Research of an Improved Wavelet Threshold Denoising Method for Transformer Partial Discharge Signal

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***Abstract*—In order to overcome the discontinuance of the hard thresholding function and the defect of seriously slashing singularity in the soft thresholding function, improve the denoising effect and detect the transformer partial discharge signal more accurately, in this paper an improved wavelet threshold denoising method is put forward through analyzing the interference noise of transformer partial discharge signals and studying various wavelet threshold denoising method, especially the wavelet threshold denoising method that overcomes the shortcomings of the hard and soft threshold. Simulation results show that the denoising effect of this method has been greatly improved than the traditional hard and soft threshold method. This method can be widely used in practical transformer partial discharge signal denoising.**

***Index Terms*—transformer, partial discharge, wavelet threshold denoising, threshold**

1. Introduction

The monitoring of transformer partial discharge signal is an important technical measure to ensure the reliability of power supply, but the signal extracted in equipment operation site contains a lot of interference noise, which seriously affects the detection sensitivity and reliability and even leads to judgment mistakes of the inspectors. Therefore how to effectively eliminate the interference noise interference has become the key issue of partial discharge signal detection.

Partial Discharge is a kind of discharge phenomenon for some insulation weak links in large electrical equipments, which takes place under the role of local high electric field [1]. Partial discharge has two damaging effects for the insulation medium: one effect is due to the discharge points' bombarding the insulation medium directly, which makes the local insulation medium be destroyed and gradually expanded, and finally leads to insulation breakdown. Another effect is chemical reactions of heat, ozone, nitrogen oxides and other reactive gases produced by discharge, which make the partial insulation medium be eroded and the dielectric loss increase, and finally lead to insulation breakdown. Whichever kind of effects will bring tremendous damages and losses, so it is important for us to do well the detection of partial discharge signal in order to avoid such damage as possible. The monitoring of transformer partial discharge signal is an important technical measure to ensure the reliability of power supply, but the signal extracted in equipment operation site contains a lot of interference noise, which seriously affects the detection sensitivity and reliability, and even leads to judgment mistakes of the inspectors.

On the base of learning the large number of domestic and foreign related information, we understand that the main transformer partial discharge signal denoising methods include frequency domain denoising method and time domain denoising method.

Frequency domain denoising methods:

(1) FFT threshold filter method

FFT threshold filter method is mainly used to remove periodic narrowband interference. In this method, we make the FFT transform for the signal firstly, then we can get the signal spectral distribution, finally we can easily remove narrowband interference through setting a threshold on the signal spectrum, and make all values greater than the threshold equal zero. The disadvantages of this method are that the selection of threshold is very difficult especially under field conditions. Because the interference signal changes with time, it is more difficult to determine the threshold that affects the filtering results. In addition, the advantages of this method are that it is simple and easy to be implemented [2].

(2) Finite impulse ring(FIR)filter method

The frequency range of finite impulse ring filter needs to be determined in advance according to the scenes. This method can remove not only the cycle narrow-band interference, but also the part of the White Noise. The advantages of this method are good stability and better denoising effect for the Narrowband Interference. Because it requires higher order of the FIR filter in the applications, the computation time is too long and the frequency range needs to be determined in advance. This

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method is only applied to specific site conditions, and the denoising ability is limited. In a word, it is difficult for us to achieve the desired effect.

(3) Infinite impulse response (IIR) filter method

The method has high rejection ratio for periodic interference signal and requires less processing time, it can well suppress the periodic interference signal in the case of PD pulses that produce the minimum distortion, and it applies to all of the oscillation and non-oscillation pulses with different widths, so we can foresee that the applications of cascaded second-order notch IIR filter in online detection of partial discharge signal can receive very good results [3]. However, the method has some disadvantages in practical applications, for example, the stability is poor, interference frequency is difficult to be determined, and computation time is too long.

Time domain denoising methods:

(1) Kalman filter method

Kalman filter is a modern filter which adopts the information provided by the observational data in the course of the recursive filter to improve the precision of the filter and reduce the state estimation error by the online estimation model parameters of filter itself and noise statistics [4]. It is mainly used to remove periodic narrowband interference. The main drawbacks are that the energy loss of PD signal after the filter is larger, the waveform distortion is serious, and the computation time is long. So this method is less to be used.

(2) Adaptive filtering method

The method can automatically adjust the filter coefficients according to the change of the signal characteristics; currently the minimum mean square adaptive algorithm is more adopted. The advantages of this method are that it is unnecessary to know the frequency of the periodic disturbance in advance, and it has a good effect for the suppression of periodic interference [5]. The drawbacks are that the convergence is poor, it is very easy to divergence, and the filtering effect is unstable especially when a variety of interference frequencies appear in the signal at the same time.

In theory, these methods mostly belong to the time domain or frequency domain analysis, which is not a good combination of signal time-frequency characteristics to be analyzed. With the rapid development of wavelet theory, the wavelet analysis has the advantage of time-frequency analysis, and it has been more and more widely applied in denoising of partial discharge signals. There have been many new methods used in partial discharge signal denoising processing, and good effects have been showed, but the existing wavelet threshold denoising method has some drawbacks. On the base of learning the large number of domestic and foreign-related information, analyzing the partial discharge signals and various interference signals, and studying various partial discharge wavelet denoising method in detail, this paper puts forward an improved wavelet threshold denoising method based on existing methods.

II. The Partial Discharge Signal Interference Noise Analysis

In partial discharge signal monitoring process, there are three kinds of main interference noise.

(1) Continuously periodic interference. Continuous periodic interference includes the interference caused by electric power systems carrier communication and the protection of high frequency signal, and radio interference, electric power system harmonic interference and power electronic conversion devices generated interference. Under the general situation continuous periodic interference is the result of the comprehensive effect of the above interferences. Each continuously periodic interference of the time domain waveform has the fixed harmonic frequency and the bandwidth, some of them have high frequency, and the others have lower frequency. The signal of periodic interference in on-line PD monitoring system is one of the important interference sources that exist in the course of monitoring, and the energy of which is very powerful. In frequency domain waveform we can see that the interference includes some isolated spectral lines, and each line corresponds to a frequency component, which is called the narrow band interference [6].

(2) White noise interference. White noise includes all kinds of random noises, such as transformer winding thermal noise, the grounding grid noise, and the various noises caused by the coupling of the power distribution lines, transformers relay protection signal lines, and the electronic components scattered grain of noise from partial discharge measurement system [7]. White noise spectrum in the whole frequency range is of values and has similar characteristics of time domain and frequency domain to the partial discharge signals. In practical applications if the spectrum of noises has the continuously flat characteristics in wide band of frequency, then it can be considered a white noise.

(3) Pulse interference. Pulse interference signal includes power lines or high voltage corona discharge, the interference caused by the division of the power switch and the thyristor rectifier equipment, and the interference caused by other testing equipment discharge in power system, and the interference caused by the test lines or adjacent lines badly connect to the ground, and the interference caused by the discharge of floating objects in other device, and the other random interference [8].

These interferences have many types and occur randomly, some of which are very similar to partial discharge signals.The signal mixed by the interference and partial discharge signals is relatively complex. So how to eliminate noise interference is very difficult. With development of modern digital processing technology and the theory of wavelet, partial discharge signals denoising method is more and more incline to software method which is the digital processing for collected signal. At the same time, people try to combine the hardware and software processing to maximize the suppression and eliminate noise interference, and get partial discharge information, which forms a set of complete denoising systems.

III. An Improved Method for Wavelet Thresholding Signal Denoising

A. Existing Wavelet Denoising Methods

Due to the rapid development of wavelet theory, the wavelet analysis in denoising of partial discharge signals is increasingly used, at the same time a variety of wavelet denoising method appeared.

(1)Wavelet decomposition and reconstruction denoising method

In 1988, Mallet put forward the concept of multi resolution analysis and gave the wavelet decomposition and reconstruction algorithm (Mallet algorithm) [9]. Supposing f_k is the discrete sampling data of the signal $f(t)$ and $f_k = c_{0,k}$, then the orthogonal wavelet decomposition formula of $f(t)$ can be expressed as

$$\begin{cases} c_{j,k} = \sum_n c_{j-1,n} h_{n-2k} \\ d_{j,k} = \sum_n d_{j-1,n} g_{n-2k} \end{cases} \quad (k = 0,1,2,...,N-1) \qquad (1)$$

Where $c_{j,k}$ is the coefficient of the scale, $d_{j,k}$ is the wavelet coefficient, h and g is a pair of quadrature mirror filter banks (QMF), and j is the decomposition level, n is the discrete sampling points.

Wavelet reconstruction is the inverse operation process of wavelet decomposition, the corresponding reconstruction formula can be expressed as

$$c_{j-1,n} = \sum_n c_{j,n} h_{k-2n} + \sum_n d_{j,n} g_{k-2n} \qquad (2)$$

The process to use wavelet decomposition and reconstruction for denoising can be divided into the following three steps:

(1) Signal decomposition: The wavelet function is chosen, and the number of the layers N of the wavelet decomposition is determined [10]. Then the signal is decomposed by N layers wavelet (wavelet packet) transforms.

(2) Threshold value: A threshold is selected for the coefficients of every layer, and the detail coefficient soft threshold is dealt. The key problems are how to select the thresholds and how to quantify the thresholds. There are a variety of rules and methods to solve these problems.

(3) Signal reconstruction: The original signal is restored by processed wavelet coefficients based on wavelet (wavelet packet) reconstruction.

There are mainly four forms, as following, for the threshold selection ways of wavelet threshold denoising method [11].

The method is mainly applied in the deterministic noise situation under which the useful signal and noise frequency bands are separated from each other, and it can remove noise basically and denoising effect is very good. But for the useful signal and noise band overlapping condition, the effect is not very ideal. The advantages of this method are that the algorithm is simple and the calculated speed is fast. The disadvantage is that the scope of application is not very extensive, especially white noise denoising and the denoising effect is poor.

(2) Wavelet threshold denoising method

In Stanford University an academic group led by Donoho proposed wavelet threshold denoising method that is most widely used in current engineering method. In 3.2, the method would be introduced in detail.

(3) The translation invariant wavelet denoising method

Translation invariant wavelet denoising method is an improved method put forward on the basis of the threshold method and improvements. In the threshold denoising, when the signal has a mutation in the discontinuous point or when the signal has the low SNR, Pseudo Gibbs Phenomenon will appear in wavelet transform denoising, namely the signals near discontinuous point will jump up and down at a specific target level. Therefore, the method does not adopt a single translation but usually adopts N cycles of translation to denoise the translated signals by thresholding method, and then takes the average values of the denoised results, which is known as "the translation-denoising-average" of the translation invariant wavelet denoising method that it is used in the case that signal contains several discontinuous points [12].

For example, the signal which contains noise can be transformed by Haar wavelet. When the singular point is located in the N/2 position, Pseudo-Gibbs Phenomenon almost does not appear in the transform results, whereas in other locations such as N/3, the significant Pseudo-Gibbs Phenomenon will appear in the results. The singular point which not located originally in the N/2 position is translated to the N/2 position by the advance translation, which can restrain the Pseudo-Gibbs Phenomenon. Then the order of the original signal is restored by the reverse translation to achieve the purpose.

Translation invariant method has the advantage of being able to remove the Pseudo Gibbs Phenomenon of thresholding denoising and the denoising effect is good. Its shortcoming is the calculation at a slower speed [13].

(4) Denoising method based on modulus maxima

In 1992, Mallat and others proposed the representation of signal and image multi-scale edges based on signal singularity by using Lipschitz index in multiple scales to describe the signal and the mathematical feature of image noise, and then proposed the filtering method of modulus maxima reconstruction [14]. Partial discharge signal is the singular signal and the modulus maxima increases with scale, and it has a positive Lipschitz exponent. The modulus maxima of the noise decreases with increasing scale, and it has negative Lipschitz exponent, the modulus maxima in the wavelet transform has the different change trend .

The principle is as following: the singularity of the signal is a signal catastrophe point, Lipschitz index is a measure which expresses the characteristics of local signal singularity, which is defined as: if n and

$n \le \alpha \le n+1$ are positive integer, and if there exists a positive integer $A > 0$ and the polynomial $p_n(x)$, which makes

$$\left| f(x) - p_n(x - x_0) \right| \le A \left| x - x_0 \right|^{\alpha} \tag{3}$$

where $x \in (x_0 - \delta, x_0 + \delta)$, then it is called that $f(x)$ is Lipschitz α at the x_0 point.

The Lipschitz index of the function at a point expresses the size of point singularity [15]. The larger α is, the higher smooth the point has, and the smaller α is, the larger singularity the point has. If the function is derivable at a point then its Lipschitz index satisfies $\alpha \ge 1$; if the function is discontinuous at a point but its value is limited then its Lipschitz index satisfies $0 \le \alpha \le 1$. For the general signal $\alpha \ge 0$; The α of pulse signal is $\alpha = -1$; The α of white noise satisfies $\alpha < 0 (\alpha = -\frac{1}{2} - \varepsilon, \varepsilon > 0)$.

In the scale of S, if $\forall x \in \delta_{x0}$ there is

$$|Wf(s,x) \le | Wf(s,x_0)| \tag{4}$$

Then x_0 is called the local modulus maxima in the scale of s of the wavelet transformation. The Lipschitz index of signal $f(x)$ and the modulus maximum value of wavelet transform are satisfied with

$$\log_2 \left| W_{2^j} f(t) \right| \le \log_2 k + j\alpha \tag{5}$$

Because of the Lipschitz index of partial discharge signal is $\alpha \ge 0$, the modulus maximum of wavelet transform will increase with the increasing of the scale j, but the Lipschitz index of white noise signal is $\alpha < 0$ and its modulus maximum will decrease with the increasing of the scale j. After many times of wavelet transform, the modulus maxima of white noise has been removed basically or its amplitude is very small, and the remainder of extreme points are mainly useful signal extreme point [16]. Then the retained modulus maxima points are reconstructed by the alternating projection method. Finally it can achieve the purpose of denoising.

B. Comparison of Denoising Indicator

Signal denoising effect can be described by the signal to noise ratio (SNR) and root mean square error (RMSE). SNR can be defined as

$$\text{SNR} = 10\lg \frac{\sum_{i=1}^{N} \left| f(i) \right|^2}{\sum_{i=1}^{N} \left| \hat{f}(i) - f(i) \right|^2} \tag{6}$$

where $f(t)$ is the original signal, $\hat{f}(t)$ is the denoised signal, N is the length of the signal.

The RMSE between original signal and the estimated signal can be defined as

$$\text{RMSE} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} \left| \hat{f}(i) - f(i) \right|^2} \tag{7}$$

If the SNR of the signal is higher, and the RMSE between original signal and estimated signal is smaller, then the estimated signal is more close to the original signal and the denoising effect is better. TABLE Ⅰ lists the contrast of SNR and RMSE of 4 kinds of denoising methods [17].

C. Comparison of Denoising Comprehensive Performance

We derive Table II by studying the wavelet denoising methods and analyzing the wavelet denoising indicators.

It can be seen from Table II, a variety of wavelet threshold denoising methods aim at different noise, the speed and effect of denoising are different, each method has its own advantages and disadvantages, and the wavelet threshold method in comprehensive performance is more prominent. When selecting the denoising method, we need to combine specific denoising environment with the requirement of denoising and the denoising method features to achieve better denoising effect. The combination of wavelet denoising methods with other methods may achieve better denoising effect.

D. An Improved Method for Wavelet Thresholding Signal Denoising

After the study of various wavelet denoising methods, this paper proposes an improved wavelet threshold denoising method that is based on the original wavelet threshold denoising methods, and adopts the application of the comprehensive theory to improve the original wavelet threshold denoising methods.

In wavelet threshold denoising method, suppose that a noisy signal can be expressed as

$$f(t) = s(t) + n(t) \tag{8}$$

TABLE I.
THE CONTRAST OF WAVELET DENOISING INDICATOR

Indicator	Wavelet decomposition and reconstruction denoising method	Wavelet threshold denoising method	The translation invariant wavelet denoising method	Denoising method based on modulus maxima
SNR	19.137	22．8981	2．4462	28．146
RMSE	4．04	29．2123	21．782	1．96

TABLE II.
THE COMPARISON OF WAVELET DENOISING COMPREHENSIVE PERFORMANCE

Denoising method	Denoising speed	Denoising effect	Advantage	Disadvantage
Wavelet decomposition and reconstruction denoising	Fast	Better	The algorithm is simple and the calculation speed is fast	The scope of application is small
Wavelet threshold denoising	Faster	Better	The calculation speed is fast and the denoising effect is good	In some cases there will be a Pseudo Gibbs phenomenon
The translation invariant wavelet denoising	Slow	Good	It can effectively remove Pseudo Gibbs Phenomenon	Denoising speed is slow
Based on modulus maxima	Slower	Good	It can effectively retain the signal singularity information	Denoising speed is slower

where $s(t)$ is the original signal, $n(t)$ is the Gaussian white noise with variance σ^2 and obeys $N(0,\sigma^2)$.

Wavelet threshold denoising process can be divided into the following three steps [18]:

(1) By making discrete wavelet transform of the noisy signal $f(t)$, the wavelet coefficients $w^{j,k}$ can be got, wher k is the wavelet coefficients of the j-th layer wavelet space order;

(2) After the scales corresponding to the wavelet coefficients have been treated by the threshold function, we get the estimated wavelet coefficients $w^{j,k}$;

(3) Using the wavelet coefficients processed by the threshold to make inverse discrete wavelet transform to reconstruct signals, we can get the denoised signal $\hat{f}(t)$.

The key of the method mainly depends on the threshold and the selection of threshold function which is related to the denoising effect [19]. The main threshold functions include the following three kinds:

$$\hat{w}_{j,k} = \begin{cases} w_{j,k}, & |w_{j,k}| \geq \lambda \\ 0, & |w_{j,k}| < \lambda \end{cases} \quad (9)$$

The hard threshold function

$$\hat{w}_{j,k} = \begin{cases} sign(|w_{j,k}|)(|w_{j,k}| - \lambda), & |w_{j,k}| \geq \lambda \\ 0, & |w_{j,k}| < \lambda \end{cases} \quad (10)$$

The soft threshold function

$$\hat{w}_{j,k} = \begin{cases} 0, & |w_{j,k}| \leq \lambda_1 \\ sign(w_{j,k}) \dfrac{\lambda_2(|w_{j,k}| - \lambda_1)}{\lambda_2 - \lambda_1}, & \lambda_1 < |w_{j,k}| \leq \lambda_2 \\ w_{j,k}, & |w_{j,k}| > \lambda_2 \end{cases} \quad (11)$$

The semi-soft threshold function

In the equation (11) λ_2 is the upper threshold, λ_1 is the under threshold.

There are mainly four forms, as following, for the threshold selection ways of wavelet threshold denoising method [20].

(1) Using the fixed threshold form (sqtwolog): The threshold is got by multiplying threshold σ of minimum value in maximum variance and a coefficient $\sqrt{\log N}$. This threshold form can get an intuitively good denoising effect in the process of soft-threshold.

(2) Soft-threshold estimation based on Stein unbiased likelihood estimation (rigsure): The different thresholds are chosen in different scales, and the wavelet coefficients of corresponding scales are scaled down. Suppose $P = [p_1, p_2, \cdots p_n]$, and $p_1 < p_2 < \cdots p_n$, all elements of P are a sequence array increasingly sorted by the squares of the wavelet coefficients. The risk vector R is defined, whose elements are

$$r_i = [N - 2i - (n-i)p_i + \sum_{k=i}^{i} p_k] / N, i = 1, 2, \cdots N \quad (12)$$

The corresponding threshold that $T_2 = \sigma\sqrt{p_a}$ can be obtained by subscript of a minimum value r_a of the elements in R.

(3) Selection of the heuristic threshold: It is the combination of sqtwolog form and rigsure form, The chosen threshold is the best predicable variable threshold. If the signal to noise ratio (SNR) is very small, the form sqtwolog is use to select the threshold; if SNR is large, rigsure form will be used.

(4) Minimum maximum variance threshold: As the sqtwolog, it is also a fixed threshold form. It makes the selected threshold have minimum maximum variance. The formula is:

$$t = \begin{cases} 0, N \leq 32 \\ 0.3936 + 0.1829^* \log_2^N \end{cases} \quad (13)$$

The focus of wavelet threshold denoising method is the threshold function and threshold selection methods which directly determine the advantages and disadvantages of this method. However, there are still some deficiencies for this method, for example, hard threshold function discontinuity makes the denoised signal have larger deviation, and still contains a significant noise compared with the original signal; Using soft threshold method, its continuity is good, but there is constant deviation between the estimated wavelet coefficients and the wavelet coefficients of noisy signal , which makes the denoised signal's variance be too large, and when noise signal is too irregular it appears too smooth; The semi-soft threshold function is the eclectic form of hard threshold function and the soft threshold function，which retains a larger coefficient and continuity, but semi-soft threshold function needs to determine two thresholds, which increases the complexity of the algorithm, and the selection of upper threshold or under threshold would affect the accuracy of the reconstructed signal.

Because the wavelet threshold denoising method has the mentioned above disadvantages, it is difficult to reach the expected effect of denoising. This paper puts forward the improved wavelet threshold denoising method which integrates soft threshold with hard threshold denoising method and low pass filter method and improved the method with the comprehensive theory. The denoising effect of the improved wavelet threshold denoising method is ameliorated obviously.

IV. Simulation Results and Evaluation

In order to test the denoising effect of improved wavelet threshold denoising method, this paper uses Matlab software to carry out the simulation experiment.

Fig. 1 is a simulation of the original transformer partial discharge signal. Fig. 2 is the simulation of the signal that 10dB Gauss white noise is added in the original signal. Fig. 3 is the signal that is denoised by the traditional soft threshold denoising method. Fig. 4 is the simulation of using the improved wavelet threshold denoising method in denoising the signal.

From the results of simulation we can see, soft threshold denoising method and the improved wavelet threshold denoising method can basically restored the original partial discharge signals. Soft thresholding denoising has good continuity but not good to retain the original signal singular point, and the original signal can not be recovered well, and some signals are weakened. Improved wavelet threshold denoising method less weaken the signal’s singularity under the premise that ensure continuity of the signal, and denoising speed will not change too much. Therefore, the original signal can be restored, and the denoised signal distortion degree can be reduced. The improved method has greatly increased the denoising integral effect.

V. Summary

This paper introduces the transformer partial discharge signals of denoising methods, which focuses on the wavelet threshold denoising method studying. Then based on analyzing the disadvantages of the wavelet threshold denoising method an improved wavelet threshold denoising method is proposed. Finally, compared with the denoising results of the improved denoising method and traditional threshold denoising method, the result shows that the denoising result of the improved wavelet threshold denoising method has the better denoising effect. Compared with traditional wavelet threshold denoising method, the method doesn’t reduce the speed, and the denoising effect is improved greatly, and it also has better stability. But from the overall effect of the method it still can not achieve the desired effect in signal denoising, and some distortions will still appear at singular point. To explore the best transformer partial discharge signal denoising method, to realize the signals low distortion recovery, and to improve the accuracy of determine partial discharge are the next targets.

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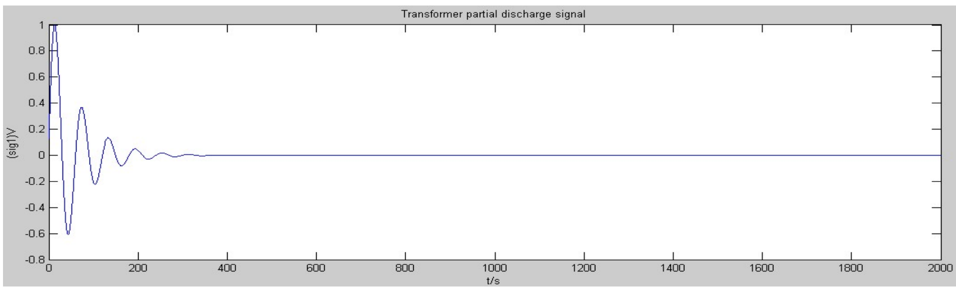

Figure 1. The transformer partial discharge signal.

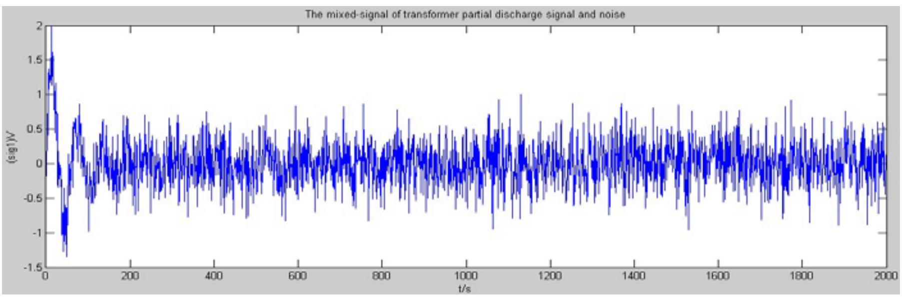

Figure 2. The transformer partial discharge signal and noise of mixed signal

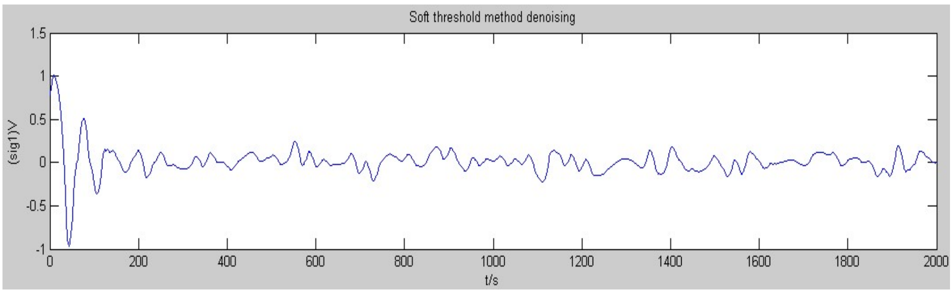

Figure 3. The signal after denoised by the soft threshold denoising method

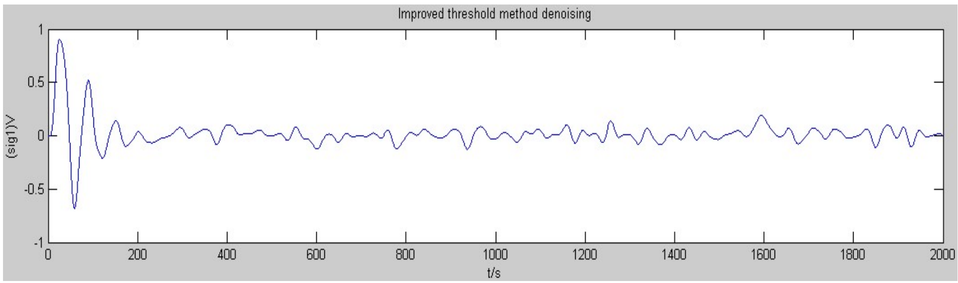

Figure 4. The signal after denoised by the improved threshold denoising method

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