On-line Partial Discharge Monitoring System and Data Processing Using WTST-NST Filter for High Voltage Power Cable

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Abstract: - Defects inside insulation of HV XLPE cable accessories can lead to partial discharge (PD) activity. When PD activity happens, leakage current may flow through the grounded line. To acquire the PD current signal, one practicable and effective method is placing a high frequency current transformer (HFCT) winding the grounded line. In order to measure the insulation degradation, a partial discharge on-line monitoring system is developed and reported in this paper. Through the field test, the presented monitoring system is effective and available for power cable in the condition based maintenance (CBM). However, on-site partial discharger detection on XLPE cables and cable accessories are very difficult of variable noise interference, which gives much trouble to partial discharge detecting. This paper introduced an adaptive filter stationary-non stationary filter based on the wavelet transform (WTST-NST) to de-noise the stationary noise interference in partial discharge detecting. The proposed method is a wavelet domain filtering technique, based on the iterative multi-resolution decomposition reconstruction (MRD-MRR) with hard threshold, for extracting PD signals from stationary interference noise. Quantitative and qualitative analysis of the experimental results, while using the WTST-NST filter to PD signals recorded from power cables, prove that the ability to extract the PD from noise hidden in it.

Key-words: - Power cable, Adaptive WTST-NST filter, On-line monitoring, Partial Discharge, MRD-MRR Algorithm, Stationary noise interference, condition based maintenance(CBM)

1 Introduction

With the increasing use of cross-linked polyethene (XLPE) power cable in power grids, the accidents and failure of power cable and cable accessories arising from insulation degradation, is becoming one of the main challenges against power system stability and safety. As most cables are laid underground in form of direct-buried, pipeline and tunnel, condition monitoring of power cables are becoming much more difficult. Therefore, it has great practical significance to evaluate the insulation status of the suspected cable by some detection methods before breakdown.

In recent years, utilities have shown a growing interest in applying partial discharge (PD) testing to their existing cable network in order to detect, locate and access week components of the cable system including accessories. The objectives of on-line monitoring are to prevent failures, reduce maintenance costs and predict the life of the power system equipment [1-4]. PD detection picks up the discharge characteristic from insulation degradation inside the power cables

Preferable sensitivity is achieved with certain digital signal processing. Compared with other diagnostic methods, the major and most effective tool to detect local damage, defects, and/or localized aging processes in extruded cable systems is, as is well known, the measurement and analysis of partial discharge (PD) [5-7]. The PD detection method is non-destructive and also cost-effective due to its ability to be applied when the equipments are in-service without taking them off from service. It means that all in-service high voltage apparatuses being detected can still be on-line and keep working. This makes it possible to execute continuous power system trends determination, condition based maintenance (CBM), and asset management [8,9].

As we all know, PD activity may result in eventual breakdown of insulation. Therefore, the PD detection is particularly important. However, the basic technique of PD measurement is how to acquire the PD signals from power cables or cable accessories and to discriminate a PD signal from all kinds background noises, since the higher the detection sensitivity is, the more noise will be also detected. Besides, PD signals are often hidden by, or mistaken for, noises and disturbances.

Thus the PD sampling hardware system and the suppression or removal of noises are the two big problems to be solved in PD on-line monitoring of power cables.

Due to the features of PD detection technique, some international organization such as IEEE and CIGRE, have issued some guides and standards to normalize the application of PD method [10, 11]. Furthermore, related research has been done on on-line monitoring of power cable and cable accessories [12]. Reference [13] puts forward a PD detection scheme employing field programmable gate array (FPGA) instead of general-purpose high-speed data acquisition system. Reference [14] reports the results of an investigation of an intelligent DSP-based PD analyzer using wavelet analysis for partial discharge characterisation. The advantages of this approach are the portability and high performance with low cost. Reference [15] introduces an on-line PD monitoring system of XLPE power cable based on virtual instrument designing conception, using a PCI-5112 digitizing acquisition board product and Lab-View software diagnosis system, including FIR filter and LMS self-adapting filter. In [11], sensors are placed around grounded conductor of power cables and couple the high frequency current signal to display on oscilloscope. Reference [16] introduces some on-line monitoring experiences and insulation diagnosis methods about PD measurements for power cable joints and terminations.

The PD signal can not transmit for long distance, as it will attenuate along the distance and may be interfered by much more background ambient noises. Because the none practical for on-site continuous monitoring of the visual observation equipment, a better way is to sample the PD signal close to the coupling sensor and send the results to remote server through digital interface, which is immune to much outer noise.

In such way, the data interaction bandwidth should be choosed carefully. Fortunately, the development of the advanced analog-to-digital converter (ADC) and digital signal processor (DSP) techniques put away some available solutions to on-line continuous monitoring of PDs.

Based on the above mentioned, this dissertation provides a scheme utilizing high performance DSP to implement an on-line monitoring system of PDs.

However, because of the complex field conditions, the PD signals acquired from the on-line detecting system may contain lots of background noises, such as:

1) Corona and arcing in the power substation is unavoidable.

2) Partial discharge signals distribution line and other power equipment.

3) Carrier communication of power system, high frequency protective signals and radio transmissions.

4) Stationary random noises produced by detection system itself with the same characteristic of white noise.

5) Other random impulsive noises produced by thyristor switch, thunderstorm or others.

According to the waveform, the noises of above can be divided as: impulsive noise (such as (1), (2) and (5)), continuous periodic noises or narrow band noise (such as (3)) and stationary random noises (such as (4)). And there are several methods for removing the above noise.

For continuous periodic noises, Fast Fourier Transform (FFT) threshold filtering method was presented in [17]. This method is based on the impulsive characteristic of continuous periodic noises in frequency domain, and removes the impulse whose amplitude in frequency domain is above the threshold. Actually, it is a digital multi-stop-band filter. As to the stationary random noise, due to its existence in the whole detection frequency and very small amplitude in frequency domain, it cannot be suppressed by FFT threshold filtering method.

Multi-wavelet was used for suppressing the white noise, and proved good performance than the wavelet [18]. But considering the periodic pulse interference, the multi-wavelet is helpless. And reference [19] introduced the Empirical Mode Decomposition (EMD) with the common adaptive filter, and propose a new scheme for suppressing DSI signals.

For the above problems, this paper introduce a wavelet transform-based stationary-non stationary (WTST-NST) filter for the separation of discontinuous PD signals (non-stationary waves) from periodic interrupts or white noises (stationary waves), which is based on an iterative reconstruction-decomposition process, deriving weighted WT coefficients at each iteration. Compared with other filtration methods, the performance of this method is of higher accuracy, efficient and lees computational time.

2 PD On-Line Measuring System

Nowadays, with the popular use of XLPE cable in power stations, the XLPE cable and GIS are jointed by cable termination, which has a conductor strap connecting the metallic screen of cable to the ground. According to the manufacturing quality and assembly techniques, the cable terminations are always of high accident risk. When PD happens inside the cable termination, the adjacent cable body or GIS bushing, there will be some high frequency pulse PD current flowing through the grounded strap. Clamping the HFCT sensor around the earthing line may pick up the high frequency PD current pulse caused by the defects inside the cable termination and adjacent devices. And furthermore, we can use the sensor to locate and access the week components of the cable system including accessories.

Fig. 1 shows the PD on-line measuring system, which includes three main components: high frequency current transformer (HFCT), front-end sampling device and background server center. HFCT is the clamping sensor to couple the PD pulse current leaking from the inside cable termination. The pre-amplifier and the front-end sampling device are placed close to the sensor in order to acquire the internal PD signals as much as possible and to suppress the most background noises, achieve good SNR. The acquired data are transmitted to background server center by commonly used Ethernet cable. The server display and store both the acquired PD data and the statistical parameters for operators' reference. The server will give out warning signal if the PD level exceeds the pre-set threshold after analyzing the acquisition result.

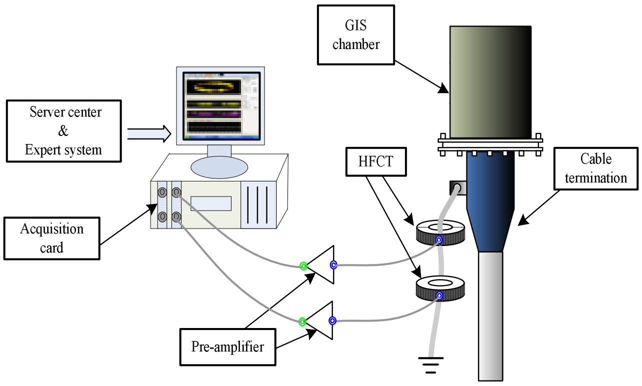


Fig. 1 Architecture of power cable on-line monitoring system.

2.1 Coupling sensor and pre-amplifier

PDs may be excited by the inside defects, and a high frequency current pulse will flow through the earthing conductor. To detect PDs, an effective way is to place a clamp-on high HFCT around the grounding line, which connects the cable metallic screen to the earth. The bandwidth of the designed HFCT is up to 10MHz, which is not only considered to be high enough to cover the main frequency range of PD pulses [11], but also can suppress some upper frequency bandwidth disturbance. In the proposed system, the rogowski coil is adopted for PDs detection, and it is recognized as the best means to detect high frequency current flowing through earthing conductor for its high frequency sensitivity, good linearity and small changes on delay using for PD detection. [20, 21].

Fig. 2 HFCT installed around the earthing strap of cable termination.

The above designed HFCT installed in field cable termination of a GIS is shown in Fig. 2.

However, as the amplitude of PD pulse signal acquired from HFCT may be too weak, about some millivolt, and the effect of background noises, a pre-amplifier is indispensable to enlarge the original signal into a measurable scale. The schematic diagram of the rogowski coil together with the matching impedance and pre-amplifier is shown in Fig. 3.

The bandwidth of the designed HFCT is up to 20MHa, which is not only considered to be high enough to cover the main frequency range of PD pulses [11], but also can suppress some upper frequency bandwidth interferences.

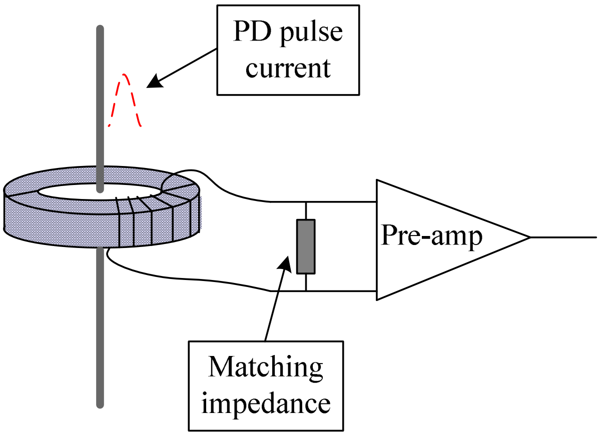


Fig. 3 The analytical diagram of HFCT sensor structure.

2.2 Front-end sampling device

The PD pulse signals should be digitized for post digital signal processing. As analog signal is more sensitive to outer noise than digital signals, reducing the distance from sensor to acquisition device should be as short as possible for effectively suppressing surrounding noise coupled to the real PD signal. Thus, it is designed to place the digitization stage near the signal sensor within 5 meters for high measurement signal-to-noise ratio (SNR). Additionally, the front-end sampling device should have the capability of high acquisition rate satisfying the Nyquist Theorem, and long distance digital communication method such as Ethernet needs to be realized for sending the pre-process result from front-end device to remote server center.

2.3 Detection server center

Detection server center plays the role of human-machine interface in the designed monitoring system. With it, the operator or user can place the sample command to the front-end device and control all the sampling procedure. The statistic parameter and phase-resolved PD diagram associated with power frequency can also be displayed on the server. The server automatically alarms when the detection of PD signals reaching or climbing above the threshold set by users. The history trends of PD level help operators to determine the insulation status of the monitored apparatus and whether maintenance is needed. All these contribute significantly to condition based maintenance, which gradually moves the maintenance effort from traditional scheduled preventative approach to a more flexible and accurate condition based predictive approach.

3 Method of WTST-NST Filter and Filter Algorithm

In this section, we introduce an algorithm used to form a wavelet-based filter, as a separation tool of partial discharge signal and stationary background noises in power cables and cable accessories.

The proposed method is a wavelet domain filtering technique based on the fact that partial discharge signals are non-stationary in time domain and has large components in many wavelet scales, while “noise” background dies out swiftly with increasing wavelet scale. Based on this fact, the coefficients with respect to their amplitude can be characterized. The most significant coefficients at each scale, with amplitude above some threshold, correspond to PD signals, while the rest correspond to stationary noises. Consequently, a wavelet domain separation of coefficients corresponding to PD and noises, respectively, can offer a time domain separation of PD from noises using an iterative multi-resolution decomposition – multi-resolution reconstruction (MRD-MRR) scheme.

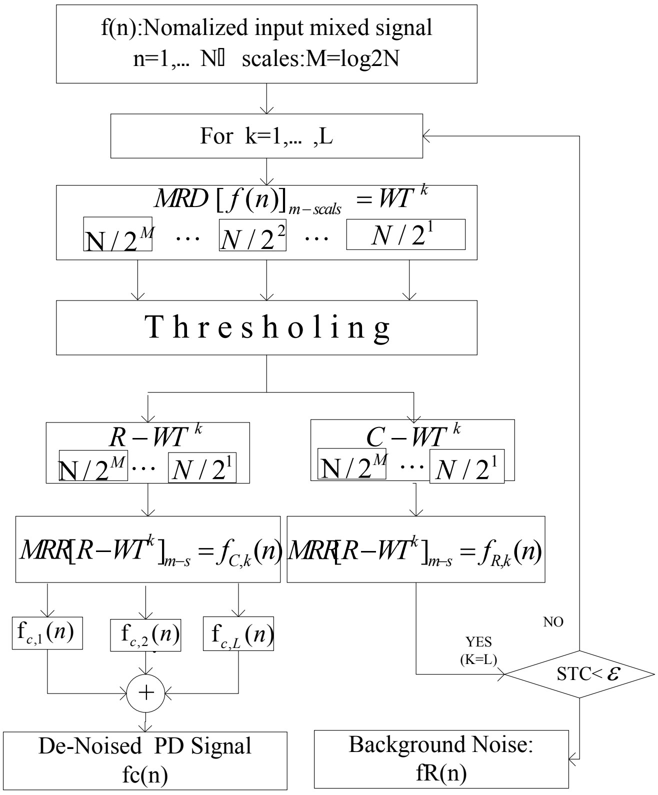


Fig.4 A schematic representation of the WTST-NST filter.

A schematic representation of the WTST-NST filter is shown in Fig.4. This algorithm is also used in [22] to the case of BS analysis. And this paper used it to distinguish and remove the stationary noise hidden in the partial discharge pulses for detecting power cables and condition assessment.

From the schematic representation, it can be seen that an iterative multi-resolution decomposition-reconstruction (MRD-MRR) scheme, is employed to form different levels of noise separation.

The MRD-MRR algorithm adopted is the Mallat decomposition-reconstruction algorithm based on the multi-resolution analysis. An analysis description and details with regarding to the implementation of wavelet analysis can be found in reference [23].

In fact, the normalized N-sample PD, denoted by f(n),(n=1,…,N), is separated into two parts, i.e., $f_C(n)$ and $f_R(n)$, partial discharge signals and stationary noises, that correlate and do not correlate well, respectively, with the WT basis of waveforms. The iterative procedure refines the estimation of the $f_C(n)$ and $f_R(n)$ parts, aiming at the best separation of the PD from the background noise. Specifically, during the kth iteration, the WT of f(n) at m adjacent resolution scales(m = 1,…,M, where M=log2N) is first calculated. Then, the wavelet transform coefficients at scale j are compared with the threshold, defined as follows:

$$THR_j^k = \sigma_j^k \bullet F_{adj} \tag{1}$$

Where σ_j^k is the standard deviation of the wavelet transform coefficients at iteration k and scale j, to be calculated as follow [24]:

$$\sigma_j^k = \sqrt{\frac{1}{N+1}\sum_{k=0}^{N}\left(A_{j,k}\right)^2} \tag{2}$$

Where $A_{j,k}$ is the coefficient at iteration k and scale j. F_{adj} is the adjusting multiplicative factor, used to sustain the threshold at a high value, at different scales.

Comparison to the threshold defined in function (1) is used to divide the WT coefficients at each scale into big ($\geq THR_j^k$) and small ($< THR_j^k$) ones, C-$WT^k(n)$ and R-$WT^k(n)$, respectively. The symbols C and R characterize the WT coefficients during the kth iteration used for the reconstruction of the $f_{C,k}(n)$ and $f_{R,k}(n)$ parts. This is achieved by applying MRR(m-scales) to C-$WT^k(n)$ and R-$WT^k(n)$, respectively. The iterative procedure stops after the following Stopping Criterion-STC is satisfied:

$$STC = \left| E\left\{R_{k-1}^2(\lambda)\right\} - E\left\{R_k^2(\lambda)\right\} < \varepsilon \right| \tag{3}$$

Where E{} denotes the expected value and $0 < \varepsilon \leq 1$, corresponding to the desired accuracy in the refinement procedure. After the last iteration L, the coherent part of the signal (PD signal) is obtained by superimposing the coherent parts derived at each iteration k (k=1,…,L) as:

$$f_C(n) = \sum_{k=1}^{L} C_k(n) \tag{4}$$

While the non-coherent part $f_R(n)$ (background noise) is estimated by the remains, i.e.,

$$f_R(n) = X_{R,L}(n) \tag{5}$$

From the above mentioned description, it is obvious that: the WTST-NST filter peels the recorded signal into layers, reveals its coherent structures and serves as a true tool for separating non-stationary signal (partial discharge) from the stationary signal (noise). Consequently, the WTST-NST filter acts as an adaptive noise removal tool for PD analysis.

4 Results and Discussions

Results obtained with the WTST-NST filter on different kinds of PD are presented in this section.

4.1 Simulation Analysis

In the engineering area, the detected signals are normally oscillating and attenuating, and this partial discharge pulse can be processed by simulating the model of double exponential oscillated and attenuated.

$$f(t) = A\left(e^{-1.3t/\tau} - e^{-2.2t/\tau}\right) \bullet \sin\left(f_c \times 2\pi t\right) \tag{6}$$

Where f_c is the oscillated frequency, A is the amplitude of PD signal, attenuation factor τ is 4us and 6us, frequency of oscillating f_c is 800KHz, sample rate is 20MHz. The waveform of the simulating on-site detected PD signal (containing noise, including narrow band periodic signals and white noises), defines as follows:

$$f_1(t) = \sum_{i=1}^{N} A_i \sin(f_i \times 2\pi \times t) \tag{7}$$

Where A_i and f_i are the amplitude and frequency of the narrow band periodic signals, respectively. From Fig. 5(a), we can see the original simulated signal, and Fig. 5(b) is the mixed signal with narrow band and white noise signals.

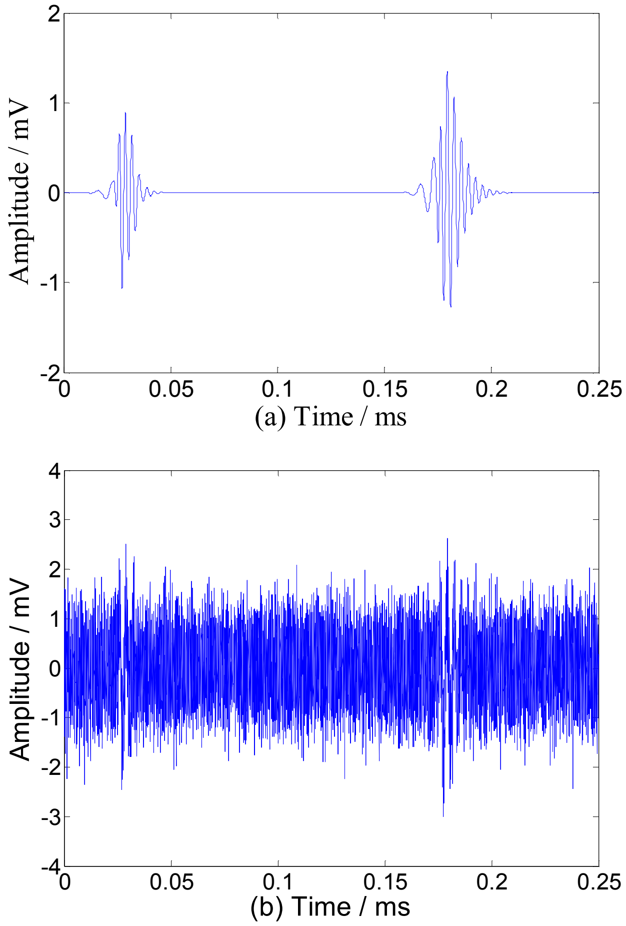
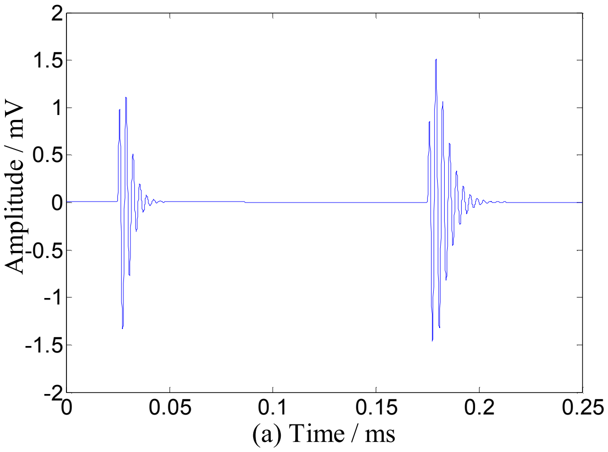


Fig. 5 Signal waveform. (a) simulated signal, (b) mixed signal with narrow band and white noise signal.

The simulated partial discharge signals in Fig. 5(b), are hidden in the interrupted signal, which cannot be distinguished from them. In order to confirm the effect of decompose non-stationary signal (PD) from stationary signal (noise) using WTST-NST filter, we compare with wavelet method, the results are in the Fig. 6(a) and (b).



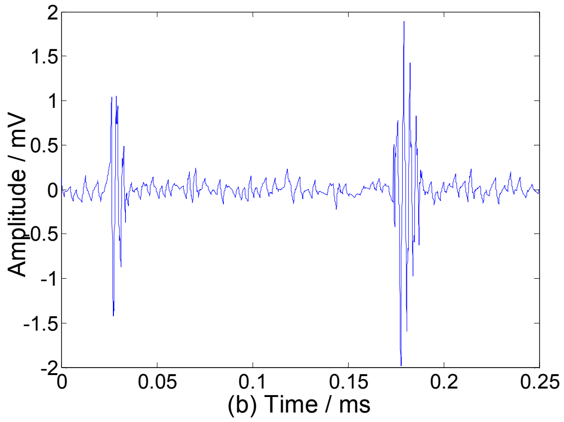


Fig.6 Filtered data. (a) by Wavelet, (b) by WTST-NST filter

The experimental results indicate that the WTST-NST filter can suppress the continuous periodic signals and stationary random noises, extract partial discharge pulses perfectly.

Table Ⅰ shows the comparison result between the WTST-NST and db2 wavelet, according to the identification functions, defined as follows:

$$d_1\left(s,s^{'}\right)=\frac{1}{R}\frac{1}{L}\sum_{n=1}^{L}\left|s(n)-s^{'}(n)\right| \tag{8}$$

$$d_2\left(s,s^{'}\right)=\frac{1}{R}\left\{\frac{1}{L}\sum_{n=1}^{L}\left|s(n)-s^{'}(n)\right|\right\}^{1/2} \tag{9}$$

$$d_\infty\left(s,s^{'}\right)=\frac{1}{R}\max_{n=1,\cdots,L}\left|s(n)-s^{'}(n)\right| \tag{10}$$

Where s and s’ are the original and processed signals with length L. d1, d2, and d_∞ are the average error, mean square error and max error of original and processed signal respectively. R is the peak-peak value, used for normalization of d1, d2, and d_∞.

Table Ⅰ Comparison of the result of WTST-NST and Wavelet

	d_1 (%)	d_2 (%)	d_∞(%)
WTST-NST	1.15	6.6	10.18
Wavelet	4.67	10.08	20.58

From Fig. 6 and Table Ⅰ, it can be seen that the WTST-NST filter can extract the PD signal from the noises and compare with wavelet, the results of the average error d_1, mean square error d_2 and max error d_∞, are all smaller than wavelet. The performance of the WTST-NST filter, in separating the non-stationary parts (PD signals) from stationary parts (background noises) on-site, is verified to be wonderful.

4.2 Experimental Analysis

The defect of partial discharge is divided into two models, one is protrusion on high voltage conductor, the other is scratch on cable extern shielding tier. Which can be found in fig. 7 and fig. 8, respectively.

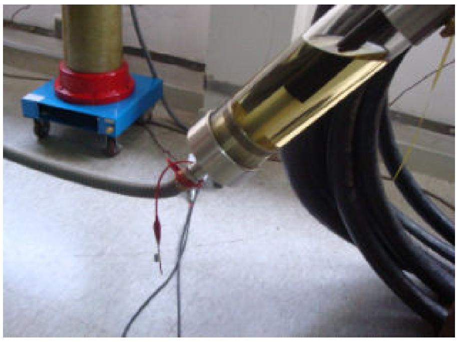


Fig.7 Model of protrusion on high voltage conductor.

Fig.8 Model of scratch on cable extern shielding tier

Fig. 9 is the original signal waveform acquired from the model of protrusion on high voltage conductor. And fig. 10(a) and (b) are the results filtered by WTST-NST and Wavelet filter with ε=0.01, respectively.

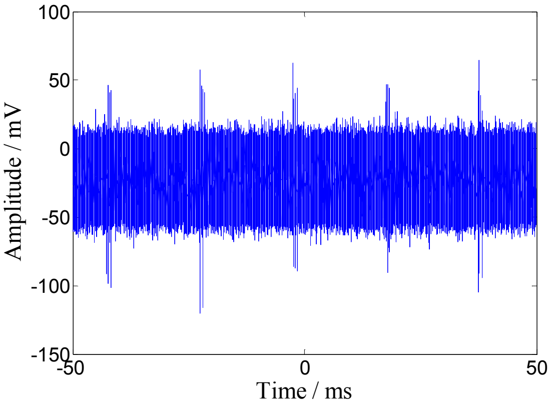
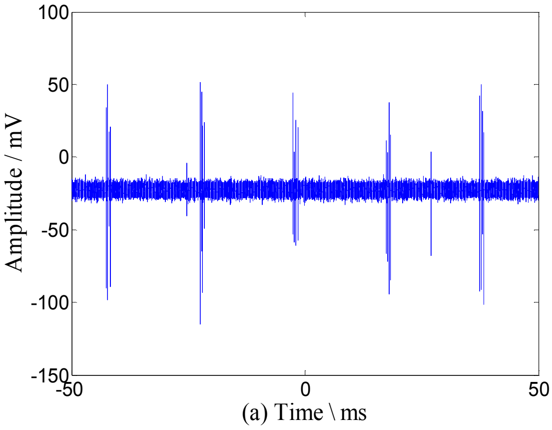


Fig. 9 Original signal waveform of protrusion on high voltage conductor.



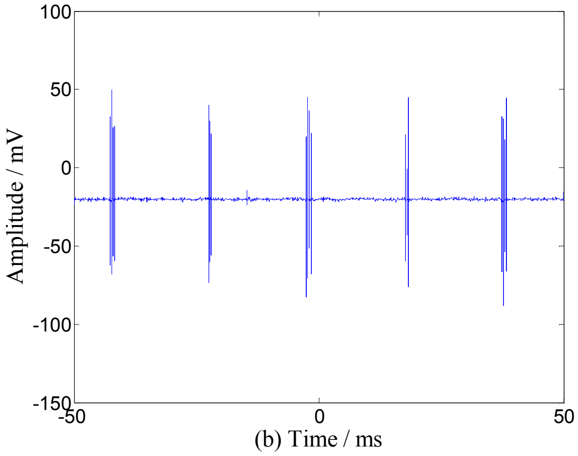


Fig. 10 Filtered data. (a) by Wavelet, (b) by WTST-NST filter

Fig 7(a) shows us that the Wavelet filter can suppress the noise contained in the original signal perfectly. However, comparing the result filtered by WTST-NST filter illustrated in fig.7(b),we can see the SNR and the filtering performance are better than the Wavelet result.

In order to verify the two results quantitatively, we use function (8) to (10) to campare the performance by WTST-NST and Wavelet filter, which can be seen in table Ⅱ.

Table Ⅱ Comparison of the result of WTST-NST and Wavelet

	d_1 (%)	d_2 (%)	**d_∞(%)**
WTST-NST	4.6	1.9	13.54
Wavelet	6.2	2.15	20.74

From table Ⅱ, d1, d2, and d_∞ are the average error, mean square error and max error of original