Analysis of Partial Discharge Detection in Power Cable by WTST-NST Filter Technology

HUI WANG, CHENGJUN HUANG, JUNHUA LIU, LINPENG YAO, YONG QIAN, XIUCHEN JIANG
Department of Electrical Engineering
Shanghai Jiao Tong University
No. 800 of Dongchuan Rd, Minhang District, Shanghai
CHINA
frankhery@hotmail.com & frankhery@powerpd.cn

Abstract: - The objectives of on-line monitoring are to prevent failures, reduce maintenance costs, and predict the life of the power system equipment. It is non-destructive and also cost-effective due to its ability to be applied when the equipments are in-service without taking them off form service. 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 denoise 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 XLPE and metro DC cables, prove that the ability to extract the PD from noise hidden in it.

Key-words: - Power cable; Adaptive WTST-NST filter; Partial Discharge; MRD-MRR Algorithm; Stationary noise interference

1 Introduction

In recent years, partial discharge (PD) on-line monitoring has been used widely for evaluating the insulation condition of power cables. The objectives of on-line monitoring are to prevent failures, reduce maintenance costs and predict the life of the power system equipment [1]. It 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.

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) [2-4]. PD activity may insult in eventual breakdown of insulation. Therefore, the PD detection is particularly important. However, the basic technique of PD measurement is how to discriminate a PD signal and noise, 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 removal and suppression of noise is the big problem to be solved in PD on-line monitoring of power cables.

The main noises occurring on-site are:
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 switching, 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 [5]. 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.

Least mean square error (LMS) adaptive filter was also used for suppressing continuous periodic noise [6]. For the stationary noise, LMS adaptive filter performs very well. But its performance is affected by the parameters, such as time delay and converging factor. If the input signal is non-stationary, such as PD signal, the degree of disperse of its covariance matrix’s characteristic value is very large. Thus the convergence property of LMS adaptive filter deteriorates seriously. Also, LMS cannot suppress stationary random noise perfectly.

In this paper, the implementation of 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) is presented, 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 less computational time.

2 Method of WTST-NST Filter and Filter Algorithm

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

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.

\[ f(n): \text{Nomalized input mixed signal} \]
\[ n=1, \ldots, N \]

\[ \text{For } k=1, \ldots, L \]

\[ \text{MRD} \left( \left[ f(n) \right]_{n=1}^{N} \right) = WT^k \]
\[ \frac{N}{2^k} \ldots \frac{N}{2} \ldots \frac{N}{2^1} \]

\[ \text{T r e s h o l d i n g} \]

\[ R \left( \left[ WT^k \right]_{n=1}^{N} \right) \]
\[ \frac{N}{2^k} \ldots \frac{N}{2} \ldots \frac{N}{2^1} \]

\[ \text{M R R} \left[ \left[ W T^k \right]_{n=1}^{N} \right] = f_C(n) \]
\[ \text{M R R} \left[ \left[ W T^k \right]_{n=1}^{N} \right] = f_R(n) \]

\[ f_C(n) + f_R(n) \]

\[ \text{De-Noised PD Signal} \]
\[ f_C(n) \]

\[ \text{Background Noise:} \]
\[ f_R(n) \]

\[ \text{YES} \]
\[ \text{NO} \]

\[ \text{STC}< \epsilon \]

Fig.1 A schematic representation of the WTST-NST filter

A schematic representation of the WTST-NST filter is shown in Fig.1. This algorithm is also used in [7] to the case of BS analysis. And this paper used it to distinguish and remove the stationary noise hidden in the partial discharge for detecting cables (XLPE cable and metro DC cable) 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 [8].

In fact, the normalized N-sample PD, denoted by \( f(n), (n=1, \ldots, N) \), 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 (\( m = 1, \ldots, M \)), where \( M = \log_2 N \) is first calculated. Then, the wavelet transform coefficients at scale \( j \) are compared with the threshold, defined as follows:

\[ THR^k_j = \sigma^j \cdot F_{adj} \]  \hspace{1cm} (1)
Where $\sigma_j^k$ is the standard deviation of the wavelet transform coefficients at iteration $k$ and scale $j$, to be calculated as follow [9]:

$$\sigma_j^k = \sqrt{\frac{1}{N+1} \sum_{i=0}^{N} (A_{j,k}^i)^2}$$  \hspace{1cm} (2)

Where $A_{j,k}^i$ is the coefficient at iteration $k$ and scale $j$. $F_{adj}$ is the coefficient at iteration $k$ and scale $j$. C-WT$h(k)$ and R-WT$h(k)$, respectively. The symbols and $R$ characterize the WT coefficients during the $k$th iteration used for the reconstruction of the $C_{k,L}(n)$ and $f_{R,L}(n)$ parts. This is achieved by applying MRR(m-scales) to C-WT$h(k)$ and R-WT$h(k)$, respectively. The iterative procedure stops after the following Stopping Criterion-STC is satisfied:

$$STC = |E[R_{k,L}^N(\lambda)] - E[R_{k,L}^N(\lambda)]| < \varepsilon$$  \hspace{1cm} (3)

Where $E\{\}$ denotes the expected value and $0 < \varepsilon \leq 1$, corresponding to the desired accuracy in the refinement procedure. The effects of $\varepsilon$ on the efficiency of noise suppression are discussed in details in section 3.2.

After the last iteration $L$, the coherent part of the signal (PD signal) is obtained by superimposing the coherent parts derived at each iteration $k$ ($k=1,\ldots,L$) as:

$$f_C(n) = \sum_{k=1}^{L} f_{C,k}(n)$$  \hspace{1cm} (4)

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

$$f_R(n) = X_{R,L}(n)$$  \hspace{1cm} (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.

3 Results and Discussion

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

3.1 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.

$$f(t) = A(e^{-\frac{t}{\tau}} - e^{-2\frac{t}{\tau}}) \sin(f_c \times 2\pi t)$$  \hspace{1cm} (6)

Where $f_c$ is the oscillated frequency, $A$ is the amplitude of PD signal, attenuation factor $\tau$ 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:

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

Where $A_i$ and $f_i$ are the amplitude and frequency of the narrow band periodic signals, respectively. From Fig. 2(a), we can see the original simulated signal, and Fig.2 (b) is the mixed signal with narrow band and white noise signals.

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

In Table 1, the comparison result between the WTST-NST and db2 wavelet, according to the identification functions, defined as follows:

\[ d_1(s,s') = \frac{1}{R} \sum_{n=1}^{L} |s(n) - s'(n)| \]  

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

\[ d_\infty(s,s') = \max_{1 \leq n \leq L} |s(n) - s'(n)| \]  

Where \( s \) and \( s' \) are the original and processed signals with length \( L \). \( d_1, d_2, \) and \( d_\infty \) 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 \( d_1, d_2, \) and \( d_\infty \).

Table 1 Comparison of the result of ST-NST and Wavelet

<table>
<thead>
<tr>
<th></th>
<th>( d_1 ) (%)</th>
<th>( d_2 ) (%)</th>
<th>( d_\infty ) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ST-NST</td>
<td>1.15</td>
<td>6.6</td>
<td>10.18</td>
</tr>
<tr>
<td>Db2 Wavelet</td>
<td>4.67</td>
<td>10.08</td>
<td>20.58</td>
</tr>
</tbody>
</table>

From Fig.3 and Table 1, it can be seen that the WTST-NST filter can extract the PD signal from the noises and compare with db2 wavelet, the results of the average error \( d_1 \), mean square error \( d_2 \) and max error \( d_\infty \) are smaller than wavelet. The performance of the WTST-NST filter, in separating the non-stationary parts of acquired signal from PD detecting on-site, was verified.

3.2 Experimental Analysis

Fig.4 shows the experimental on-site of partial discharge detecting of power cable. And experimental results are shown in Figs 5-7.

Fig.4 On-site Experimental of partial discharge of power cable

Fig.5 (a) shows an example of surface scratching experimental in protective covering of power XLPE cables. And Fig.5 (-i) and (-ii) are the extracted partial discharge and contained noises, respectively, using the WTST-NST filter, with different \( \varepsilon \) (\( \varepsilon =0.1, \varepsilon =0.001 \)). Comparing with the original part of Fig. 5(a), it is clear that, in Fig. 5(-i), all structural components of the PD signals are easily recognized, while their various morphologies and locations are clearly distinguished. Furthermore, the stationary part of Fig. 5(a), noise, is faithfully reproduced in Fig.5(-ii), retaining its original amplitude level and structure.

Another example of partial discharges, recorded from power cable with protrusion in high voltage conductor, is illustrated in Fig. 6 (a). The results of application of the WTST-NST filter on these partial discharges are shown in Fig.6 (b-i) and (c-i), with different \( \varepsilon \) (\( \varepsilon =0.1, \varepsilon =0.001 \)), respectively. And Fig.6 (-ii) are the remained noise, as in Fig. 5. From these figures it is clear that the WTST-NST filter performs well in separating accurately stationary noise from partial discharge.
From the above two failure models, processed in Fig. 5 and Fig. 6, we can extract partial discharge perfectly from background noises when $\varepsilon = 0.1$, in order to improve the precision of WTST-NST, according to the judgment criterion function (3), $\varepsilon = 0.001$ is selected in this paper.

In Fig. 7(a), the signal was obtained from a metro cable by HFCT surrounded the grounding line in a subway station, (running voltage is DC 2000V), with sampling rate 20MHz, sampling length 50ms. Because of the complex conditions on-site, current mutation will happen in short time which can introduce several interrupts, continuous periodic signal, such as power frequency component, system carrier wave, and stationary random noises, et al. Partial discharge signal may hidden among them in Fig. 7(a). From the results of WTST-NST in Fig. 7 (b-i), we can see the PD signals can be distinguished perfectly.

Besides, Fig. 8(a) shows us that the original signal acquired from metro cable, containing continuous periodic noises, and the frequency range is about 1~10MHz. Comparing with Fig. 8(a), the frequency analysis in Fig. 8 (b), has no periodic signals, confirming the efficiency performance of the WTST-NST filter.

4 Conclusion

Through the study of the wavelet-based stationary-non-stationary (WTST-NST) filter for suppressing noise and extracting partial discharge signals, the following conclusions can be drawn:

The PD signals discrimination algorithm based on the multi-resolution analysis with hard threshold-based method, is built for partial discharge analysis. Quantitative and qualitative analysis of the experimental results obtained from the analysis of XLPE power cables and DC 2000V metro cables, in which we imitate the fault deflection of protrusion on high voltage conductor and scratching experiment. From the results, WTST-NST filter can not only suppress the continuous periodic noise, but also stationary random noise produced by detecting apparatus with higher accuracy and less computation time. It has been used in the PD on-line monitoring research system successfully.

The performance of WTST-NST filter is affected strongly by the quality factor $\text{Fadj}$. From the aforementioned analysis and from experiments in all cases of fault deflection, the choice of $\text{Fadj} = 3$, proved to be the optimal value for the best performance of the WTST-NST filter in partial discharge detecting system.

References:


