TELKOMNIKA, Vol. 11, No. 5, May 2013, pp. 2771 ~ 2779
ISSN: 2302-4046

Research on The Mechanical State Parameter Extraction Method of High Voltage Circuit Breakers

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Abstract

High voltage circuit breakers play an important role in the power system. So it is necessary to implement the state detection of breakers in order to ensure stable and reliable running of the grid. The purpose of state detection is to provide reliable basis of maintenance by extracting mechanical state parameters accurately. This paper mainly focuses on the coil current signal feature extraction algorithm. To settle the problem of too much noise mixed with the current signal and signal distortion, the discrete wavelet transform algorithm is used to extract the coil current signal parameters. This paper also designs the FIR filter to extract stroke and speed parameters from travel-time waveform. The experiments show that the difference between the theoretical results and test results processed by the method in this paper is very small and the test results are able to accurately reflect operation states and mechanical features of high voltage circuit breakers.

Keywords: *high voltage circuit breaker, mechanical state parameters, wavelet denoising, FIR filter.*

1. Introduction

High voltage circuit breakers, which are used as insulation and interrupter devices, are critical equipment of power systems. As the links between power generation and electricity consumption, the performance of high voltage circuit breakers affects the reliability of power system a lot. According to the statistics of China in recent decade, the average loss per accident caused by faults of circuit breakers is as high as millions of kilowatt hours, which is thousands of times the price of circuit breakers themselves [1] [2]. Therefore, in order to improve the reliability of circuit breakers, it is necessary to conduct the regular inspection and maintenance before the failures.

As mechanical fault is the main reason of the high voltage circuit breakers, it is of great significance to detect and extract the mechanical state information for the fault diagnosis and state judgment of the high voltage circuit breakers. Mechanical state parameters are obtained through processing the data acquired in the opening/closing process of high voltage circuit breakers [3]. Many mechanical parameters such as the speed of moving contact, closing/opening time, non-synchronism time, can be extracted from recording the time-distance characteristic curve and time curve each switching time. Decreasing of the opening speed will increase the arc burning time, thus speed up the wear rate of contact and reduce the life of the breakers. However, if the opening speed is too high, the movement mechanism will bear too much mechanical stress and shock, resulting in damage to some components or shortening the service life [4]. And serious non-synchronism could lead to non-phase operation of the power lines and circuit breakers, which may cause the insulation damage, malfunction of protection and other negative phenomena. For the reasons mentioned above, circuit breaker mechanical state parameter testing is necessary, and is one of the most testing part in the high voltage circuit breaker state testing.

Due to the harsh electromagnetic environment in the scene, the coil current waveform signal and the time-distance waveform signal contain a lot of high-frequency noises, which make it difficult to extract useful information from the waveform. Taking into account the transient characteristics of the signals of high voltage circuit breakers, different types of data should be processed by corresponding processing method in order to obtain the required characteristics [5] [6]. In this paper, Mallat discrete wavelet transform algorithm is used to deal

Received January 3, 2013; Revised March 20, 2013; Accepted March 28, 2013

with closing/opening coil current waveform, and then the time characteristic parameters can be extracted. And the speed and travel are obtained from the time –distance waveform by the use of FIR filter based on the windowed method. The processing methods mentioned in this paper have been proved to be effective in the mechanical state parameter extraction of high voltage circuit breakers.

2. Mallat Discrete Wavelet Algorithm

2.1. Wavelet Analysis

Wavelet transform is based on the basis function and incorporates the characteristic of Fourier transform and time shift window function of short time Fourier transform. And the basis function of wavelet transform is oscillating and decaying. The name of wavelet is because of its limited definition domain. Wavelet analysis method with localized time-frequency has fixed window size, however, the size of time window and frequency window are changeable. Wavelet transform observes signals in different scales (resolution). By the method, signal is decomposed into different frequency bands, and so the whole picture and details of the signal can be obvious. Another advantage of the wavelet transform is the ability of multi-resolution, which means that in the low frequency part, the transform has high frequency resolution and low time resolution, however, in the high frequency part, the transform has low frequency resolution and high time resolution.

For a real-valued function $\psi(x)$ and its spectrum $\hat{\psi}(w)$ meets the following permitted conditions:

$$C_{\psi} = \int_{-\infty}^{+\infty} \frac{|\hat{\psi}(w)|^2}{|w|} dw < \infty \tag{1}$$

$\psi(x)$ is a basic wavelet or wavelet mother function.

$$\psi_{a,b}(x) = \frac{1}{\sqrt{a}} \psi(\frac{x-b}{a}) \tag{2}$$

Where a,b is real numbers, when a>0, formula（2）is named the continuous wavelet basis function generated by the mother function $\psi(x)$ and depends on the number a, b. a is the stretching factor and b is the translation factor. Set $f(x) \in L^2(-\infty,\infty)$ and define the continuous wavelet transform of $\psi_{a,b}(x)$ is:

$$Wf(a,b) = < f, \psi_{a,b} > = \frac{1}{\sqrt{a}} \int_{-\infty}^{+\infty} f(x) \overline{\psi(\frac{x-b}{a})} dx \tag{3}$$

And the corresponding inverse transform is:

$$f(x) = \frac{1}{C_{\psi}} \int_{0}^{+\infty} \int_{-\infty}^{+\infty} Wf(a,b) \psi_{a,b}(x) db \frac{da}{a^2} \tag{4}$$

The essence of wavelet transform is to use the basic function $\psi(\frac{x-b}{a})$ to decompose function $f(x)$ into sub-signals of different frequency bands. In practical use, especially realized on computer, continuous wavelet must be discretized and the distretization is for continuous scaling function a and continuous translation parameter b, rather for time variable t. If set $a = 2^{-j}, b = k2^{-j}, j,k \in Z$, for any function $f(t) \in L^2(-\infty,+\infty)$, define the discrete wavelet transform as follows:

$$WT_f(j,k) = \int_{-\infty}^{+\infty} f(t) \overline{\Psi_{j,k}(t)} dt, j,k \in Z \tag{5}$$

2.2. Mallat Discrete Wavelet Decomposition and Reconstruction Algorithm

The essence of Mallat discrete wavelet algorithm is that it is not necessary to know the specific structure of scale function and wavelet function, and the decomposition and reconstruction of signal can be realized just through the coefficient. By the algorithm, the decomposition length of signal is halved and therefore, it is a rapid decomposition and reconstruction algorithm.

Mallat discrete wavelet decomposition algorithm is [2]:

$$C_{j,k} = \sum_{m \in Z} h_{m-2k} C_{j-1,m} \tag{6}$$

$$d_{j,k} = \sum_{m \in Z} g_{m-2k} \eta_{j-1,m} \tag{7}$$

Where m=0, 1, 2, …, k-1, K is the number of signal sequences, j is the layer number of wavelet decomposition. When j=0, $C_{0,k}$ represents the samples of the original signal. $C_{j,k}$ is the low frequency component after decomposition, and $d_{j,k}$ is high frequency component after decomposition. h_{m-2k} is scale factor of multi-resolution analysis, that is, the coefficient of low-pass filter. Accordingly , g_{m-2k} is the wavelet coefficient of multi-resolution analysis, that is, the coefficient of high-pass filter.

The wavelet decomposition algorithm of Mallat algorithm is:

$$C_{j-1,k} = \sum_{m \in Z} h_{m-2k} C_{j,m} + \sum_{m \in Z} g_{m-2k} d_{j-1,m} \tag{8}$$

Reconstruction is the inverse process of decomposition, and the decomposition and reconstruction algorithm is shown in Figure 1 and Figure 2.

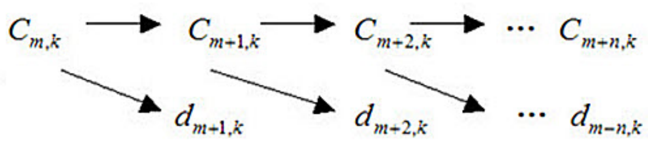

Figure 1. Mallat wavelet decomposition algorithm

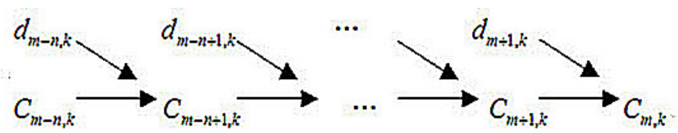

Figure 2. Mallat wavelet reconstruction algorithm

2.3. Wavelet Denoising

In the power system, the coil current signals of high voltage circuit breakers collected in the scene are mixed with high frequency noise inevitably. After the original signals been denoised , useful features can be extracted from the original signal. The noise will be removed from the coil current signal in the following steps:

Use the wavelet decomposition to process the signal mixed with noise, choose the appropriate wavelet and wavelet decomposition level j, and then decompose the signal into layer j. After the decomposition, corresponding wavelet decomposition coefficients are obtained.

Process the wavelet decomposition coefficients with threshold, there are two kinds of threshold processing [7]:

soft threshold method

$$d_{j,k}=\begin{cases} d_{j,k} & |d_{j,k}|\geq\lambda \\ 0 & |d_{j,k}|\leq\lambda \end{cases} \quad (9)$$

hard threshold method

$$d_{j,k}=\begin{cases} \operatorname{sgn}(d_{j,k})(|d_{j,k}|-\lambda) & |d_{j,k}|\geq\lambda \\ 0 & |d_{j,k}|\leq\lambda \end{cases} \quad (10)$$

Inverse wavelet transform. Reconstruct the wavelet coefficients which have been processed by the threshold with wavelet reconstruction algorithm. And then the estimate of the original signal can be obtained.

3. Design of FIR Filter

3.1. FIR Filter

FIR filter (finite impulse response filter) is often used in the digital signal processing. The system function of FIR filter only has zero point. In addition to origin, there is no pole in the function, and therefore the FIR filter is always stable. If the unit impulse response of the filter is non-causal, the causal unit impulse response can be easily obtained by appropriately shift the sequence. Thus, FIR filter does have the problems of stability and achievability. The other outstanding advantage of the FIR filter is that when a certain symmetric conditions are met, a strictly linear domain will be achieved. Linear phase filter does not change the shape of the input signal, and only cause delay in the time domain. So the linear phase characteristic is of great significance in engineering practice. For example, in domains of data communication, image processing and other applications, there should not be a significant signal distortion in the transmission and processing, thus, linear phase FIR filter have been widely used [10] [11].

3.2. Design of FIR Low-pass Filter by Windowing Method

The most simple way of designing the FIR low-pass filter is the windowing method. The method begins with a ideal necessary frequency response. The following is the design steps [4]:

Offer the frequency response $H_d(e^{jw})$ of required ideal low-pass filter . It is expressed as follows:

$$H_d(e^{jw})=\begin{cases} 1e^{-j\alpha w} & \omega\leq\omega_c \\ 0 & \omega<\omega\leq\pi \end{cases} \quad (11)$$

where ω_c is cut-off frequency, and α is sampling delay.

To obtain the unit impulse response of desired filter by inverse Fourier transform.

$$h_d(n)=\frac{1}{2\pi}\int_{-\pi}^{\pi}H_d(e^{j\omega})e^{j\omega n}d\omega=\frac{1}{2\pi}\int_{-\omega_c}^{\omega_c}e^{j\omega(n-\alpha)}d\omega=\frac{\sin[\omega_c(n-\alpha)]}{\pi(n-\alpha)} \quad (12)$$

In order to get the causal and linear phase FIR filter $h(n)$ with length N, the conditions $\alpha=\frac{N-1}{2}$ and $h(n)=\begin{cases} h_d(n) & 0\leq n\leq N-1 \\ 0 & \end{cases}$ must be full filled.

Determine the window function W(n) and window length N according to the performance indicators. The windows used commonly includes rectangle window, hanging window, hamming window, Kaiser window and so on. Table 1 shows the windows mentioned above.

Table 1 Commonly used windows

Window function	Window Spectrum: Sidelobe Peak (dB)	Window Spectrum: Main Lobe Width ($\times 2\pi / N$)	After Windowing: Transition Bandwidth ($\times 2\pi / N$)	After Windowing: Minimum Attenuation Of Stopband (dB)
Rectangle Window	-13	2	0.9	-21
Hanning Window	-31	4	3.1	-44
Hamming Window	-41	4	3.3	-53
Kaiser Winwow	-57		5	-80

Minimum stopband attenuation is only determined by the window-shaped, and not affected by N. However the transition bandwidth decreases with the increasing of N.

Obtain the unit impulse response of actual filter, the coefficient vector of FIR filter is h(n).

$$h(n) = h_d(n).W(n) \tag{13}$$

Test the performance of the designed filter.

For the reason that most of the inferences in the scene are high frequency noises, the paper proposed the following low-pass filter design indicators: passband cutoff frequency ωp=0.1π, stopband cutoff frequency ωs=0.25π, the actual passband ripple Rp=0.10dB, minimum stopband attenuation As=40dB. Compared with other windows, Hanning window, Hamming window and Kaiser window can provide minimum stopband attenuation greater than 40dB. However, the sidelobe peak of Hanning is relatively smaller, while the main lobe width is the same as Hamming window. So the Hanning window is able to make the filter order much more less. The window function and magnitude function of Hanning are shown as equation (14) and equation (15):

$$w(n) = [0.5 - 0.5\cos(\frac{2\pi n}{N-1})R_N(n) \tag{14}$$

$$W(\omega) = [0.5W_R - 0.25[W_R(\omega - \frac{2\pi N}{N-1}) + W_R(\omega + \frac{2\pi N}{N-1})] \tag{15}$$

After the window have been chosen, the low-pass filter based on Hanning window can be designed as the steps introduced above.

4. Experiment Result and Analysis

In the experiment, Hall current sensor is used to test the opening/closing coil current and for the testing of travel-time signal, a resistance scale is fixed with the rob of actuator, and the output of the resistance scale indicates the information of the travel and speed. The algorithms mentioned in this paper are used to process and extract the feature parameters of LW9-72.5 high voltage circuit break. The data sampling frequency is 10KHz, and operation test voltage is 220DC. Mechanical parameters of the circuit breaker are as follows: closing speed: 5.0 ~ 6.5 m / s, opening speed: 1.0 ~ 2.5m / s, duration: 150 ± 2mm, overtravel: 27.0 ± 3mm. Installation of Hall sensor and resistance scale are shown in Figure 3 and Figure 4.

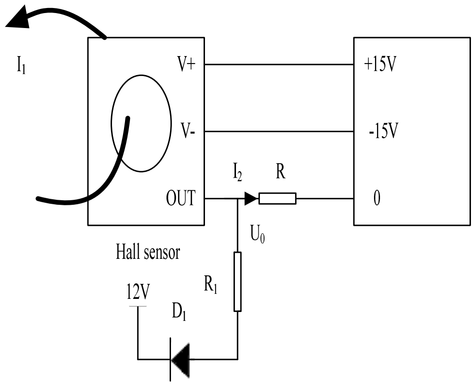

Figure 3. Connection of Hall current sensor

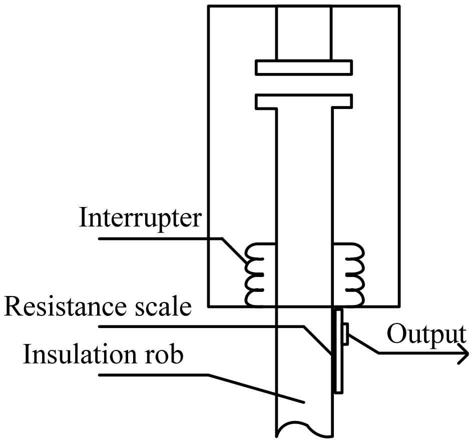

Figure 4. Installation of resistance scale

The coil current signal of high voltage circuit breaker which is mixed with high frequency noises is firstly decomposed by Mallat discrete wavelet algorithm, and then the decomposition coefficients are processed by soft threshold method, and finally the signal is reconstructed by Mallat discrete wavelet algorithm. After processing, it is easily to extract the parameters of different critical time point. The waveform of signal after being denoised is shown in Figure 5.

Design the FIR low-pass filter by windowing the Hanning window method just as the steps mentioned before. The travel-time waveform before and after being processed by the filter is shown in Figure 6 and Figure 7. It can be seen from the figures that the travel-time waveform is very smooth after being processed, and the high frequency interference has been filtered, what's more, the filter also eliminates the waveform distortion. According to the definition of stroke and speed, it is conveniently to calculate the travel and time parameters from the waveform.

After filtering the travel-time waveform , it is possible to extract mechanical features by using the following definition:

Closing speed: average speed of 80% stroke in the closing process.

Opening speed: average speed of 80% stroke in the opening process.

Travel: the total displacement of the moving contact between the start and en position.

Overtravel: displacement from the connection of all polar contacts to stable position of closing process.The comparison between the extracted mechanical feature parameters and the theoretical ones are shown in Table 2 and Table 3.

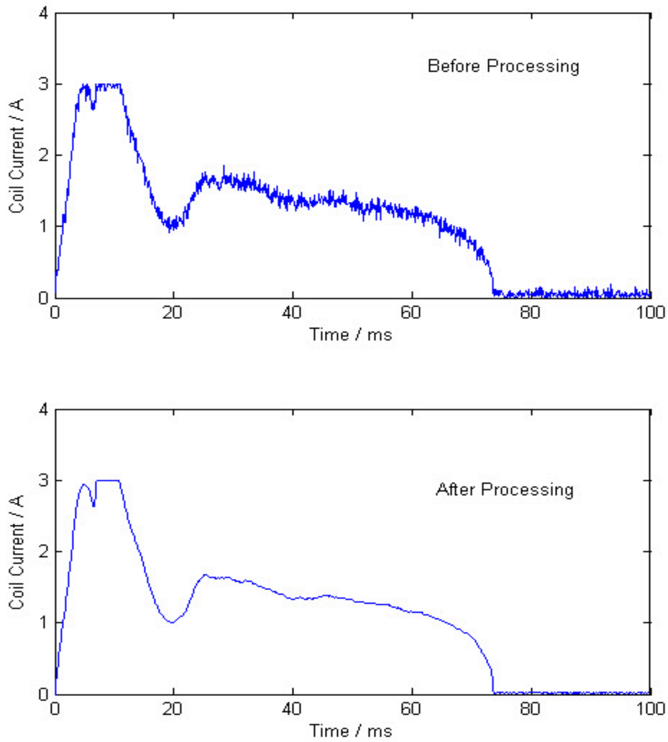

Figure 5. Coil current before and after denoising

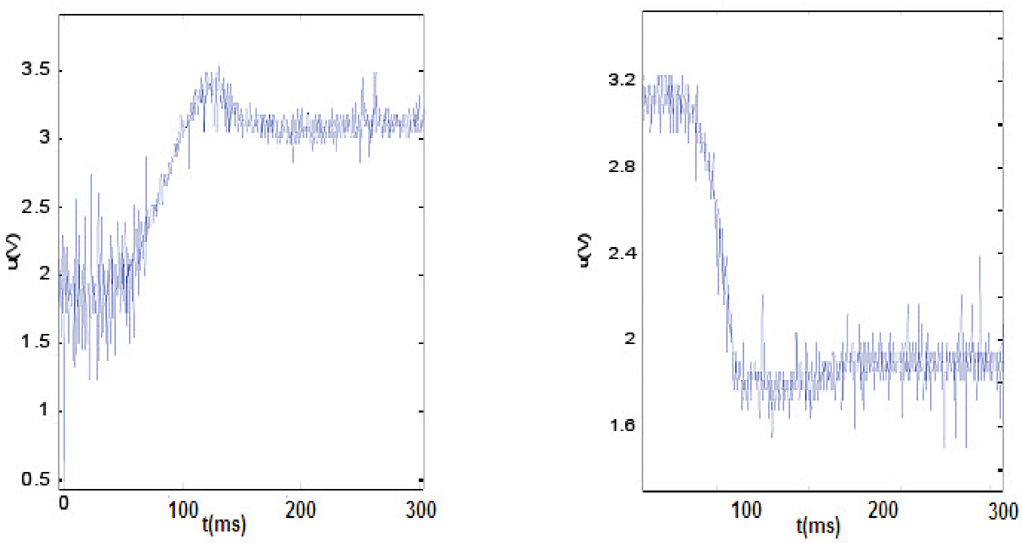

Figure 6. Closing (opening) travel-time waveform before filtering

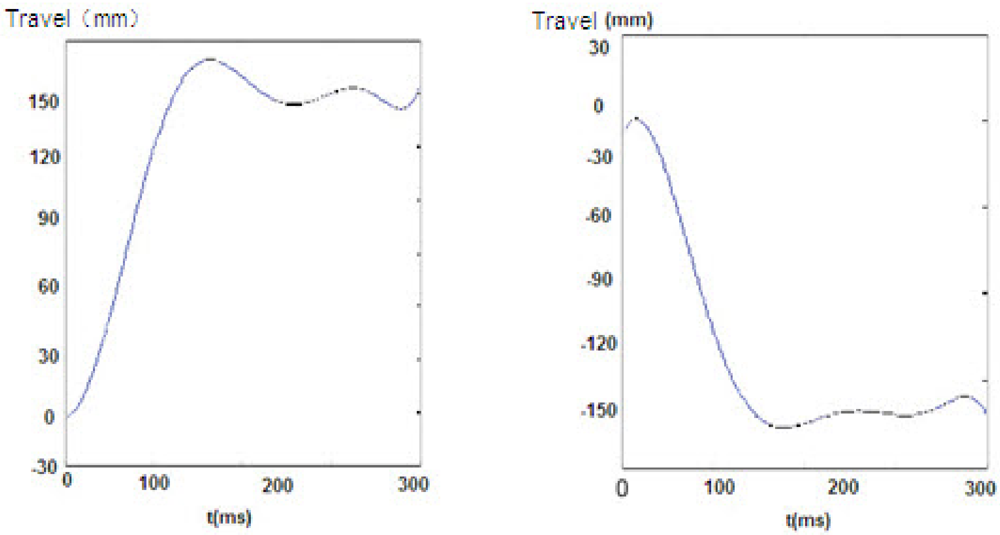

Figure 7. Closing (opening) travel-time waveform after filtering

Table 2. Comparision of mechanical parameters of closing

	Overtravel (mm)	Travel (mm)	Closing speed(m/s)
Standard Value	27.1	150.0	5.20
Test Value	27.2	149.9	5.26
Absolute Error	0.6	-0.1	0.06
Relative Error	0.36%	-0.06%	1.1%

Table 3. Comparision of mechanical parameters of opening

	Overtravel (mm)	Travel (mm)	Closing speed(m/s)
Standard Value	27.1	150.0	1.52
Test Value	27.0	150.0	1.53
Absolute Error	-0.1	0	0.01
Relative Error	-0.36%	0	0.65%

The experiment result shows that in the condition of the exact calibration values of the mechanical parameters, the difference between the testing results processed by the algorithm in this paper and the actual values is very tiny. Thus, the testing results are able to reflect the actual running state of the high voltage circuit breaker.

5. Conclusion

In this paper, the extraction methods of the mechanical characteristics of high voltage circuit breaker are proposed. The Mallat discrete wavelet transform is adopted to eliminate the noises of coil current signal and then this paper designs the FIR low-pass filter based on the windowing method. After being processed by the design of low-pass filter, many mechanical parameters are able to be extracted from the travel-time waveform. The experimental results show that the algorithm in this paper is able to extract the mechanical characteristic parameters of high voltage circuit breakers during the closing and opening process and the results can provide reliable basis for maintenance and judgment of working conditions of high voltage circuit breakers.

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