) is added to the DOP signal to form noisy PD signal. Therefore, the measured PD signal can be simulated by

\[
\chi(i) = s(i) + \delta(i), i = 1, 2, \ldots, N
\]
In the paper, the de-noising effect of the proposed method are evaluated based on the PD signal with different SNR, besides, DTCWT method, ASVD method and LMS method are also adopted for de-noising to make a comparison with the proposed method. The de-noising performance is evaluated with mean square error (MSE) or reduction in noise level (RNL), which are calculated by

\[ \text{MSE} = \frac{1}{N} \sum_{i=1}^{N} [y(i) - s(i)]^2 \]

\[ \text{RNL} = \frac{1}{N} \sum_{i=1}^{N} [x(i) - y(i)]^2 \]

where \( y(i) \) denotes the de-noised signal, \( x(i) \) denotes the original noisy PD signal, \( s(i) \) denotes the original noise-free PD signal, \( N \) is the length of the signal. Generally, the smaller MSE and larger RNL means the better de-noising performance.

Figure 4 shows the de-noising results of the simulative noisy PD signal with the SNR of 10 dB by four different methods. The mother wavelet used in the wavelet de-noising method is ‘db5’ in MATLAB and the threshold value is set as 0.8 for best de-noising results. The selection of singular value in ASVD method is adaptive and it doesn’t need setting. The step size in LMS method is 0.002 and the order of filter is set as 40. It can be found that the four methods have similar de-noising performance, the MSE of the three methods are \( 9.5 \times 10^{-6}, 3.8 \times 10^{-4}, 9.9 \times 10^{-4} \) and \( 6.2 \times 10^{-4} \) respectively. The de-noising performance of coherence average method is a little better than the three other methods.

Figure 5 shows the results of the simulative noisy signal with the SNR of \(-10\) dB, the mother wavelet used in the wavelet de-noising method is ‘db5’ and the threshold value is set as 0.2 for best de-noising results. The step size in LMS method is 0.002 and the order of filter is set as 40. It can be found the coherence average can effectively reduce the noise, while another three methods have poor performance for the low-SNR signal. The MSE of four methods are \( 9.6 \times 10^{-4}, 0.035, 0.058 \) and 0.024, the MSE of coherence method is quite smaller than the three other methods.

Figure 6 gives the relationship between MSE and the SNR of noisy signal. When the signal has a positive SNR, the de-noising performance of the four methods just show little difference, when the SNR of noisy signal get smaller, the coherence average method (\( M = 200 \)) can still have a good performance, while the performance of the three other method are not good enough. The coherence average method has great advantage over the three other methods for the low-SNR signals.

In the end, we give the relationship between de-noising performance of the proposed method and the parameter \( M \) based on the simulative noisy signals with the SNR of \(-10\) dB, just as Figure 7 shows. As the \( M \) increases, the MSE gets smaller and the RNL get larger, which means the de-noising performance gets better. The result corresponds to the theoretical analysis.

### 4 EXPERIMENTAL CASE STUDY

To study the de-noising effect of the proposed method for actual PD ultrasonic signal, an experiment is also conducted based on an actual transformer. Two typical transformer PD models are used to generate UHF signal and ultrasonic signal, UHF method based on dielectric window and ultrasonic method are adopted to measure the UHF pulses and ultrasonic signals. The start point of actual PD signal can’t be easily captured like that of simulative signal, therefore, in this section, the UHF signal must be used as synchronization signal. Then the measured ultrasonic signal is used for the evaluation of de-noise effect of proposed method, besides, DTCWT method, ASVD
method and LMS method are also adopted for de-noising to make a comparison with the proposed method. As the original noise-free signal can't be obtained for actual PD signal, the MSE used in simulative case can't be used for the evaluation of de-noising performance, then in this section, the reduction in noise level (RNL) is used for the evaluation of de-noising performance.

4.1 | Experiment system

The experiment system is based on an actual 220-kV single phase oil-filled transformer, with complete internal structure including iron core, windings, insulation paper utilized, as showed in Figure 8. The size of the transformer is $355\,\text{cm} \times 208\,\text{cm} \times 216\,\text{cm}$. The experiment system diagram is shown in Figure 9. The voltage is applied to the low-voltage (LV) winding of transformer, the high-voltage (HV) winding of transformer is open-circuited. A PD simulation cell is used to place PD sources, as is showed in Figure 10. The PD simulation cell is installed into the transformer through the flange at the top surface of the transformer, the one end of the PD simulation cell is connected to the HV winding, while the other end is connected to the shell. The UHF antenna is installed in the dielectric
window on the transformer shell, and the ultrasonic sensor is stuck on the transformer shell. The measured UHF signal is amplified by a low noise amplifier (LNA) with a frequency band from 200 to 800 MHz and a gain of 40 dB, while the measured ultrasonic signal is amplified by a LNA with a frequency of 20–300 kHz and a gain of 40 dB. The oscilloscope used in the experiment is Agilent DSO-S 254A with an analog bandwidth of 1 GHz. The sampling rate is set to 5 GS/s.

4.2 UHF antenna and ultrasonic sensor

In this part, the details of the UHF antenna and ultrasonic sensor used in the experiment is described. The UHF antenna is installed through a dielectric window in transformer shell. Figure 11 provides the simplified structure of the dielectric window and internal UHF antenna. The window diameter $\phi$ is 180 mm and the window depth $h$ is 80 mm. The antenna is a double dipole antenna with the transfer characteristic shown in Figure 12. The ultrasonic sensor used in the experiment is PAC R.45I, the measuring characteristic of it is showed in Figure 13. The ultrasonic sensor is stuck on the transformer shell, the distance between PD source and ultrasonic sensor is 48.1 cm.

4.3 Typical PD models

In the experiment, two typical PD sources are adopted to generate ultrasonic signals, they are protrusion discharge and insulation air void discharge. Protrusion discharge is used to generate ultrasonic signals with relatively good SNR, while the ultrasonic signal of insulation air void is relatively weak and the measured signal has a low SNR. In this way, the de-noising performance of proposed method and conventional methods for high-SNR signals and low-SNR signals can be compared clearly.

The physical structures of the two PD sources are shown in Figure 14. These models were installed in the PD simulation cell with the HV electrode connected to the HV winding of the transformer and the LV electrode grounded. Figure 14(a)
FIGURE 14  Physical arrangement and dimension of typical PD source models: (a) Protrusion, (b) insulation air void, unit: mm

FIGURE 15  Typical waveforms caused by protrusion discharge, (a) UHF pulse, (b) ultrasonic signal

depicts the protrusion discharge model, in which the metal taper is 2 mm in diameter, 15 mm long, and 10 mm from the LV electrode. In Figure 14(b), the insulation air void discharge model consists of two 100 mm × 100 mm × 5 mm pressboards stuck together with a small dug out area between them in the centre to form the air void; the pressboards are fixed by two disk electrodes, 30 mm in diameter and 10 mm high.

5  EXPERIMENTAL RESULTS AND ANALYSIS

In this section, the de-noising effect of the proposed method is presented and analysed fully, besides, a comparison with the DTCWT method, ASVD method and LMS method is also made.

5.1  Protrusion discharge

Figure 15 shows a group of measured UHF pulse and ultrasonic signal of protrusion discharge with the apparent charge of 100 pC in the laboratory experiment, the applied voltage is 20 kV. The measured ultrasonic signal has a relatively clear waveform despite of some noise, in other words, the measured ultrasonic signal has a high SNR. The measured UHF pulse also has a good SNR and the peak point of it can be clearly picked up, the time delay between UHF pulse peak point and the start point of ultrasonic signal is about 340 μs. As the propagation velocity of ultrasonic signal in transformer oil is about 1420 m/s, the calculated distance between PD source and ultrasonic sensor is 48.3 cm, which is consist with the actual distance 48.1 cm. The duration of UHF pulse is about 200 ns, which is far smaller than the time delay, therefore, the pick-up error of UHF pulse peak point has little influence on the alignment of ultrasonic signal.

Using the peak point time of UHF pulses as the reference of the start time of ultrasonic signals, the measured ultrasonic signal is de-noised with coherence method in which the average times $M$ is 20, the de-noised signal is showed in Figure 16(b). It can be found that the noise is removed effectively and the de-noised signal has similar waveform with the measured signal. It can be concluded that the proposed method has a good de-noising performance for the ultrasonic signals with a relatively high SNR.

To make a comparison, the measured ultrasonic signal is also de-noised with DTCWT method, ASVD method and LMS method by coherence average method $(M = 20)$, DTCWT method, ASVD method, LMS method.
method, just as showed in Figure 16(c–e). The mother wavelet used in the wavelet de-noising method is ‘db5’ in MATLAB and the threshold value is set as 0.5 for best de-noising results after many attempts. The selection of singular value in ASVD method is adaptive and it doesn’t need setting. The step size in LMS method is 0.001 and the order of filter is set as 40. The RNL of three methods are $7.3 \times 10^{-5}$, $2.3 \times 10^{-5}$, $1.9 \times 10^{-5}$ and $2.6 \times 10^{-5}$ respectively. It can be found that for ultrasonic signal with a good SNR, the de-noising performance of the four methods are similar, the proposed method is a little better than the three other methods.

5.2 Insulation air void discharge

The applied voltage of insulation air void discharge is 12 kV, the measured signal of insulation air void discharge with the apparent charge of 40 pC is showed in Figure 17. The ultrasonic signal of air void discharge is buried by noise entirely, in such situation, it’s difficult to pick up the start point of ultrasonic signal directly and accurately, therefore, it’s necessary to use a UHF pulse as a synchronization signal. The UHF pulse has a good SNR and the peak point of it can be easily picked up, the duration of it is about 200 ns.

Figure 18 shows the de-noised ultrasonic signals by different methods. The mother wavelet used in the wavelet de-noising method is ‘db5’ and the threshold value is set as 0.2. The step size in LMS method is 0.001 and the order of filter is set as 40. Figure 18(a,b) gives the de-noised signals by coherence average method under different average times $M$, it can be found that the coherence average method can remove the noise effectively, and the larger the average times $M$ is, the better result can be obtained. According to the de-noised signal, the time delay between UHF pulse peak point and the start point of ultrasonic signal is about $340 \mu$s, which is consistent with that of protrusion discharge and can indicate the accuracy of the de-noising indirectly.

Figure 18(c–e) give the result by DTCWT method, ASVD method and LMS method, it can be found that the de-noising effect is not satisfying enough. The RNL of coherence average method ($M = 200$) is 0.014, while RNL of the three other methods are 0.0012, 0.0016 and 0.00042. Therefore, it can be confirmed that conventional methods have poor performance for the de-noising of low-SNR signals. Actually, for signals with large SNR, the wavelet coefficients in DTCWT method or the singular values in ASVD method which represent clean signal and noise can be easily distinguished, therefore, the two methods have a good de-noising performance. However, as to the low-SNR signals, the wavelet coefficients or the singular values which represent clean signal and noise are difficult to tell apart, which leads to the poor de-noising results.

Figure 19 shows the influence of average times $M$ on the de-noising performance of the proposed method based on the actual PD signals by air void insulation discharge. For actual signals with noise, it is difficult to obtain original noise-free PD signal, the MSE can’t be calculated, therefore, we just use the RNL to evaluate the de-noising performance in Figure 18. It can be found that the de-noising performance improves with
the increment of $M$, which is consistent with the simulated result and theoretical analysis. It can be found that the proposed method has great advantage in the de-noising of low-SNR signals. In theory, it is free from the limitation of SNR, as long as the average times $M$ is large enough. Moreover, the proposed method is free from PD types and noise condition, the structure of algorithm doesn’t need to change with the PD sources and noise condition. The applicability of the proposed method is extensive. The coherence average method is simple and is easy to program, it can offer a good solution for the de-noising of ultrasonic signal of PD in transformer.

6 1 CONCLUSIONS

This paper proposes a novel de-noising method based on coherence average for ultrasonic signal of PD in transformer, especially for the ultrasonic signal with low SNR. An experiment based on an actual transformer with artificial PD source in it is conducted to evaluate the de-noising effect of the proposed method, besides, a comparison in de-noising performance with other de-noising methods such as DTCWT method and ASVD method is made. The results indicate that the proposed method has a quite good de-noising performance for the ultrasonic signal, different from conventional methods which have poor performance for the low-SNR signal, the proposed method is free from the limitation of SNR, which means the proposed method still has a great de-noising performance even for the quite low SNR signals. What’s more, the principle of the proposed method is simpler, and the proposed method is free from empirical parameter selection or estimation, and it is free from PD types and noise condition, which makes its applicability more extensive. In a word, the proposed method can offer a practical and effective solution to the de-noising of ultrasonic signal of PD in transformer.

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How to cite this article: Cheng J, Xu Y, Ding D, Liu W. A novel de-noising method based on coherence average for ultrasonic signal of partial discharge in transformer. IET Sci Meas Technol. 2021;15:302–311. https://doi.org/10.1049/smt2.12031