Fault Diagnosis Method of Inter-turn Insulation Failure for Circuit Breaker Control Coil

Zhaolei Wang¹,², Qi Yao²*, Xingjun Tian² and Jing Yang²

¹ Maintenance Branch of State Grid Hebei Electric Power Co. Ltd, Shijiazhuang 050070, Hebei Province, China
² School of Electrical and Electronic Engineering, Shijiazhuang TieDao University, Shijiazhuang 050043, Hebei Province, China
*Corresponding author’s e-mail: 1659144384@qq.com

Abstract. The failure of insulation between control coils is an important cause of circuit breaker failure, from the perspective of engineering application, it is expected to accurately screen out this kind of indiscernible inter-turn fault, an effective diagnostic method must be explored. First, apply high-voltage dc (HVDC) pulse excitation to the control coil of the high-voltage circuit breaker, and the response voltage signal is denoised by continuous wavelet transform (CWT) to obtain the main frequency signal which can reflect the essential characteristics of the response; the V/t characteristic curves of the electromagnet coils are then compared with those of standard electromagnet coils at the same frequency and at the same voltage; finally, the variation rules of the integral flux and reluctance of the electromagnet coil under test are judged, so as to judge the inter-turn insulation fault.

1. Introduction

As the basic unit of the power system, the circuit breaker is responsible for maintaining the normal operation of the system and dispatching and controlling the power network. If the operation mechanism and the circuit breaker's own control circuit elements are not controlled, it is easy to develop into a catastrophic power accident. Among them, the insulation fault between the control coils accounts for the majority of all faults. Therefore, it is of great practical value to master the detection method of interturn fault of control coils in hv circuit breaker.

In the engineering application, the current diagnosis in the control coil is the main method to detect the internal fault of the high-voltage circuit breaker. By analyzing the transient waveform of the opening and closing coil action current, the condition of the control coil of the high-voltage circuit breaker can be accurately detected. Literature [4] can effectively detect the damage of each part of the circuit breaker by selecting the key characteristic quantity of the current waveform flowing through the control coil and relating it to the defect of typical mechanical parts of the circuit breaker.

Taking the typical V/A characteristic curve of circuit breaker closing coil as the research object, a magnetic flux change characteristic detection method based on CWT and high voltage pulse method is proposed. First, the HVDC pulse excitation is applied to the high voltage circuit breaker control coil, and the response voltage signal is denoised by wavelet transform to obtain the main frequency signal which can reflect the essential characteristics of the response; the V/t characteristic curves of the electromagnet coils are then compared with those of standard electromagnet coils at the same frequency and at the same voltage, so as to judge the inter-turn insulation fault.
2. High voltage circuit breaker closing coil high voltage pulse signal acquisition and V/A characteristic curve

2.1. High voltage pulse signal acquisition
The opening and closing electromagnet for high-voltage circuit breaker is composed of coil core return spring and tripping rod. The secondary circuit of circuit breaker is supplied by dc constant voltage. The current curve of opening and closing coil is a dynamic curve reflecting the movement process of electromagnet.

![Principle diagram for high voltage pulse method](image)

Fig. 1 Principle diagram for high voltage pulse method

The high-voltage pulse method, whose basic principle is shown in figure 1, is a method of directly applying pulse voltage to the coil under test. During the test, the DC pulse power supply first charged capacitor C, and when the charging voltage reached a certain value, the bulb gap discharged, and the capacitor C and the Rw and L of the test coil formed a damped oscillation circuit.

In the LC oscillation circuit, the oscillation frequency changes with the change of the inductance of the coil under test. By selecting the appropriate pulse capacitance value, the oscillation frequency can be controlled within a certain range without affecting the voltage resistance effect between turns.

Take the control coil of the circuit breaker as the part under test. If the coil has inter-turn insulation defects, there will be inter-turn short circuit fault under the action of impulse voltage. Therefore, the change of coil inductance can be judged by recording and analyzing the voltage waveform change diagram of the coil under test, so as to accurately diagnose and control the turn-to-turn insulation state of the coil.

2.2. V/A Characteristic curve analysis mechanism
In the LC oscillation circuit, if the circuit breaker control coil is short-circuited between turns, the number of turns of the control coil will change accordingly, which will affect the inductance value of the whole control coil, reflecting that the oscillation frequency of the LC oscillation circuit will also change accordingly; And circuit breaker control coil short circuit circulation inside the turn will also cause the change of control coil loss increase, make the voltage and current attenuation speed of the whole LC oscillation circuit become faster. Therefore, by comparing the voltage waveform change diagram of the circuit breaker control coil at a certain point at the rated voltage, it can be determined whether the modified control coil has the defect of interturn insulation drop.

3. Signal processing algorithm and fault recognition criterion

3.1. Signal denoising algorithm based on wavelet
The voltage signal of the control coil of the high-voltage circuit breaker is a typical nonlinear dynamic signal, and the voltage signal of the inter-turn circuit inevitably produces non-stationarity, so it is suitable to choose the wavelet threshold denoising algorithm with the characteristics of multi-resolution de-correlation and low entropy.

If \( x(t) \) is a squared integrable function (let's call it \( x(t) \in L^2(R) \)), and \( \psi(t) \) is called a basic wavelet or mother wavelet function, then the continuous wavelet transform of \( x(t) \) can be expressed as:
\[ W_x(a, b) = \left| a \right|^\frac{1}{2} \int x(t) \psi^*\left(\frac{t-b}{a}\right) dt \]  

(1)

In the face of amplitude or frequency mutation, wavelet can precisely analyze the time and spatial distribution of signal mutation. However, the basis of wavelet is not fixed. The main consideration in selecting the generating function of wavelet is the wavelet which is similar to the shape of the signal waveform. The Daubechies2 wavelet was selected after a large number of experiments. Wavelet decomposition can decompose the original signal into a series of approximate components and detail components, and the noise of the signal is concentrated on the detail components. After processing the detail component with a certain threshold value, the smooth signal can be obtained by wavelet reconstruction.

![Wavelet noise reduction flow chart](image1)

![Wavelet processing signal rendering](image2)

The most critical of the above processing steps is the threshold processing method, because the discrimination between noise and useful signals depends directly on the selection of the threshold. So we adopted the processing method of hard threshold. The noise suppression method based on orthogonal wavelet transform and adaptive threshold algorithm is applied in this paper. The signal effect after wavelet analysis and processing is shown in figure 3.

3.2. Characteristic quantity construction and fault identification criterion

3.2.1. Characteristic quantity structure. By comparing the waveforms, the differences between the two waveforms are examined. We plan to use the method of making the difference between the two waveforms for standard detection. And an empirical value is set to judge the aging degree of the coil, and the final result is whether the coil is intact coil, has a certain degree of aging coil, or has been completely damaged coil.

After obtaining the voltage waveform of the coil under test and the standard coil successively, the voltage waveform characteristics of the same point at the same voltage and frequency can be used to describe its variation information. It is assumed that in the first operating frequency cycle, the interturn voltage signal of the high-voltage circuit breaker is decomposed into \( k \) bands (including the allowance), then the characteristic difference of the coil voltage signal is

\[ U_k = U_1(k) - U_0(k) \]  

(2)

Where, \( U_1(k) \) is the voltage component of the signal in the \( k \)-band of the test coil; \( U_0(k) \) represents
the voltage component of the signal in the k-band of the standard coil.

Then, the weight value representing the voltage characteristics of the band can be expressed as equation (3), after the normalization of $\lambda_k$, we get $\tilde{\lambda}_k$.

$$\lambda_k = \frac{U_k}{U_1(k)}$$

$$\tilde{\lambda}_k = \frac{\lambda_k}{\sum_{i=1}^{k} \lambda_i}$$

Therefore, in the first power frequency cycle, the characteristic vector $J(n)$ of the voltage signal between the control coils of the high-voltage circuit breaker can be constructed as

$$J(n) = -(\tilde{\lambda}_k \times \ln \tilde{\lambda}_k)$$

According to equation (5), the larger the characteristic vector of the circuit breaker's interturn voltage is, the higher the damage degree of the coil is.

3.2.2. Fault identification criterion. When the circuit breaker control coil has a short circuit turn, in the pulse voltage test circuit will cause the voltage or current oscillation frequency change and attenuation speed change, so by observing the voltage at both ends of the coil or the current flow through the coil waveform can be judged by the circuit breaker control coil coil turn insulation.

4. Instance analysis

4.1. Testing experiment of insulation state

The testing principle of the circuit breaker control coil interturn insulation testing device is based on the LC oscillation circuit composed of the built-in capacitance and coil inductance. The high voltage pulse control technology is used to draw the voltage characteristic curve of the electromagnet coil under test, and then the voltage characteristic curve is compared with the standard voltage characteristic curve to find the difference and diagnose the insulation state between the control coils. Its detection process is shown in figure 4.

![Fig. 4 Testing process of interturn insulation state of high voltage circuit breaker](image)

In order to more accurately and effectively diagnose the different states of the decline of the insulation performance between the loops of the electromagnet coil of the high-voltage circuit breaker, a total of eight gears were set for the high-voltage pulse of 300V 400V 500V 600V 700V 800V 900V during the experiment. The distribution of inter-turn signal test characteristics of circuit breakers is shown in table 1.

| test sequence | DC Pulse (V) | measured value (V) | reference ranges (V) | proper vector (%) | qualify |
|---------------|--------------|--------------------|----------------------|------------------|---------|
| 1             | 300          | [295,299]          | [285,315]            | [3.4,5.0]        | qualified |
| 2             | 400          | [396,401]          | [380,420]            | [4.0,4.5]        | qualified |
| 3             | 500          | [494,498]          | [475,525]            | [3.8,5.1]        | qualified |
4.2. Experimental data analysis under multiple combinations

The new standby and three representative hv circuit breaker control coils used in circuit breaker rejection accidents were selected as test objects to verify the use effect of the device. The coil types tested were 5KA520400.

The experimental results show that the test device and the direct resistance measurement method can get accurate results for the completely damaged and intact control coils. However, for the control coil with aging insulation, the measurement method of direct resistance is in the case of power failure, and the insulation is not completely damaged. Therefore, the measurement result is qualified and cannot accurately reflect the actual insulation state. The device can be tested under different voltage shocks. When the voltage level is relatively low, the measurement result is qualified. When the voltage level is raised, the insulation aging state is easily exposed in the high-voltage impact, and the test result is unqualified.

5. Conclusion

According to the high voltage circuit breaker opening and closing, its voltage contains a wealth of frequency components, and the inter-turn short circuit current overall maintains the fundamental frequency sine wave characteristics. Taking the typical V/A characteristic curve as the research object, by drawing and comparing the V/t characteristic curve difference between the tested coil and the standard coil using the high-voltage pulse control technology, the insulation state between the control coils can be diagnosed accurately.

The characteristic vector of interturn voltage of hv circuit breaker can accurately reflect the working state of interturn. If the calculated characteristic vectors are small, the circuit breaker coil passes the detection; the more the characteristic vectors exceed the threshold of difference degree, the higher the damage degree of the circuit breaker coil is. The characteristic vector shows the phenomenon of the fluctuation of the threshold value range, which indicates that the circuit breaker coil has a certain degree of aging.

References

[1] Han Chenlong. Research on fault detection of interturn insulation of control coil for substation high-voltage circuit breaker[D].North China Electric Power University,2018.
[2] Song Yakai, ZhangYiming, ZhangWentao, et al. Research on Extraction Algorithm of Current Waveform Characteristic Value of Circuit Breaker Opening and Closing Coil[J].High Voltage Apparatus, 020, 56(01):181-187.
[3] Zhao Hua, ZhaoMaolin, XiaWei. State assessment of high-voltage circuit breaker operator based on k-means and SOM hybrid algorithm[J]. High Voltage Apparatus, 2020, 56(01):36-42.
[4] SUN Yinshan, ZHANG Wentao, ZHANG Yiming, et al. Research on feature value extraction and fault recognition of coil current signal in high-voltage circuit breaker[J]. High Voltage Apparatus, 2015, 51(9):134-139.
[5] Zhang Hao, ZhaoLihua, JingWei, et al. State assessment of breaker operating mechanism based on Relief characteristic quantity optimization and SOM network[J]. High Voltage Apparatus, 2017, 53(09):240-246.
[6] X. Kong et al., "High-Voltage Circuit-Breaker Insulation Fault Diagnosis in Synthetic Test Based on Noninvasive Switching Electric-Field Pulses Measurement," in IEEE Transactions on Power Delivery, vol. 31, no. 3, pp. 1168-1175, June 2016.
[7] Y. V. Parfenov, L. N. Zdoukhov, A. V. Shurupov, A. V. Kozlov, "Research of Flashover of Power
Line Insulators Due to High-Voltage Pulses With Power ON and Power OFF". IEEE Trans. Electromagn. Compat. vol. 55, no. 3, pp. 467-474, Jun. 2013.