On-line Monitoring System based on Vibration Signal of High Voltage Circuit Breaker

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***Abstract*—High voltage circuit breaker is one of the most important switch apparatus in electrical power system. It play a role in the switch control, which can be used to switch the operating mode during normal operation (the equipment run or quit). In order to ensure the normal operation of the grid, it can be removed quickly when a malfunction on the device or circuit. Real-time online monitoring of high voltage circuit breaker can understand the running status, master the operation characteristics and its tend of development. As early as possible find the potential faults then take preventive measures timely, so as to ensure the reliable operation of power system. Online monitoring of high voltage circuit breakers can reduce the premature or unnecessary maintenance and maintenance cost, improve pertinence of the maintenance firstly. Secondly, it can improve the life of the switching device and improve the reliability of electric power system significantly. In this paper, on-line monitoring system based on vibration signal of high voltage circuit breaker is presented.**

***Index Terms*—High Voltage Circuit Breaker; On-Line; Vibration Signal; Coil Current in Switching; Wavelet Analysis**

I. INTRODUCTION

Initially, the maintenance mode of electrical equipment is corrective maintenance after faults' occurrence, called accident maintenance, and then develops into regular maintenance of a fixed time interval [1, 2]. A new overhaul mode gradually is into our line of sight with the continuous advance of China's electric power system [3, 4, 5]. The so-called state maintenance is based on an advanced condition monitoring and diagnostic technology provide state of equipment and determine the abnormal equipment, predict equipments' failures and overhaul before they occur. The advantages of state maintenance is to prevent fatal accidents, to avoid accidents cause because of the lack of maintenance, or a waste of money because of excess repair, thus prolonging the life of equipment, optimize the operation of the device [6, 7, 8].

High voltage circuit breaker, played the role of protection and control in the power systems [9, 10, 11]. As an important device of power system, its reliability directly affects the safe operation of the entire power grid. With the improvement of power system integrated automation level, the higher requirements have been put forward for the reliability of high voltage circuit breakers. In the supply and distribution system, high voltage circuit breakers are often numerous, maintenance costs greatly. And there is a high frequency of unexpected power outages caused by high voltage circuit breakers, so the indirect losses it caused is far greater than the cost of the device [12, 13, 14] itself. Therefore, we need to strengthen monitoring the state of the circuit breaker.

With the development of computer technology, DSP and sensor technology, the running real-time monitoring for electrical equipment has become possible. This method can proactively monitor whether the operation of electrical equipment is normal, and is able to detect the hidden faults inside, greatly reduce the accident rate of the power grid, reduce workload of equipment maintenance, improve power grid's reliability [1].

In this paper, Several characteristics of the signal on the high voltage circuit breakers (breakers' moving characteristics, coil current in switching and vibration signal) for real-time monitoring based on the on-line monitoring system, after information fusion for remote communication via RS-232-C and data analysis in the remote management module [15, 16, 17]. Compare the various features of the signal and the standard database information one by one in order to determine the type of fault. In this paper, the research focused on the vibration signal, Minimaxi rule finalized by comparing various methods of de-noising.

While using wavelet packet analysis method to analysis the circuit breaker vibration signal collected at the scene, with a focus on high frequency band portion of the signal, Compare with fast Fourier algorithm (FFT) spectrum analysis results, further research on larger probability in experimental results of multiple sets of experiment.

II. RELATED WORK

Research shows that the vast majority of the breaker failure was caused by an internal mechanical failure, and

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most of them are due to the operation of institutions, such as rejecting to open and close, etc. For a long time, maintenance personnel use portable instrument for regular preventive tests when they handover electrical equipment or during a power outage, then repairs based on test results [2]-[4]. This off-line detection method may cause some devices running in dangerous, also cause excessive overhaul of some equipment which are of lower utilization. But it's very complex to get the mechanical state of the operating mechanism. When a certain kind of failure had arisen, the status of organizations may be a lot. Meanwhile, when there is a change in the state characteristic of mechanism, the position of failure or reason is often not unique. Currently, monitoring circuit breaker operating mechanism mainly used the method of extracting feature quantity and the signal comparison. When there's a deviation between the detection signal and the original characteristic signal, a failure may occur. The reason for the specific type and location of the fault is still requires experience coupled with theoretical analysis.

There's many ways of online monitoring of the circuit breaker operating mechanism, such as spectral analysis, infrared analysis, system dynamic response analysis, dynamic test analysis of system pressure, vibration signal analysis component of the housing, ultrasonic analysis, etc. These methods are different principles, and the difficulty of implementation and cost are very different. Therefore, if we want to obtain all the feature quantity of actuator, it will be difficult to achieve in terms of economic or practice [5].

At present, the state monitoring research of the circuit breakers is mainly concentrated in the following several aspects:

A. Monitoring of Breakers' Moving Contact'S Tripping Characteristics

With the development of the science and technology, moving contacts' trip-time curves of breaker's every motion can be recorded. By combining with other parameters, all kinds of mechanical motion parameters can be extracted, such as moving contacts switching time, moving trajectory, switching speed, moving maximal speed and average speed, speed-motion curve, etc. In general, all sorts of mechanical motion parameters have the best working range, above or below which, unbalanced work would appear [6]. For example, if the moving contact's maximal switching speed is too large, it would have large impact on the breaker's internal components and bring great burden on the buffer. If the maximal speed is too small, it would decrease the moving contact's stability, thus the breaker would lose the inherent protecting function. Above all, the monitoring of moving contact's trip-time curve is so important that it has been one of the most important research contents on the state monitoring of high voltage breakers.

B. Monitoring of Coil Current in Switching

In the process of circuit breakers' switching, coil current is time-varying. The current waveform contains lots of information, which reflects the working situation of electromagnets, door locks, valves, and chain contacts, such as whether core motion mechanism, mechanical loads works properly and whether the states of coils, door locks connected with core rods and valves are normal. Through the monitoring of coils' action currents, the working situation of breakers' secondary control circuit and mechanical operating devices are generally understood, which provide a strong evidence for maintenance.

Most of high and ultra-high voltage circuit breakers are equipped with hydraulic pressure, springs, pneumatic operation mechanism, which would produce problems during the long time operation, such as bending deformation, corrosion or contamination attached, all of which would keep the electromagnets from working properly and prevent the circuit breakers switching properly eventually. Such failure accounted for about thirty percent of the total accidents every year. However, the action situation of electromagnets' core can be reflected by the relationship between cores' motion and current. Thus, if the current waveforms of the electromagnet can be recorded when the breaker switches, the action situation of cores can be mastered, so that those problems can be detected as early as possible [7]-[9].

Opening (closing) operation coil is a key component controlling the operation of circuit-breaker. The application of the Hall current sensors can be easily used to help to monitor the current of opening (closing) coil under various states. We can diagnose changing trends of breaker's mechanical failure by analyzing each change of waveforms. It is very effective in diagnosing the rejection of opening (closing) and malfunction fault, both of which are of the biggest probability of occurrence and greatest danger.

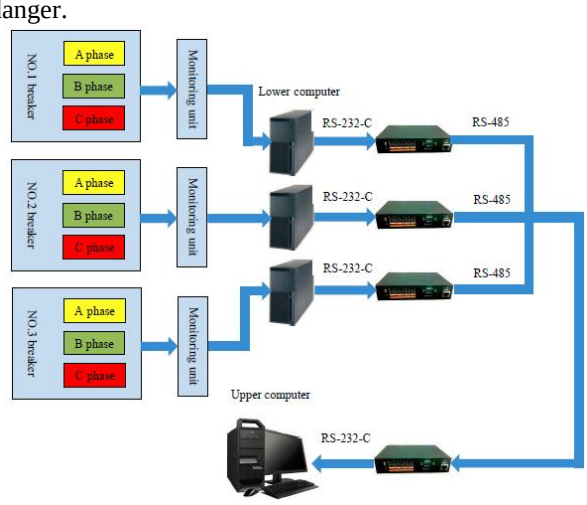

Figure 1. On-line monitoring system of circuit breaker design

Despite of this, online monitoring of high voltage circuit-breaker still has prevalent problems, which will be shown below:

1) It is difficult for the accuracy and cost of sensor, which is fit for extracting online monitoring parameters, to achieve a balanced point .The cost is too high when the accuracy of the precision reaches the required standard, or the accuracy of the precision is too low when the cost is suitable;

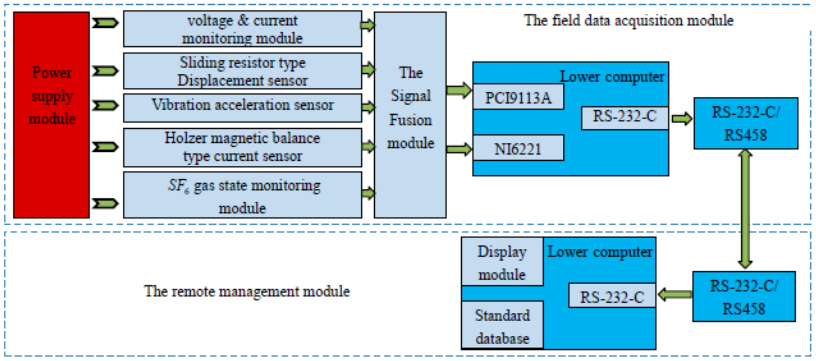

Figure 2. On-line monitoring diagram of single breaker unit

2) Function of on-line monitoring system is imperfect. Most are only limited to studies of one or several parameters on the electrical and mechanical properties of circuit-breakers, such as monitoring breaking current, cumulative frequency of trips, which is not conducive to accurately determine fault ;

3) We are still lack in effective mathematical methods and techniques to analyze and discriminate the operating status of the circuit breaker;

4) Development of equipment lacks systematicness, monitoring of the circuit-breaker is only developed as a single protection or recording device;

Finally, since there are many components in the circuit breaker, such as the actuator, it is difficult to determine which part is prone to failure in order to be monitored. This results in the monitoring of blindness for a lack of previous experience. It also results in a lack of critical data, which is not conducive to the accumulation of experience since the circuit breaker rarely occurs action in normal operation. Meanwhile there are also some controversy in some of the parameters to reflect the operating state and we can't reach a consensus in judgments based on the overhaul.

Thus, although there have been a number of online monitoring devices of circuit breakers at home and abroad, online monitoring of the state of the circuit breaker operation is still in upswing development. The existing online monitoring device features a single function and a lack of sufficient empirical data and adequate analysis capability of fault diagnosis. Therefore, it is of important theoretical and practical value to carry out a comprehensive monitoring technology of status of high voltage circuit breaker.

III. SYSTERM DESIGN

The solution aims to the LW12-252 type circuit breaker, which was commonly used in high voltage power grid in our country. Combining with the characteristics of the structure of the circuit breaker, a complete set of on-line monitoring system of circuit breaker design is shown below in Fig. 1.

Monitoring system can be divided into two parts, field data acquisition module and the remote management module. The field acquisition module is composed of a power supply module, sensor module, signal conditioning circuit, acquisition card and the lower computer. The remote management module is a PC which is located in the surveillance room, as is shown in Fig. 2. Here, we use the data acquisition software, which is developed by VC, to control the acquisition of a number of monitoring parameters. In order to store, analysis, display and print the data collected by the lower computer, we set up the database within the upper computer and use VC to develop the circuit breaker monitoring system software.

We focus on the brake process firstly. When the circuit breaker closed, the site operators use velocity rod draw the wave, as shown in Fig. 3. The total length S is the travel of the circuit breaker moving-contacts; t_1 is the period of time that circuit breaker dynamic and static contact travel from the beginning to the complete detachment, and S_1 refers to the corresponding displacement, that is, the travel of the arcing contact; t_2 refers to the period of time that dynamic contact link at the end of the piston rod from the start into the oil buffer to a complete standstill. S_2 refers to the corresponding displacement. In the whole process of break-brake, S_1 and S_2 section movement damping coefficient is bigger, the curve of equation motion can't approximated as a straight line, however, the middle section, that is, the section of $(S-S_1-S_2)$, considering of the small damping coefficient(Moving contacts only friction with SF_6), the curve of equation motion can approximated as a straight line, and can reflect just the speed of the contact at the time of detachment. General considerations of circuit breaker's break-brake average speed mainly refers to the speed of detachment, that is the speed of A point in the figure, where $V_0 = (S-S_1-S_2) \big/ (T-t_1-t_2)$.

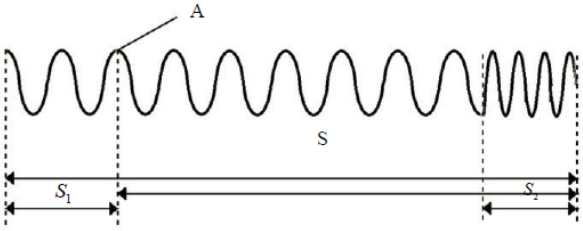

Figure 3. The circuit breaker contact's stroke of the opening

Process of closing is almost the opposite. The opening is by pushing the piston in the cylinder of compressed air

to drive, while the closing is by closing spring pushing the interlocking mechanism where the crank arm to drive; the S_1 segment in Fig. 4 corresponds to the S_2 segment in Fig. 4, because the driving force leading to the movement is much larger than the frictional resistance, so the impact of damping movement is negligible. Analogous, the $(S-S_1)$ segment can reflect the speed when the contact close. Generally, we consider the average speed of the circuit breaker's closing into the speed when the contact close, that's the speed of point B in Fig. 4, $V_0 = (S-S_1)/(T-t_2)$.

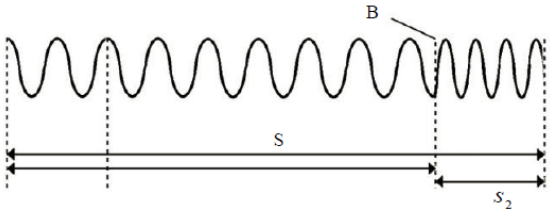

Figure 4. The circuit breaker contact's stroke of the closing

Based on the parameters provided by the site, S=200mm, S_1=25mm, S_1 is 12.5% of the total stroke S; $S_2 \le 10mm$, is 5% of the total stroke S; Apparently, according to the actual situation analysis, the derived formulas and the value of the parameters is different with the commonly used method, in which both S_1 and S_2 subtract 10% of the S. While the actually measured contact travel - time curves is discrete time series. That's the corresponded time of the trip cannot be determined based on an arbitrary value; however, we can find the corresponding stroke based on the specified discrete time points. Therefore, we can solve the average speed like this, for the opening process, in the head of stroke curve, we should try to obtain discrete sampling time point t_1', whose corresponding stroke $S_1' \ge 12.5\%$; similarly, at the end, we take the discrete sampling time point t_2', whose corresponding $S_2' \ge 10\%$; In this case, the moving contacts of the circuit breaker opening average speed $V_O = (S-S_1'-S_2')/(T-t_1'-t_2')$. The solution process of the closing average speed V_C is basically the same with opening situation, no details specific process, the moving contacts of the circuit breaker closing average speed $V_C = (S-S_1'')/(T-t_2'')$.

IV. PERFORMANCE ANALYSIS

In actual operation, the vibration signal is always accompanied by a lot of random noise, although at the majority of the time domain amplitude of the noise is small, but there's still a few moments at which the amplitude is large, manifested as high-frequency signals. The status information characterizing a change of the circuit breaker's state is also contained in the high frequency components. In addition, the data collection process will inevitably be affected by noise, resulting in unwanted clutter, the actual vibration signal is often superimposed with many random external disturbance, the synthesized signal is over a wide frequency band. To minimize interference such as this, ensure the signal status information to be accurate and retention, we should improve the signal to noise ratio (SNR) of vibration signals as soon as possible. Vibration signal preprocessing on software can weaken interference factors at no extra hardware cost, reducing the dispersion of vibration signal. Therefore, the signal de-noising is an essential pre-processing means [9].

Depending on the mode of action of the threshold, the threshold method can be divided into soft threshold, hard threshold and minimum variance threshold method.

i Hard threshold

$$\omega'_{j,k} = \begin{cases} \omega_{j,k} & |\omega_{j,k}| \ge c \\ 0 & |\omega_{j,k}| \le c \end{cases} \quad (1)$$

ii Soft threshold

$$\omega'_{j,k} = \begin{cases} sign(\omega_{j,k})(|\omega_{j,k}| - c) & |\omega_{j,k}| \ge c \\ 0 & |\omega_{j,k}| \le c \end{cases} \quad (2)$$

$\omega_{j,k}$ represents the wavelet transform coefficients after using threshold method; $\omega'_{j,k}$ represents the wavelet transform coefficients without using threshold method.

iii Minimum variance Threshold (MSE Threshold)

Construct an optimal objective function:

$$\min(k = 0,1,2,\ldots,N-1)\left[\frac{1}{N}\sum_{n=0}^{N-1}[\hat{s}_n - s_n]^2\right] \quad (3)$$

Select a threshold so that the objective function value in the last equation is least, where N is the length of the data, the high power of 2(128,512), s(n) is original signal, $\hat{s}(n)$ is reconstructed signal.

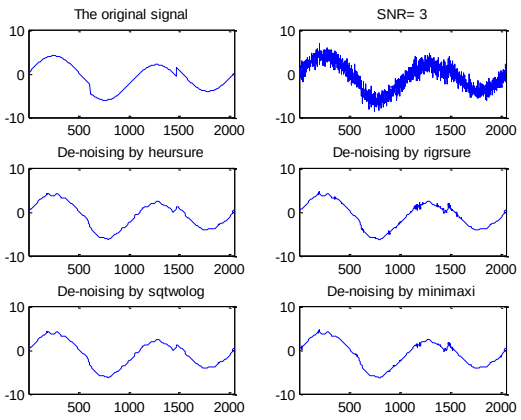

Figure 5. Wavelet de-noising effect under four threshold criteria

Simply speaking, the hard threshold is to make signal all set to zero, the absolute value of whose wavelet coefficients is less than the threshold. Obviously this method will produce a discontinuous point in some areas.

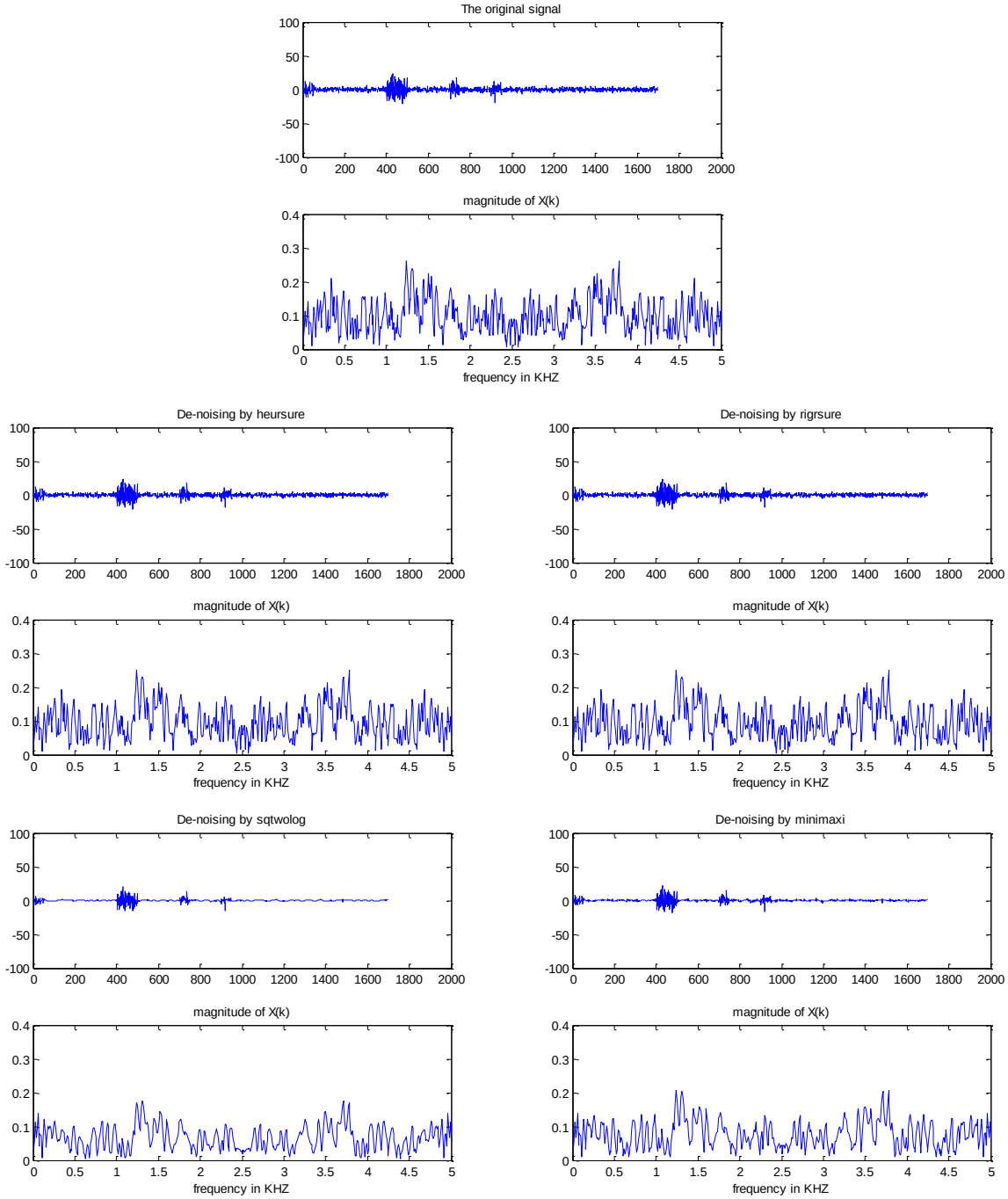

Figure 6. Wavelet de-noising effect in Circuit breaker vibration signal under four threshold criteria

Soft threshold is to make the discontinuity point appeared on the boundary shrink to zero on the basis of hard threshold, can avoid discontinuity point emerges and make the reconstructed signal becomes continuous [10].

Wavelet de-noising has the following advantages:

Low entropy: Non-uniform distribution of the wavelet coefficients, make entropy reduced at a certain extent after the signal converted.

Multi-resolution features: The signals' non-stationary features can be very good characterized, such as edges, spikes, mutation, etc.

De-correlation: Signal correlation can be removed, and the noise in the wavelet transform has whitening trend, so in this case the domain is more conducive to de-noising.

Select base function flexibly: The wavelet transform can choose basis functions flexibly, so we can choose suitable wavelet according to the signal characteristics and de-noising requirements.

The following use a non-stationary noise provided by Matlab2012a as polluted noise, to examine the role of de-noising wavelet analysis of non-stationary signals. Here we use db3 from Daubechies wavelet series, and deal with the noise signal with the above 4 kinds of threshold rules. De-noising results is shown in Fig. 5:

From the de-noising simulation results under four threshold criteria, we can see:

1) Heursure and Rigrsure are more conservative in selecting threshold, the noise they removed is less than the other rules, but they are closer to the original signal, so the useful component of the signal will not be lost. So if there's only a little High frequency information of signal in the range of noise, we can choose these two threshold rules to extract weak signals;

2) Sqtwolog and Minimaxi are more effective in de-noising, the wave curve after de-noising is more smoother, but some useful high-frequency signal may be removed as noise. Simulation results shows, in the wavelet de-noising process with standard Gaussian white noise signal, we can get optimal predictor variables threshold with Heursure to get better de-noising effect [11]- [16].

Use breaker vibration signal collected at the scene of an example, threshold rule on four kinds of wavelet de-noising were done, do wavelet packet de-noising preprocessing, and gives fast Fourier algorithm (FFT) spectrum analysis, comparing the effect of de-noising.

Several experiments showed that, wavelet transform method can eliminate the general noise signals of high or low frequency. Relatively speaking, the main impact of wavelet de-noising effect is to choose threshold and its quantization. According to the characteristics of the actual signal, and the advantages and disadvantages of these types of threshold, we can decide which method to choose.

Circuit breaker vibration signal is non-stationary signal, composed by the low-frequency and high-frequency components [17]. Generally, the high-frequency components refer to the shock signal generated when dynamic and static contact crash. And the useful information is usually concentrated in the high frequency portion of the signal, which reflects changes in the mechanical state of the circuit breaker.

V. SUMMARY

For breaker vibration signal collected at the scene, we analysis and compare the effects of wavelet de-noising and wavelet packet de-noising under the four threshold rules. For the Minimaxi, wavelet de-noising can eliminate the low-frequency part of the noise, and preserve the useful information of the high-frequency portion. The use of wavelet packet method can also achieve a similar effect, and the de-noising effect is much better than the wavelet.

Using wavelet packet analysis method to analysis the circuit breaker vibration signal collected at the scene, we found: the most intense band which reflect breaker mechanical status changes is more concentrated in the high frequency band portion of the signal, consistent with the fast Fourier algorithm (FFT) spectrum analysis results. But the distribution of the band is more divergent, not concentrated at a certain frequency regularly. So we select two frequency band, which is of larger probability in experimental results of multiple sets of experiment, as the feature band of the signal.

Despite the statistical properties of the circuit breaker vibration signal are non-stationary, but in the actual operation, there have different levels of performance of its non-stationary under different working conditions. Through derive formula for field data and the result of experiment in literature, we confirmed that when working normally or the status changed little, the breaker vibration signal's first-order and second-order statistical properties hardly change over time, can be approximated as a smooth random process.

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