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Research on Calculation of Mechanical Parameters of Circuit Breaker and Engineering Application in On-line Monitoring System

Mechanical parameters are important contents of on-line monitoring system of high voltage circuit breaker(HVCB). Among mechanical parameters, closing and opening moments are the most important ones, which are difficult to be acquainted in on-line systems. In this paper, a novel method of the judgment of closing and opening moments is proposed by dealing with three phase displacement data based on signal processing technique. According to the features of sampling signals, three steps are employed to capture the characteristic points of displacement curves: Firstly, interferences are eliminated through wavelet de-noising processing session. Secondly, characteristics of three phase displacements are highlighted through wavelet decomposition and reconstruction procedure. Lastly, closing moment, mostly adopted to calculate the mechanical parameters, is obtained through Hilbert transform. This method is used to analyze and process displacement data of VMB5-12 HVCB with rated voltage 10kV. The calculation results of experiments are much more precise.

Keywords: High voltage circuit breaker, Mechanical parameters, On-line monitoring system, Wavelet transform, Hilbert transform.

1. Introduction

The high voltage circuit breaker (HVCB) is one of the most important control and protection equipments in power system. In order to ensure stable and reliable operation of power system, regular inspection and maintenance are required. However, with the rise of the voltage grade and the enlargement of power grid’s scale in recent years, traditional scheduled maintenance cannot meet these high requirements. Therefore, condition-based maintenance gradually replaces the traditional scheduled maintenance. Promoted by the requirement of condition-based maintenance, on-line monitoring system has developed rapidly since it can monitor operation condition and provide credible information for condition-based maintenance [1]-[2].

According to statistical data, vacuum circuit breakers (VCB) with spring operating mechanism play a dominant role in the field of medium voltage [3]. Since operation mechanism faults account for most of the faults of VCB [4], mechanical parameters are always considered to be the important contents of on-line monitoring system because they can reflect working condition of VCB and provide useful information for fault diagnosis [5]-[8]. Traditionally, mechanical parameters are measured offline. Through putting measurement voltage on three-phase circuit, closing and opening moment can be obtained by detecting three-phase current when switching. Based on the obtained closing and opening moment, mechanical parameters can be calculated. Unfortunately, this method cannot be used in on-line system [9].

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Large numbers of researches have been done on closing and opening moment of HVCB which are regarded as the premise and basis of mechanical parameters calculation [10]. Especially, the results of some researches have been applied successfully to engineering application [11]-[13]. In [11], judgment method of catastrophe points in the velocity curve is adopted after collecting displacement data by linear sensors. In [13], the appearance point of closing (or trip) circuit is regarded as closing (or opening) moment. In [12], the authors proposed an analysis method for vibration signals based on the wavelet packets extraction algorithm and short time analysis for three-phase synchronism. All of these methods have been proved to be effective.

However, it is hard to apply these methods to the on-line monitoring system of VCB. There exist three reasons responsible for it: Firstly, with interference in the sampling data, catastrophe points are hard to be detected. Secondly, owing to the mechanical delay of spring operating mechanism, appearance point of closing circuit doesn't coincide with the closing moment. Thirdly, three-phase vibration signals are mixed with each other because of operating mechanism's compact structure and short distance between contacts. Moreover, three extra signal channels are needed which will result in higher cost and more advanced data acquisition unit. Therefore, using existing data from on-line monitoring system, a new mechanical parameters algorithm is designed with high stability and low cost.

In this paper, by analyzing the displacement curve, three characteristic points can be found: starting point, contact point and stopping point. Wavelet transform with its multi-resolution and good time-frequency localization characteristics make it easy to focus into details of the signal [14]-[16], especially in de-noising field. Therefore, it has been widely used to track the catastrophe point of non-stationary signal now [17]-[18]. However, a great deal of noise exists in displacement signals due to the complexity of operation mechanism and influence of the field environment, which makes it difficult to extract characteristic parameters directly. As a consequence, wavelet de-nosing pretreatment to eliminate interferences is needed firstly. Through wavelet transform, catastrophe points can be lightened. Then, characteristic points can be easily obtained through detecting peak points of signal envelope created by Hilbert transform, which can be regarded as the closing point. At last, mechanical parameters can be calculated. This method can seek out characteristic points accurately by signal processing without any extra signal channels. Its simplicity and practicability make it possible to apply to on-line monitoring system. The accuracy and stability of the results have been proved satisfactory through simulation and test.

2. Theory of Wavelet Transform and Hilbert Transform

2.1. Wavelet decomposition and reconstruction

Wavelet transform is a pervasively-used method in signal processing. Continuous wavelet transform is defined as the inner product between wavelet sequence $\psi_{a,b}(t)$ and original signal $f(t)$. $\psi_{a,b}(t)$ is the expansion and translation of basic wavelet $\psi(t)$. a is the scale factor and b is the displacement factor. The formula of continuous wavelet transform is:

$$W_f(a,b)=\langle f,\psi_{a,b}(t)\rangle=|a|^{-\frac{1}{2}}\int_R f(t)\overline{\psi\left(\frac{t-b}{a}\right)}dt \tag{1}$$

Discretization of continuous wavelet is necessary in engineering application. That is to say, while $a = a_0^j$, $b = ka_0^j b_0$, $n, k \in Z$. Discrete wavelet function is:

$$\psi_{j,k}(t) = a_0^{-\frac{j}{2}} \psi\left(a_0^{-j} t - kb_0\right) \tag{2}$$

Then discrete wavelet transform is obtained as the following:

$$WT_f(j,k) = \int_{-\infty}^{+\infty} f(t) \overline{\psi_{j,k}(t)} dt \tag{3}$$

Wavelet transform can change the amplification of the observed signal by changing the parameter j . This is the multi-resolution characteristic that can be realized through Mallat algorithm. Orthogonal wavelet basis is used to decompose signal into components in various scales. As Fig 1 shows, discrete signal $X(n)$ is decomposed into low frequency component coefficients $cAj(k)$ and high frequency component coefficients $cDj(k)$ in scale j [19].

Wavelet reconstruction is the inverse process of wavelet decomposition. Low frequency components $Aj(k)$ and high frequency components $Dj(k)$ can be got through single branch reconstruction of $cAj(k)$ and $cDj(k)$.

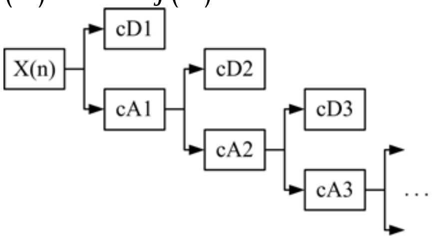


Fig. 1, Diagram of Mallat multi-resolution decomposition

2.2. Wavelet threshold de-noising

Generally, wavelet coefficients of signal are bigger than that of noise after wavelet decomposition. Therefore, with reasonable threshold value, wavelet transform can eliminate noise and preserve useful part of signal. The de-noising process is as the following:

- Firstly, wavelet type is selected and the number of decomposition layers is determined. Then signal is decomposed and high frequency coefficients are generated.
- Secondly, soft threshold, hard threshold or threshold functions of other kinds are chosen to process high frequency coefficients.
- Lastly, signal is reconstructed according to high frequency coefficients remained after threshold quantization.

The choice and quantization of threshold are the cores of de-noising processing. There are four threshold selection rules: (1) Stain unbiased risk estimation. (2) Fixed threshold $\sqrt{2\ln(N)}$, in which N is the length of discrete sampling data. (3) Heuristic threshold choice. (4) Threshold selection of minimax theory. In these rules, heuristic threshold choice is the best choice because it combines the advantages of the aforementioned two threshold selection rules.

Threshold quantization involves two ways: soft threshold and hard threshold. The mathematical expression is shown in equation (4) as follows:

$$\text{soft threshold} \quad W_{\delta}=\begin{cases}\operatorname{sgn}(W)(|W|-\delta), & |W|\geq\delta \\ 0, & |W|<\delta\end{cases} \tag{4}$$

$$\text{hard threshold} \quad W_{\delta}=\begin{cases}W, & |W|\geq\delta \\ 0, & |W|<\delta\end{cases}$$

δ is the selected threshold.

2.3. Hilbert transform

Through analysing envelope waveform obtained by Hilbert transform, signal's abrupt information can be got. This method has been widely used in signal processing and fault diagnosis. Hilbert transform of a real signal is:

$$\hat{x}(t)=\frac{1}{\pi t}\bullet x(t)=\frac{1}{\pi}\int_{-\infty}^{+\infty}\frac{x(\tau)}{t-\tau}d\tau \tag{5}$$

Analytic signal is constructed of $x(t)$ as real part and $\hat{x}(t)$ as imaginary part:

$$z(t)=x(t)+j\hat{x}(t) \tag{6}$$

Amplitude of signal $z(t)$ is:

$$A(t)=\sqrt{x^{2}(t)+\hat{x}^{2}(t)} \tag{7}$$

$A(t)$ is the envelope of real signal $x(t)$ [20].

3. Analysis of Displacement Curve

3.1. On-line monitoring system and data acquisition

Collection of VCB's displacement data is challenging because the sensors are difficult to install due to the small volume and the complex structure. For traditional measurement method, the photoelectric encoder first acquires angular signal of the spindle. Then, displacement data will be got by transforming data from angle to displacement. However, we can just acquire three-phase general displacement through this method rather than displacement of each phase respectively. Therefore, other technical means are necessary to get three-phase synchronism. In which condition, additional signal channels will be needed.

In this paper, an on-line monitoring system is developed based on 10kV VCB with spring operating mechanism, which type is VMB5-12. The on-line monitoring system comprises of a host computer and a slave computer. The main functions of host computer include receiving data from slave computer, establishing database, processing data and displaying results. It is a miniature industrial control computer. Slave computer is the embedded system based on Advanced RISC Machines (ARM) and Field-Programmable Gate Array (FPGA), which is used to collect and transfer data. Owing to large numbers of data with various types, we choose FPGA to gather them. FPGA has abundant I/O interfaces and high-speed parallel processing ability. ARM has the good capability of data processing and favorable Ethernet interfaces. This structure can take full advantage of both of them. The sampling rate is 25 KHz. Therefore, real-time and high-speed data flow is established. The real picture and the structure of on-line monitoring system are shown in Fig 2 and Fig 3.

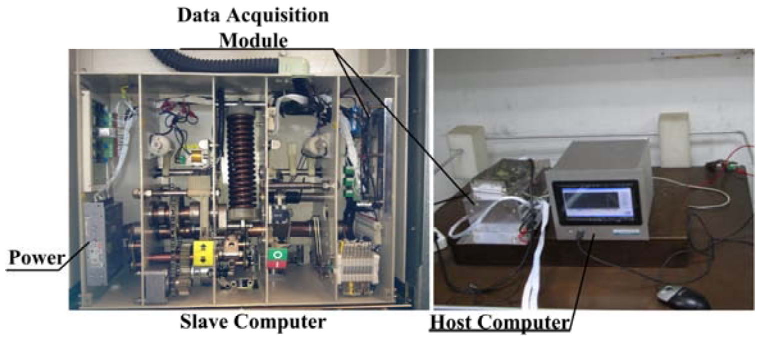


Fig. 2, Real picture of on-line monitoring system

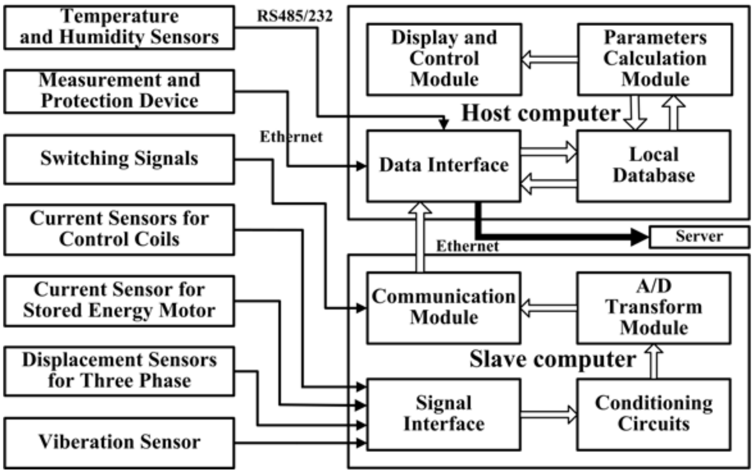


Fig. 3, Structure of on-line monitoring system of vacuum circuit breaker

The measurement of the three-phase displacement depends on linear displacement sensors. In this paper, micro sensor which type is KTS-25 with linearity of 0.25% and repeatability of 0.01mm is selected. As Fig 4 shows, slider of sensor is fixed on the underpart of insulating pole and shell on the frame. Therefore, the moving of slider and insulating pole are the same.

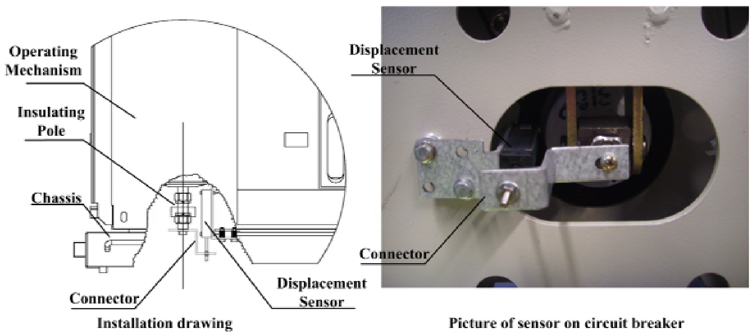


Fig. 4, Diagram of displacement sensor position on vacuum circuit breaker

3.2. Analysis of displacement curve of closing process

The typical displacement waveform of VCB with spring operating mechanism collected by displacement sensors is shown in Fig 5. Then four obvious stages in the closing process can be observed.

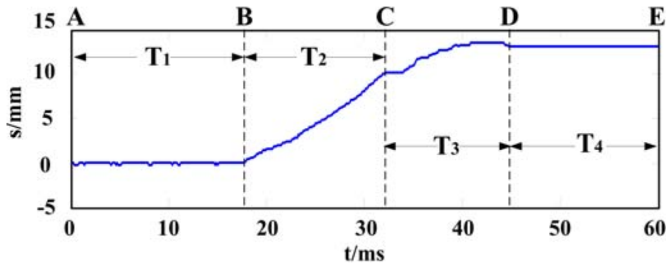


Fig. 5, Typical waveform of closing displacement signal of vacuum circuit breaker

(1) Stage T1: Circuit breaker remains opening and its displacement is approximately zero.

(2) Stage T2: Closing coil begin to active (B point) and moving contacts start to move towards static contacts with relatively stable speed.

(3) Stage T3: Moving contacts and static contacts touch with each other. However, moving contacts will not stop until contacting travel generated with lower speed.

(4) Stage T4: Contacts stop and circuit breaker becomes closed.

At the closing moment, the acceleration of moving contact will drop to zero instantly due to the reaction force. Therefore, an abrupt change will occur at this point in displacement curve. Then its position can be got and be regarded as the closing moment.

4. Judgment of Closing Moment Based on Wavelet and Hilbert Transform

It can be seen from Fig 5 that a great deal of noise remains in displacement signal. These noises come from two sources: the influence of electromagnetic environment and the vibrating disturbance. Because displacement sensors are fixed on the frame of operating mechanism, they will vibrate along with the operation of VCB, resulting in a large number of glitches in displacement curve. Therefore, filtering is needed in order to avoid the difficulty of extracting characteristics.

4.1. Preprocessing of displacement signals

Wavelet de-noising is one of the effective means for interference elimination. In this paper, wavelet sym8 is determined to decompose displacement signals into five layers, and heursure threshold with soft threshold method are chosen for threshold quantization of wavelet coefficients. The original and de-noised waveforms of displacement signals during closing process are shown in Fig 6 (a) and (b).

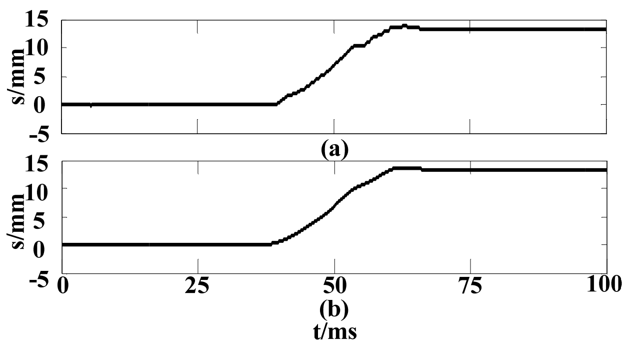


Fig. 6, Original and denoised waveform of closing displacement signals

Deduced from Fig. 6, a conclusion can be drawn that wavelet threshold de-noising is effective in eliminating glitches of sampling signals. Curve becomes smoother and characteristic points are preserved, which will both benefit further signal processing and feature extraction.

4.2. Feature extraction based on wavelet transform

It is challenging to extract characteristics conveniently and rapidly since characteristic point of closing moment (point C) is not obvious. Therefore, further signal processing is necessary. In this paper, wavelet db2 is chosen to decompose signals into five layers and reconstruct them with the first layer. Then signal envelopes can be obtained by Hilbert transform. Fig 7 (a) and (b) show the waveform after signal processing.

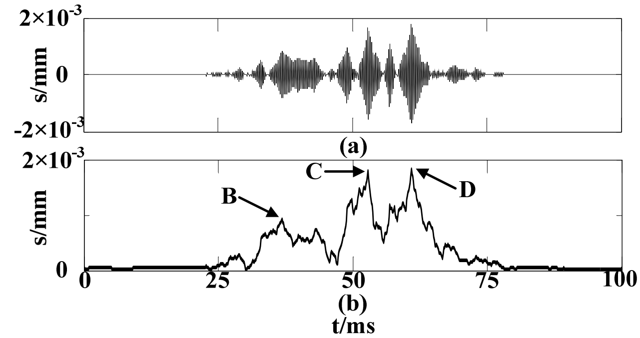
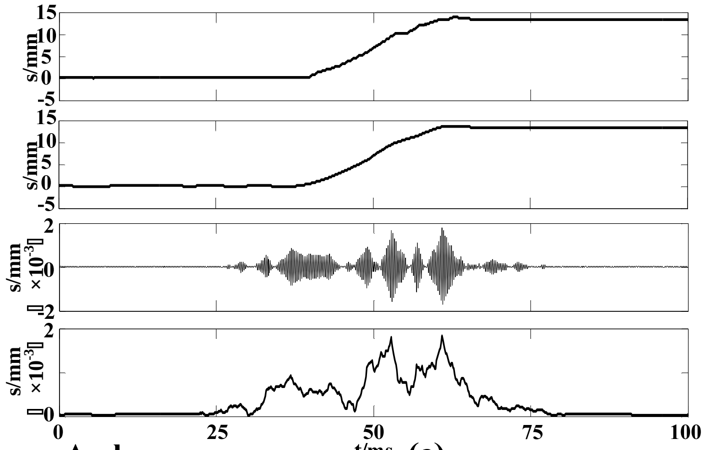


Fig. 7, Waveform of displacement signal after wavelet transform and Hibert transform

From Fig 7, we can see there exist three clear characteristic points in the closing process: starting point, contact point and stopping point, respectively corresponds to points B, C, and D in Fig 5. By simple comparison, characteristic point can be obtained, which is exactly the contact point.

5. Experiment

The method aforementioned is accepted to analyze the five data sets that are collected by the circuit breaker on-line monitoring system. Due to the limited space, this paper only presents one of the five signal processing waveform. Fig.8 (a), (b) and (c) represent the collected signal and processed waveform of the three-phase A, B and C respectively. From the top to bottom, original signal, denoised waveform, wavelet transform waveform and Hibert transform waveform are shown.



A phase (a)

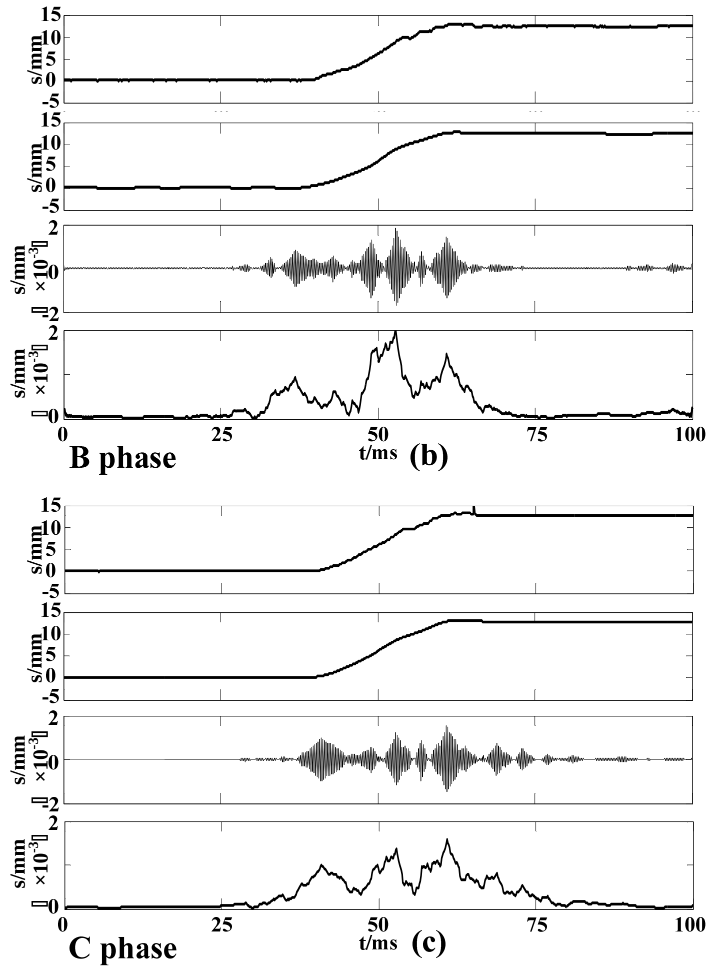


Fig. 8, Waveform of original signals and processing results of three-phase displacement

The contacting travel of VCB is the distance of moving contacts from the circuit breaker contact's closing point to the stopping point. Its measurement accuracy can directly represent the calculation accuracy of the mechanical parameters. The data in Table 1 represent contact travels, which are after the process of the collected five sets of data applying the algorithm in this paper. At the same time, we compare the data with the test results of circuit breaker's characteristics tester SA100 (the three phases A, B and C are all 3.5mm). The results show that the error is within 5%. The stability of the data is good and the algorithm meets the demands of on-line monitoring system.

Table 1: Experiment data of contacting travel of circuit breaker

Number	Data of A phase (mm)	Error of A phase (%)	Data of B phase (mm)	Error of B phase (%)	Data of C phase (mm)	Error of C phase (%)
1	3.3287	4.89	3.3780	3.49	3.5961	2.74
2	3.3873	3.22	3.3493	4.31	3.6680	4.80
3	3.3255	4.99	3.4157	2.41	3.5901	2.57
4	3.3769	3.52	3.4152	3.33	3.6129	3.23
5	3.3338	4.74	3.3746	3.58	3.6498	4.28

The data in Table 2 is typical mechanical parameters of VCB from the field tests of on-line monitoring system. In this paper, contacting travels in closing prosess and opening process are considered the same. Therefore, opening moment can be obtained easily. Then all of the mechanical parameters can be calculated.

Table 2: Experiment data of circuit breaker on-line monitoring system

type	A phase	C phase	C phase
Contact Distance(mm)	3.2850	3.3531	3.6001
Contacting Travel(mm)	9.8150	9.6469	9.1999
Closing Velocity(m/s)	0.6857	0.6569	0.7241
Closing Time(ms)		40.5	
Closing Synchronization(ms)		0.625	
Opening Velocity(m/s)	1.0811	1.2121	1.1302
Opening Time(ms)		25.1	
Opening Synchronization(ms)		0.125	

5. Conclusion

In this paper, wavelet de-noising is adopted to eliminate noise from sampling signals while wavelet transform as well as Hibert transform utilized to highlight catastrophe points in displacement curves during the closing process. This method is simple and practical for extracting circuit breakers' opening and closing points. It has been proved that the proposed method is effective and stable through experiments. This algorithm has been applied to our VCB on-line monitoring system. In addition, the stability of the device has been proved by field tests.

Furthermore, with continuous development of microelectronics computer technology, the hardware support platform of on-line monitoring system will be more effective. Therefore, the accuracy of this method must be further improved.

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