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Application of spectrum estimation and wavelet packet transform in suppression of partial discharge's discrete spectral interference

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Abstract: Based on the modern spectrum estimation theory and wavelet packet analysis (WPA), a new method is proposed for suppressing discrete spectral interference (DSI) within partial discharge (PD) signal. Firstly, the frequencies of DSI are determined based on the FFT of measured signal. Then, a model of DSI could be assumed and its parameters, such as amplitude and phase can be calculated by using the maximum likelihood estimation (MLE) theory. The measured signal and assumed DSI are de-composed by utilizing WPA. On the last level of decomposed tree, the node coefficient of measured signal, which contained the dominant frequency of DSI, minus that of DSI, then the coefficient difference is substituted for the coefficient of the right node of signal, while other nodes coefficient of signal is still invariability. Finally, the decomposed node tree of signal is renewed and by re-constructing the renewed decomposed node tree, the PD signal without narrow bandwidth noise is obtained. Simulation and experiment results are shown the validity of this proposed method.

Key-words: spectrum estimation theory, wavelet packets transform, partial discharge, discrete spectral interference

1 Introduction

It is now well recognized and accepted that partial discharge (PD) on-line monitoring is fundamental for insulation system in High Voltage (HV) power apparatus. Therefore, it is important to obtain the efficient PD signal. However, there are many kinds of internal noise and external interference during the HV apparatus operation, among which one of the most serious is discrete spectral interference (DSI). Normally, they are caused by radio interference or carrier wave jamming in power system, and they are periodic or repetitive signal, which has a narrow-band spectrum centered around dominant frequencies [1]. These disturbances greatly degrade the sensitivity of detecting PD. Thus the suppression of any noise as well as interference is a key problem in PD signal analysis.

In order to solve this problem, considerable effort has been expended to develop suitable de-noising techniques or other measuring methods those maybe employed for the purpose of DSI suppressing with the aim to make PD measurements sensitive enough [2-5]. In 1988, Feser et al. [2] have suggested an FFT-based approach to eliminate DSI. However, it is computationally intensive. In 1993, a digital filtering method based on a cascaded 2nd order IIR lattice notch filter had been proposed by Nagesh and Gururaj [3]. Compared with other filters, the proposed method gave the best performance, low distortion to a sequence of PD pulses, good stability and fast filtering time.

Wavelet transform is a new and good fool for analyzing non-stability signal. Its application in detecting PD signal is developed prosperously now [4-5].

In this paper, a new method combined wavelet packet transform with modern spectrum estimation theory is proposed in order to suppress DSI. Simulation and experimental results have validated the proposed scheme correctness and efficiency.

2 Principles and Algorithm

Because PD signal is an instantaneous pulse, while DSI is a periodic or repetitive signal, the spectral characteristics of the PD and DSI signals are very different: the former has a broad spectrum, while the latter has a narrow-band spectrum centered around dominant frequencies and has very huge energy compared to PD. This difference could be used to design a new algorithm for suppressing DSI.

2.1 Principle of wavelet packet analysis

Compared with wavelet analysis, wavelet packet analysis (WPA) can supply a more detailed analytic method. The key idea underlying the WPA strategy is that a given signal can be decomposed into low frequency content and high frequency content, the former being known as the signal's "approximations" and the latter known as its "details". Furthermore, both of the contents could still be decomposed into low and high frequency contents respectively. Therefore, WPA can decompose PD signal more detailed than wavelet analysis. The sketch figure of decomposed course of a signal is shown in Fig. 1, which the 'l' means 'low frequency content' and the 'h' means 'high frequency content'.

x(t)							
l				*h*			
ll		*lh*		*hl*		*hh*	
lll	*llh*	*lhl*	*lhh*	*hll*	*hlh*	*hhl*	*hhh*

Fig. 1 three level decompose of WPA in frequency domain

The decomposed algorithm of WPA is described as:

$$x_{2m}^{j}(n)=\sum_{k}h(k-2n)x_{m}^{j-1}(k) \quad (1)$$

$$x_{2m+1}^{j}(n)=\sum_{k}g(k-2n)x_{k}^{j-1}(k) \quad (2)$$

and the reconstructed algorithm of WPA is:

$$x_{m}^{j-1}(n)=\sum_{k}\overline{h}(n-2k)x_{2m}^{j}(k)+\sum_{k}\overline{g}(n-2k)x_{2m+1}^{j}(k) \quad (3)$$

where xmj(n) means the mth decomposed sequence of the sequence x(n) on decomposed j level of WPA; h and g are decomposed coefficients of WPA function; $\overline{h}$ and $\overline{g}$ are the pairing arithmetic operators of h and g respectively.

It should also be pointed out that different wavelet packet function has different decomposed coefficient h and g, it is therefore necessary to select appropriate wavelet packet function to analyze different signal when we used WPA.

2.2 Maximum likelihood estimation theory

For analyzing a finial serial measured data, based on the principle of signal processing, we can at first assume a mathematical model, and then those parameters of the mathematical model could be worked out by using Maximum Likelihood Estimation (MLE). MLE is one sort of modern spectral estimation theory. For example, if a mathematical model is assumed as a sine wave, and supposing frequency of the sine wave is known, then its amplitude and original phase can be worked out by MLE algorithm.

In this paper, the parameters of a DSI model are calculated by MLE and the detailed processes is described as followed:

For a given discrete signal x(n), its power spectral density can be gained by Fast Fourier Transform (FFT). Because it is generally considered that the dominant frequency of a signal are corresponding to the maximal value of power spectral density, the frequency of the signal can be calculated. When the signal model is assumed as s(t)=A1sin(2 f1t+ 1), utilizing the calculated frequency f1, its amplitude and original phase can be worked out by MLE:

$$\hat{A}_1 = \left| \frac{1}{N} \sum_{n=0}^{N-1} x[n] \exp(-j2\pi \hat{f}_1 nt) \right| \tag{4}$$

$$\hat{\phi}_1 = \arctan\left[\frac{\mathrm{Im}(\sum_{n=0}^{N-1} x[n]\exp(-j2\pi \hat{f}_1 nt))}{\mathrm{Re}(\sum_{n=0}^{N-1} x[n]\exp(-j2\pi \hat{f}_1 nt))} \right] \tag{5}$$

where N is the number of sampling.

Furthermore, it should also be taken into account that there are multi-frequency values of DSI within signal. For the equation (6):

$$S(A_c, F) = (X - EA_c)^H (X - EA_c) \tag{6}$$

where: $E = [e_1\ e_2 \cdots e_p]$, $A_c = [A_{c1}\ A_{c2} \cdots A_{cp}]^T$,

$A_{ci} = A_i \exp(j\phi_i)$, $F = [f_1\ f_2 \cdots f_p]^T$,

$e_i = [1\ \exp(j2\pi f_i)\ \exp(j4\pi f_i)\ \cdots\ \exp[(j2\pi f_i(N-1)]]^T$,

and X is the matrix of sampling value, Ac means amplitude, f means the frequency of DSI, i and p are integers.

The multi-frequency of DSI can also be gained by FFT, so the matrix E and F of equation (6) are known matrixes. Therefore, equation (6) is a standard Least Square Error (LSE) form and it can be calculated by LSE algorithm. Consequently, the amplitude of every DSI signal is calculated by equation (7):

$$\hat{A}_c = (E^H E)^{-1} E^H X \tag{7}$$

Furthermore the phase of every DSI signal can also be calculated by equation (5).

2.3 the algorithm of suppression DSI

Reference [6] proposed a useful algorithm to suppress DSI based on entropy threshold algorithm. The basic idea is: for a signal x(t), under a certain level of WPA, if the Shannon entropy of a node is evidently bigger than that of others, then it is considered that the energy of this node is the same as that of DSI. So via setting the node’s coefficient to zero, and then reconstructing the signal, a PD signal without DSI could be obtained.

However, simulation research reveals that this method would lose some PD pulses if directly setting a certain node coefficient to zero. The reason of this phenomenon is maybe that when PD pulse has the same frequency as that of DSI, setting the node coefficient zero will throw off PD information as well as DSI information.

In this paper, based on above analysis and research, a new algorithm is proposed to suppress DSI without losing PD information. The detailed procedure is given as following:

1) The measured signal x(t) is calculated by FFT at first, then according to the power spectral density, the frequency of DSI is determined corresponding to the maximum energy;
2) Given an assumed mathematical model of DSI. In this paper, all of the assumed models are sine waves or their superposition linearly. It should be noted that even the real DSI model in measured signal is not assumed model, the effect of suppressing DSI is still good, and this has been validated by simulation test;
3) Utilizing modern spectral estimation theory, the amplitude and original phase of assuming model of DSI can be obtained, so all the parameters of model can be determined;
4) Decomposed measured signal and assumed model of DSI by utilizing WPA respectively. On the last level of wavelet packet decomposed tree, the node contained the dominant frequency of DSI should be on the 2level-1+Nth node, where N=fix(f/(fs/2level+1)), fix(*) means integer, fs is the sampling frequency of signal, level means the level of wavelet packet decomposed.
5) On the last level of decomposed tree, the right node coefficient of measured signal minus that of DSI, then the coefficient difference is substituted for the coefficient of the right node of signal, while other nodes coefficient of signal is still invariability;
6) After doing all the procedures to every DSI, a new wavelet packet decomposed tree can be obtained, and then the perfect PD signal without DSI is gained by reconstructing the renewed

decomposed tree.

3 Simulation test and discussion

For studying the performance of proposed algorithm, simulation tests have been done in this paper. For showing the merit of the proposed way, the results of the method proposed in this paper, i.e. 'difference value method' and the method propose in [6], i.e. 'zero setting method', are presented in same figures.

3.1 when the frequency of PD and DSI are same

Supposed there is a pure PD signal, which contains four normal mathematical model of PD pulse, i.e. single/double damped exponential function and single/double damped exponential and oscillatory function [7]. Its parameters are given in Tab. 1, and its waveforms are shown in Fig. 2(a). The simulation sampling frequency is 1GHz, and the number of sampling is 60000. Symlet wavelet packet is used to decompose the signal, and the decomposed level is 5.

Tab. 1 simulation parameters of PD pulses

Model	Damped	Frequency	Amplitude
1	0.5	None	1
2	0.02	None	5
3	0.5	10M	1
4	2	1M	4

The DSI, which is joined into the simulation signal, is designed as $S=A\sin(2\pi ft+\varphi)$, where A=5mV, f is setting to 1MHz (the same frequency as that of the 4th PD pulse), $\varphi=0^{o}$. The amplitude of added white noise is 0.3mV, and the whole signal with noise and DSI is shown in Fig. 2 (b). For narrating simply, In the following figures of all simulation tests, Fig. (a) means the pure PD signal; and Fig. (b) means the signal confused with noise and DSI; and Fig. (c) means the suppression result of 'zero setting method'; and Fig. (d) means the suppression result of 'difference value method'.

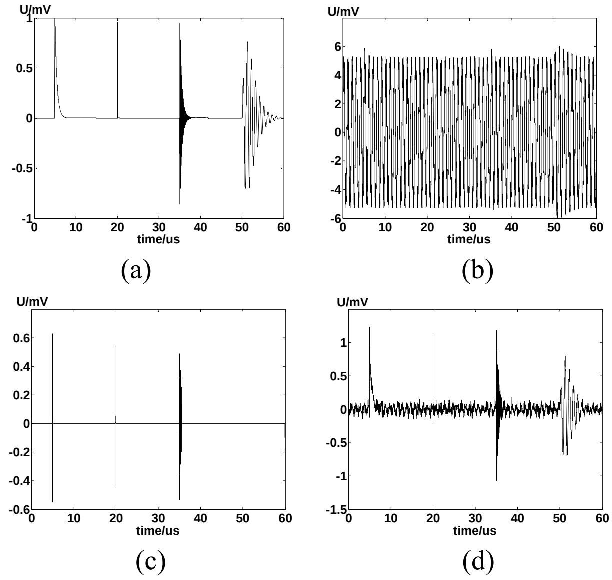

Fig. 2 the same frequency of PD and DSI

From Fig. 2(d), it can be seen that the effect of suppression DSI and noise is perfect even though the PD signal have been submerged under noise and DSI, and when the DSI has the same frequency with some PD pulse, the proposed method in this paper can pick out the PD pulse correctly. But it can be seen from the Fig. 1(c) that the extracted result of 'zero setting method' is not good and the original 4th PD pulse is wiped off. The result is accordant with analysis in section 2.3.

3.2 suppression results of different model of DSI

In order to illuminate that the different model of DSI does not affect the performance of proposed algorithm, different mathematical model of DSI are simulated and the results are shown in this section. Model 1 represents the superposition of two sine waves, i.e. $S_1(t)=A_1\sin(2\pi f_1t)+A_2\sin(2\pi f_2t+\varphi)$; model 2 represents amplitude modulation wave, i.e. $S_2(t)=A_1\sin(2\pi f_1t)\sin(2\pi f_2t)$; model 3 represents phase modulation wave, i.e. $S_3(t)=A_1\sin(2\pi f_1t+\sin(2\pi f_2t))$.

In the following three simulation tests, the assumed DSI model is all designed as model 1. When the actual DSI, which is joined into the simulation signal, is designed as model 1, the suppression result is shown in Fig. 3(d). From this figure we can see that the method could restrain the disturbance. Furthermore, the amplitude and polarity of extracted PD pulse are accordance with the pure

PD signal.

When the actual DSI is model 2, while the assumed model is still model 1, the suppression result is shown in Fig. 4(d). When the actual DSI model is model 3, the suppression result is shown in Fig. 5(d).

It can be seen from these figures that when assumed DSI model is not same as actual DSI, the proposed algorithm still keep good suppression performance. Furthermore, compared with ‘zero setting method’, the proposed method can preserve the characteristics of PD pulse such as amplitude and polarity of PD.

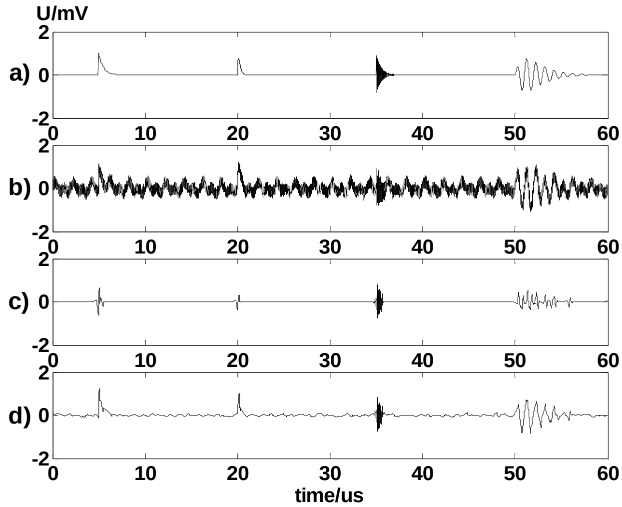

Fig. 3 actual DSI model is model 1

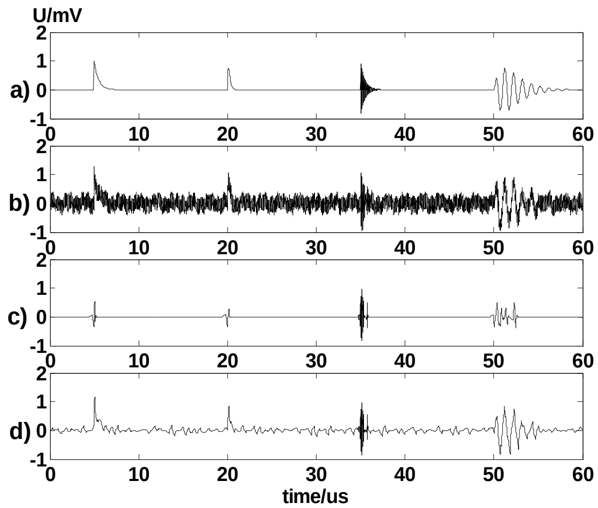

Fig. 4 actual DSI model is model 2

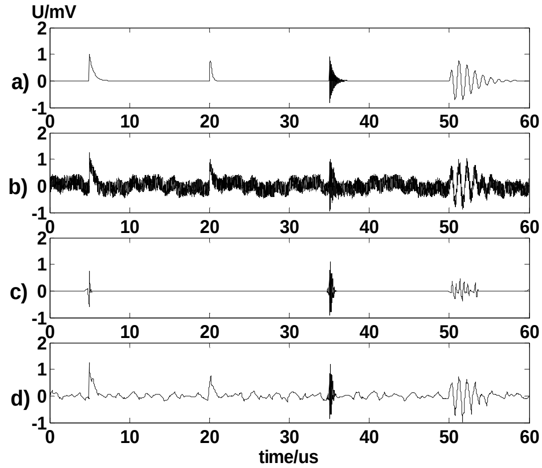

Fig. 5 actual DSI model is model 3

4 Experimental result and discussion

A partial discharge experiment is designed in a gas insulation switchgear (GIS) component, which has a metallic spine on the surface of high voltage conductor. The experimental signal is collected through an external ultra-high frequency (UHF) sensor, whose frequency range is from 0.5GHz to 1.5GHz. The sampling frequency is 10GHz. The measured signal is shown in Fig. 6, and its power spectral density is shown in Fig. 7.

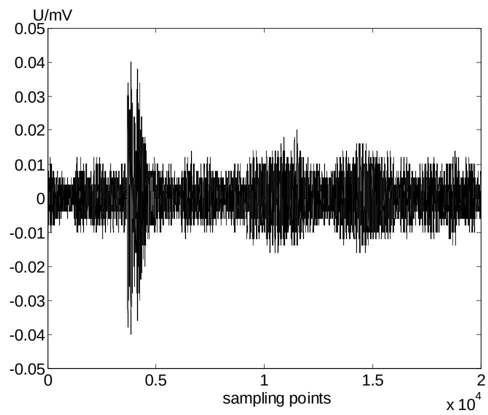

Fig. 6 measured PD signal in GIS

Because the energy of DSI is greatly larger than that of PD, we considered that the frequencies corresponding to the hugest three energies are possible DSI frequencies, i.e. 750MHz, 880MHz and 950MHz.

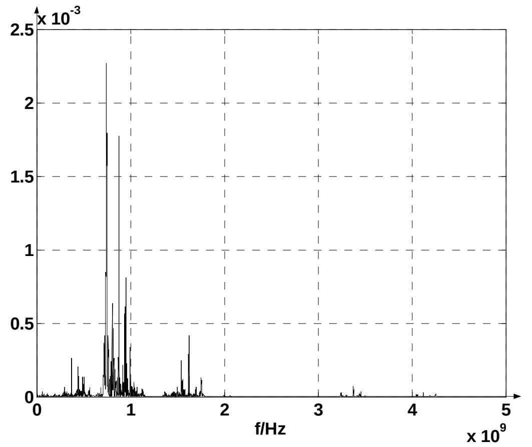

Fig. 7 power spectral density of measured signal

According to the three frequencies and the above-mentioned way, we can obtain the pure PD signal without DSI and noise, which is shown in Fig. 8(d).

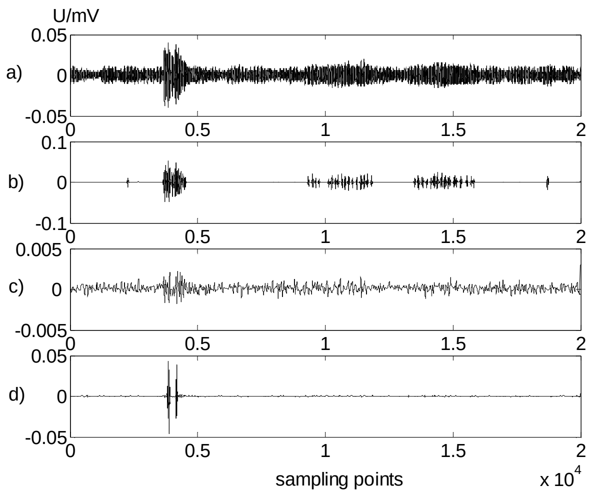

Fig. 8 the suppression result of experimental data

For experimental measured signal, the suppression result of 'zero setting method' is shown in Fig. 8(c). It can be seen that the PD pulses are not distinctly distinguished from disturbances, and the amplitude of PD pulse lose largely. The suppression result of the proposed method is shown in Fig. 8(d), and it can be seen that PD pulses are clearly displayed and no interference existed anymore.

In addition, signal to noise ratio (SNR), correlation coefficient (xy) and mean square error (MSE) are used to quantify the performance of proposed method and 'zero setting method'. These values are shown in Tab. 2.

Tab. 2 compared performance of two methods

Method	SNR	MSE	ρ_{xy}
Zero setting	0.0339	3.3274×10^{-5}	0.0625
Difference value	0.4581	3.1688×10^{-5}	0.2268

It can be seen from Tab. 2, the proposed method in this paper has higher SNR and bigger correlation coefficient than 'zero setting method', while the MSE of the two methods is almost similar.

5 Conclusion

Based on modern spectral estimation theory and WPA, a new method is proposed in this paper to suppress DSI within PD signal. A large number of simulation and experimental results have validated its correction and efficiency. The conclusion of this paper is summarized as follow:

1) Using the proposed method, DSI can be suppressed efficiently and its performance is not affected even under the condition of having same frequency of DSI and PD pulse;
2) As long as determined the frequency of DSI, the assuming model does not influence the suppression effect, i.e. even though unknown the actual DSI, the suppression effect of proposed method is ideal;
3) The proposed method can not only suppress DSI from PD signal, but also reserve the characteristic of PD signal, such as the amplitude and polarity of PD pulse.

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