

Article

Online Monitoring Method for Opening and Closing Time of 10 kV Spring Energy Storage Circuit Breaker Based on Transient Electrical Signal Characteristic Point Marking and Self-Calibration

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Abstract: Among all circuit breaker faults, mechanical failures account for a considerable proportion, and online monitoring of their mechanical characteristics is of great practical significance. The opening and closing time is a very important feature of the mechanical characteristics of the circuit breaker. Online monitoring of the opening and closing time of the circuit breaker has always been the focus and difficulty of the intelligent technology of switchgear. In this paper, for a 10 kV spring energy storage vacuum circuit breaker, transient voltage and current signals are innovatively used to calibrate the opening time, breaking time, and closing time, and an online monitoring method for the opening and closing time of a vacuum circuit breaker based on transient electrical signals is proposed. An online monitoring platform was built and a multi-group closing test was carried out to simulate the power plant environment. The opening and closing time samples of a spring energy storage vacuum circuit breaker were measured and compared with the measurement results of the mechanical properties tester. The comparison results show that this method has good stability, and the calculation error is controlled within 1% after self-calibration, which provides a new idea for the online monitoring research of the mechanical characteristics of spring energy storage vacuum circuit breakers.

Keywords: circuit breaker; online monitoring; opening and closing time; self-calibration

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1. Introduction

In modern power systems, high-voltage circuit breakers are one of the most important control and protection devices. In order to prevent high-voltage circuit breakers from failure, they need to be frequently inspected and maintained. Too low a frequency of circuit breaker inspection will reduce system reliability, while too frequent inspections will bring new man-made risks and higher costs. Among all circuit breaker failures, mechanical failures account for a considerable proportion [1]. Therefore, online monitoring of their mechanical characteristics is of great practical significance.

The opening and closing time of the circuit breaker is a very important parameter in the online monitoring of the circuit breaker and an important indicator to measure the performance of the circuit breaker. The opening and closing time is closely related to the health of the operating mechanism and directly affects the breaking performance of the circuit breaker [2]. Therefore, accurately extracting the opening and closing time characteristic values through the online monitoring system is of great significance for judging the health and working status of the circuit breaker.

Regarding the online monitoring method of the mechanical characteristics of the vacuum circuit breaker during the opening and closing process, some scholars have conducted research on the aspects of the opening and closing coil current signal [3,4], the moving contact travel-time curve during the opening and closing operation [5], and the circuit breaker vibration signal [6–12]. Reference [13] proposed an online monitoring method for the closing point based on the travel curve of a vacuum circuit breaker. It analyzed the stress conditions of the moving contact before and after the closing point, and based on the analysis results, proposed using the closing speed curve as key information. The wavelet decomposition and reconstruction method was used to extract feature quantities from the closing speed curve for calculating the closing point. Reference [14] extracted time characteristics from the opening/closing coil current waveform signal and the circuit breaker auxiliary contact voltage waveform signal, constructed a degradation degree index that takes into account the influence of monitoring data uncertainty, and introduced a sequential Bayesian algorithm to achieve real-time updating of circuit breaker status assessment results that integrate historical records and monitoring data; [15] proposed a circuit breaker state assessment method based on vibration signal envelope analysis; and [16] proposed a novel, non-intrusive method for circuit breaker arcing time, which combined vibration-acoustic fusion and convolutional neural network [17]. By measuring and analyzing the high-definition transient voltage waveform of the high-voltage circuit breaker closing process, the time interval between the auxiliary contact bounce and arc extinguishing is extracted as the characteristic parameter to realize the state evaluation of the auxiliary contact bounce. Reference [18] selected the closing coil current and travel signal as the experimental monitoring quantities, extracted three types of principal component features with orthogonal contributions, and constructed a ternary feature map based on this, which intuitively displayed the evolution path of the curve under different faults. Reference [19] normalized and preprocessed the different characteristics of the circuit breaker from multiple angles such as current and vibration signals, used the PCA method to fuse the features and extract the principal components containing the richest information on mechanical property degradation, and obtained a comprehensive health index of the mechanical properties of the energy storage operating mechanism. References [20,21] used the method of angular displacement sensor to detect the mechanical characteristics of the circuit breaker. Based on the analysis of the circuit breaker connecting rod structure, the relationship between the main shaft rotation angle and the contact line displacement was established, and the accuracy of the angular displacement sensor for contact monitoring was verified through experiments.

The traditional method of mechanical and time characteristic testing must be carried out under power outage maintenance. The power outage offline switch characteristic test will reduce the number of switch operations and reduce the switch operation life. The switch wiring is also prone to component damage. In addition, the offline mechanical characteristic test of the switch consumes human resources and cannot continuously measure data, which is not conducive to the fault diagnosis and status monitoring of the circuit breaker. This paper takes the ZN28-12 indoor vacuum spring energy storage circuit breaker commonly used in power plants as the research object, and studies the method for determining the opening and closing time during its online operation. An online

monitoring method for the opening and closing time of the circuit breaker that only relies on voltage and current sensors is proposed. This method starts from the characteristic that the transient waveform of the electrical signal before and after the opening/closing point changes significantly, and innovatively uses the primary side transient signal to calibrate the opening time, breaking time, and closing time. Compared with the traditional calibration of the secondary side opening and closing coil signal or displacement sensor and vibration sensor, this method is more direct. This use of electrical signals to realize online monitoring of mechanical characteristics can more truly and effectively reflect the operating status of the circuit breaker, with a faster response speed, and has guiding significance for real-time detection of circuit breaker fault information.

2. Calibration of Opening and Closing Points Based on Transient Electrical Signal Characteristics of Circuit Breaker Opening and Closing

The transient voltage and current during the opening and closing process of the circuit breaker are caused by the arc generated between the moving and static contacts during the opening and closing process. The “arcing” phenomenon occurs when the circuit breaker is opened, and the “pre-breakdown” phenomenon occurs when the circuit breaker is closed. “Arcing” and “pre-breakdown” are essentially the breakdown of the vacuum medium at the break when the moving and static contacts are not fully in contact. According to the classical vacuum break breakdown theory, when the voltage applied to the break exceeds the insulation strength of the gap medium, the break will break down, causing transient electrical signals to appear.

Through Paschen’s law or Paschen curve, we know that when the voltage intensity of the vacuum circuit breaker is greater than the insulation strength of the vacuum, a breakdown will occur, and an arc will be generated. When the circuit breaker is opening and closing, the distance between the moving and static contacts will change, so the insulation recovery strength between the moving and static contacts will show dynamic changes. When the voltage intensity between the contacts is greater than the recovery strength of the insulation, the medium will be broken down and an arc will be generated. The generation of the arc is accompanied by transient voltage and current.

Due to the existence of the cut-off value, the transient current signal generally exists for a shorter time than the transient voltage signal, because when the current flowing through the circuit breaker is less than the cut-off value, the transient current signal disappears. However, at this time, a transient recovery voltage will be generated between the contacts, which is part of the transient voltage existence process. Comprehensive calibration can be performed through transient voltage and current signals. For example, the starting points of transient voltage and transient current correspond to the time when the arc is generated. In some tests where the transient voltage is not obvious, the transient current can assist in calibrating the characteristic points. It can be seen that there is a close connection between the distance (mechanical stroke) between the moving and static contacts of the circuit breaker, the arc, and the transient electrical signal. After the circuit breaker contacts are separated, an arc is generated between the contacts, and the arc is extinguished when the arc current passes through zero.

2.1. Relationship Between Transient Electrical Signal of Circuit Breaker Opening and Closing and Moving Contact Travel Curve

When the circuit breaker receives the opening signal, it starts to perform the opening operation. At the moment when the moving and static contacts of the circuit breaker separate, the distance between the contacts is the shortest. If the voltage reaches the

breakdown voltage of the vacuum, breakdown occurs, an arc is generated, and a transient signal is generated at the same time. When the distance between the moving and static contacts increases and is not enough to cause the vacuum to break down, the arc is extinguished, and the transient signal disappears. Figure 1 is a timing diagram of the opening transient electrical signal and the moving contact travel curve. It can be seen from the figure that after the circuit breaker receives the opening command at time T_{command} , it takes a time interval T_{opening} from the energization of the circuit breaker opening coil to the separation of the circuit breaker contacts.

$$T_{\text{opening}} = T_{\text{separate}} - T_{\text{command}} \quad (1)$$

$$T_{\text{arcing}} = T_{\text{end}} - T_{\text{separate}} \quad (2)$$

The time point of contact action is T_{separate} . After the contact action, since the contact surface of the circuit breaker cannot be completely flat, the current will always flow through the separated convex point when the moving and static contacts separate, causing local overheating and melting, and then generating a diffuse arc. The time from the arc generation to the extinction is called the arcing time. Transient voltage and current are also generated with the arcing, and their existence time is T_{arcing} .

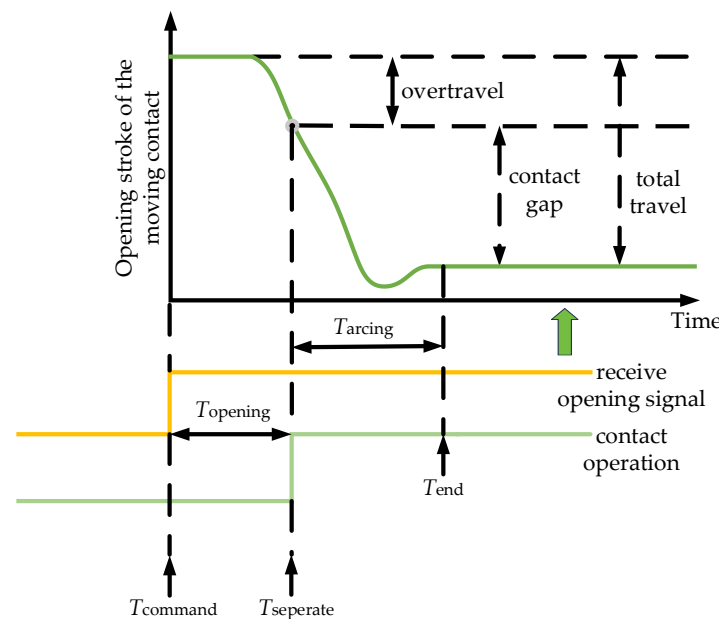


Figure 1. Timing diagram of the opening transient electrical signal and the moving contact travel curve.

The arcing time is not fixed, but it has certain random characteristics. The arcing time of each circuit breaker satisfies the normal distribution law, and the existence time of transient electrical signals (voltage, current) also satisfies certain normal distribution laws. Through multiple groups of tests, the distribution interval of the transient electrical signal existence time T_{arcing} can be measured.

Similar to the opening operation, after receiving the closing command, it takes a period of time ΔT_{known} from the energization of the circuit breaker tripping coil to the start of the circuit breaker contact action. After the contact moves, as the gap between the breaker and the circuit breaker continues to decrease, pre-breakdown may occur under certain conditions. The occurrence of pre-breakdown will cause the circuit to be connected in advance before the contacts touch. As shown in Figure 2, the timing diagram of the closing

transient electrical signal and the moving contact travel curve, the time of the entire closing process is divided into three parts, as shown in the formula:

$$T_{\text{closing}} = \Delta T_{\text{known}} + \Delta T_{\text{stochastic}} + T_{\text{prestrike}} \quad (3)$$

where T_{command} is the moment when the circuit breaker receives the closing command, and T_{separate} is the moment when the moving contact starts to move. Pre-breakdown occurs after the moving contact starts to move, $\Delta T_{\text{stochastic}}$, and its value is random but satisfies the normal distribution law. The arcing time after pre-breakdown occurs is $T_{\text{prestrike}}$, and the existence time of the transient electrical signal in the closing process corresponds to its arcing time. When the closing operation is performed, it can be mainly divided into the following stages: the circuit breaker receives the closing signal, the closing coil is energized, and the iron core begins to move until the moving and static contacts of the circuit breaker are close to each other, generating transient voltage and current signals; the time from the transient electrical signal generated between the moving and static contacts of the circuit breaker to the time when the moving and static contacts of the circuit breaker just begin to touch each other is the arcing time, and the voltage signal in the system is the transient signal; from the time when the moving and static contacts of the circuit breaker just begin to touch each other to the time when the circuit breaker is closed, the transient voltage and current in the system disappear.

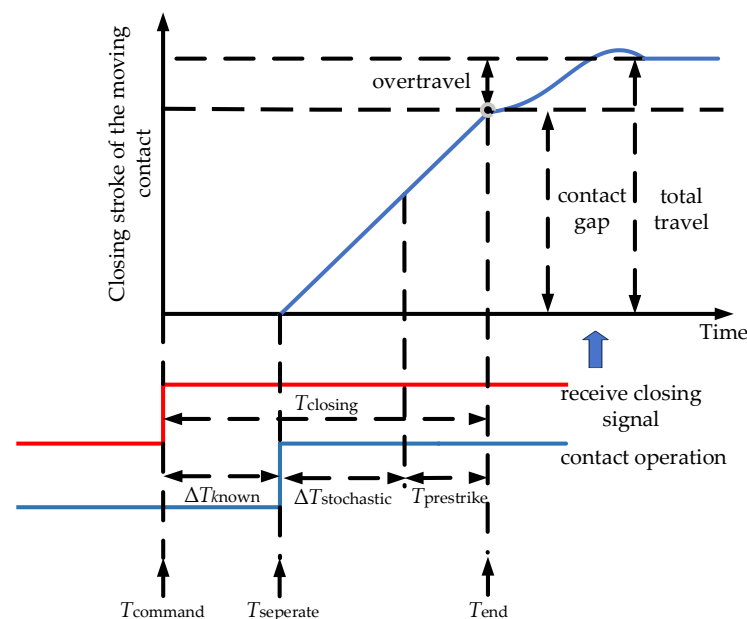


Figure 2. Timing diagram of closing transient electrical signal and moving contact travel curve.

2.2. Calibration of Opening and Closing Characteristic Points Based on Transient Electrical Signals

Figure 3 shows the waveform and time point calibration of the transient electrical signal (voltage, current) of the circuit breaker when closing. According to the principle of characteristic point identification, time T_2 is the moment when the transient electrical signal appears, which produces the “pre-breakdown” phenomenon; time T_3 is the moment when the transient electrical signal disappears, corresponding to the just-closed point in the moving contact travel–time curve, and is also the calibration point for calculating the closing time of the circuit breaker. By measuring the closing coil pulse signal, it can be known that the closing signal occurs at time T_1 , the arcing time of closing $T_{\text{prestrike}}$ depends on the existence time of the transient electrical signal, and the just-closed time T_{closing}

depends on the time difference between the disappearance point of the transient electrical signal and the occurrence point of the closing signal.

$$T_{\text{prestrike}} = T_3 - T_2 \quad (4)$$

$$T_{\text{closing}} = T_3 - T_1 \quad (5)$$

Figure 4 shows the waveform and time point calibration of the transient electrical signal (voltage, current) of the circuit breaker during opening. According to the principle of characteristic point identification, the moment T_5 is the moment when the transient electrical signal appears, which corresponds to the just-opening point in the moving contact travel time curve, and is also the calibration point for calculating the circuit breaker opening time; the moment T_6 is the moment when the transient electrical signal disappears, and the arcing phenomenon will also disappear at this time. By measuring the pulse signal of the opening coil, it can be known that the opening signal occurs at T_4 , the arcing time of the T_{arcing} of the opening depends on the existence time of the transient electrical signal, and the just-opening time T_{opening} depends on the time difference between the appearance point of the transient electrical signal and the occurrence point of the opening signal.

$$T_{\text{arcing}} = T_6 - T_5 \quad (6)$$

$$T_{\text{opening}} = T_5 - T_4 \quad (7)$$

As can be seen from Figure 3 and Table 1, when performing a closing operation, it can be mainly divided into the following stages:

- From the time when the circuit breaker receives the closing signal, and the closing coil is energized to drive the iron core to start moving until the moving and static contacts of the circuit breaker are close to each other and an arc is generated, the voltage and current signals in the system are both industrial frequency electrical signals.
- From the time when an arc is generated between the moving and static contacts of the circuit breaker to the time when the moving and static contacts of the circuit breaker just begin to touch each other is the arc burning time, and the voltage and current signals in the system are transient signals. Through the analysis in the previous stage, the time point needs to be calibrated by current assistance.
- From the time when the moving and static contacts of the circuit breaker just begin to touch each other to the time when the circuit breaker is closed, the voltage and current signals in the system are industrial frequency electrical signals.

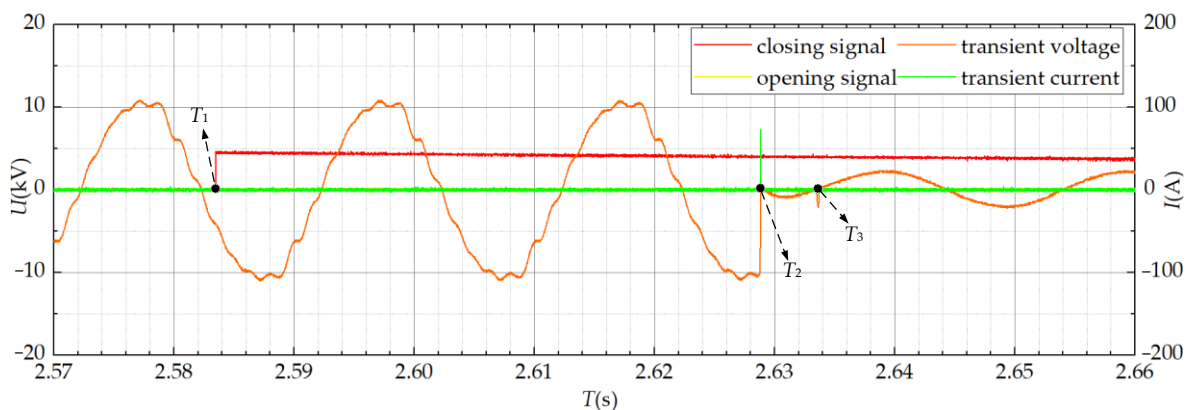


Figure 3. Waveform and time point calibration of transient electrical signals (voltage, current) when closing the circuit breaker.

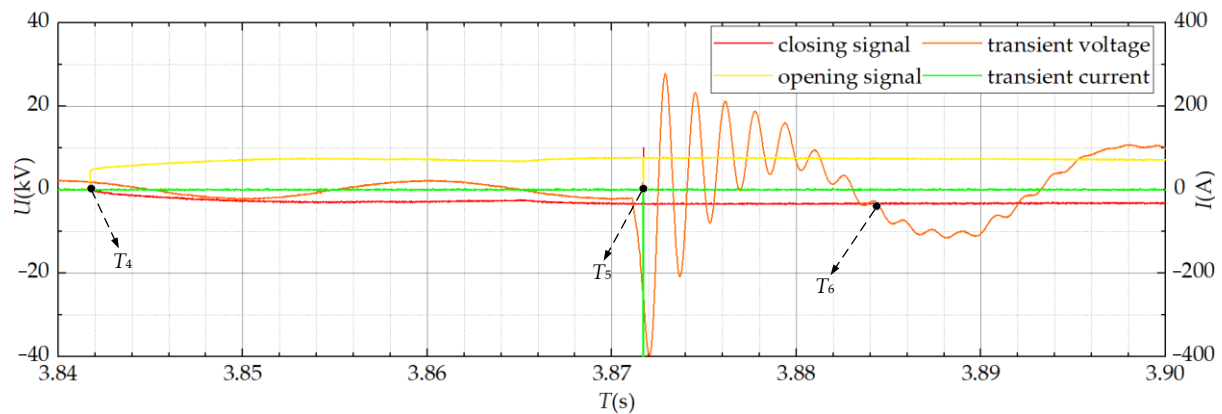


Figure 4. Waveform and time point calibration of transient electrical signals (voltage, current) during opening.

Table 1. Characteristic quantity of electrical signal during opening and closing operation.

Operate	Time	Feature Quantity
Opening	Opening trigger—just opened	Power frequency electrical signal
	Arcing time	Transient electrical signal
	Arcing ends—opening completed	Power frequency electrical signal
Closing	Closing trigger—arcing time	Transient electrical signal
	Arcing time—just closed	Power frequency electrical signal
	Just closed—closing completed	Transient electrical signal

As can be seen in Figure 4 and Table 1, when the opening operation is performed, it can be mainly divided into the following stages:

- From the time when the circuit breaker receives the opening signal, the opening coil is energized to drive the iron core to start moving until the moving and static contacts of the circuit breaker begin to separate, and the voltage signal and current signal in the system are both industrial frequency signals.
- From the time when the moving and static contacts of the circuit breaker begin to separate to the time when the arc of the moving and static contacts no longer breaks through is the arcing time, the voltage signal and current signal in the system are transient signals, and the time point can be directly calibrated by the voltage signal.
- From the time when the arcing of the moving and static contacts of the circuit breaker ends to the time when the circuit breaker is opened, the voltage signal and current signal in the system are industrial frequency electrical signals.

3. Design of Online Monitoring System for Circuit Breaker Opening and Closing Time Based on Voltage and Current Transient Signals

The overall design scheme of the online monitoring system for transient electrical signals at the circuit breaker opening and closing is shown in Figure 5. The capacitive voltage sensor converts the transient voltage at the break into a voltage signal in real time; the Rogowski coil measures the electromagnetic signal at the break, converts it into a current signal through an integrator, and then uses an acquisition card to convert the transient electrical signal into a digital signal and collect it. The host computer software processes and stores the collected signals, scans the slope of the waveform, and identifies the time point when the transient electrical signal is generated or disappears. Finally, it can realize the real-time display of the electrical signal waveform and the automatic calculation and storage of the opening and closing time.

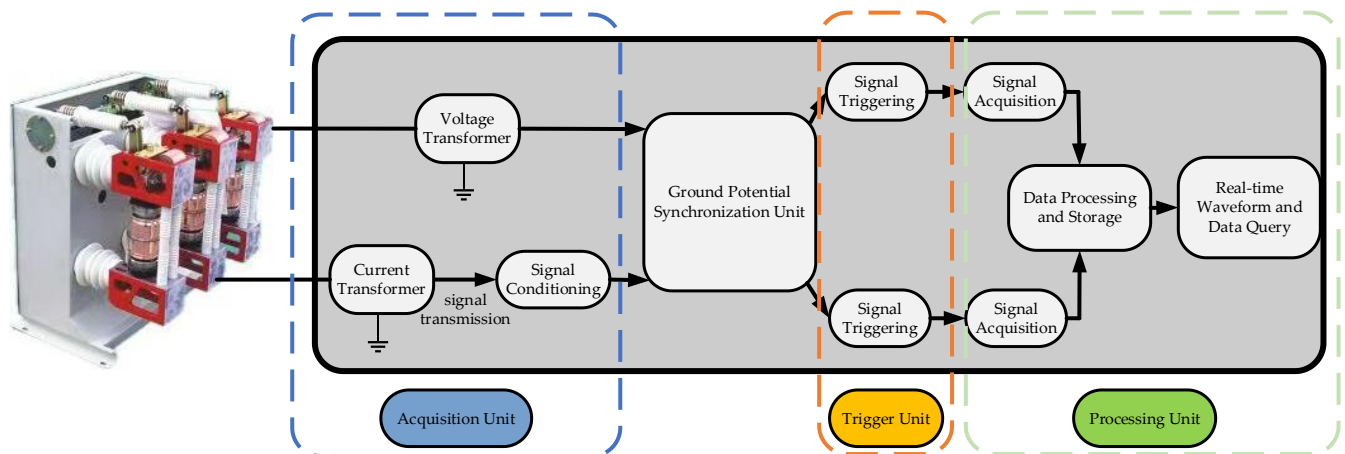


Figure 5. Online monitoring system architecture diagram.

The realization of online monitoring first requires transient electrical signal data acquisition. It is necessary to collect the transient original electrical signals at both ends of the circuit breaker break. The transient voltage signal is collected by a capacitive voltage sensor, and the transient current signal is collected by a Rogowski coil with an integrator. Finally, the acquisition card stores the data. The process of the acquisition program is shown in Figure 6.

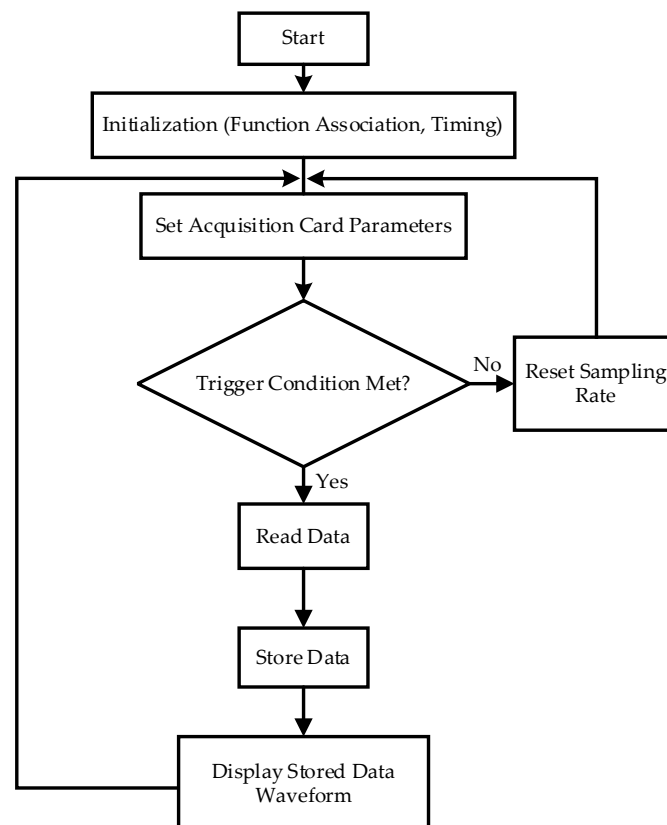


Figure 6. Signal acquisition flow chart.

The first step of program startup is to initialize, and then set the relevant acquisition parameters, such as sampling rate, trigger threshold, channel range, input impedance, coupling mode, etc. The trigger threshold is set to prevent interference from clutter. Selecting an appropriate threshold is the premise for ensuring that the signal is not lost and filtering. When the acquisition signal reaches the trigger condition, the data will be read

and stored by the host computer software, and the acquired transient electrical signal waveform will be displayed in real time on the display interface of the host computer. If the trigger condition is not met, the acquisition parameters need to be reset, considering whether the sampling rate meets the transient electrical signal acquisition bandwidth requirements of the current system.

After filtering the collected transient voltage and current waveforms of opening and closing, the clutter in the power grid is filtered out. By performing slope scanning on the filtered waveform, the time points when the transient electrical signal appears and disappears are obtained. When there is no transient signal, the slope of each point in the waveform corresponds to the sine curve, but when the transient signal appears, the slope no longer satisfies the corresponding relationship. Therefore, the characteristic points of the transient electrical signal can be found by the slope scanning method. Then, the calibration method specified in this article is used to calibrate the opening and closing points, and finally, the opening and closing time is automatically calculated.

4. Self-Calibration of Opening and Closing Time Measurement Based on Transient Electrical Signals

4.1. Selection of Reference Value for Self-Calibration of Opening and Closing Time

The proposed method is compared and corrected with the circuit breaker mechanical characteristic tester, taking advantage of the circuit breaker mechanical characteristic tester's stable measurement and applicability to multiple scenarios. In the same system, the measurement value of the circuit breaker mechanical characteristic tester is used as a benchmark to calibrate the error of the online monitoring system based on transient electrical signals. The wiring diagram of the mechanical tester used in this experiment is shown in Figure 7.

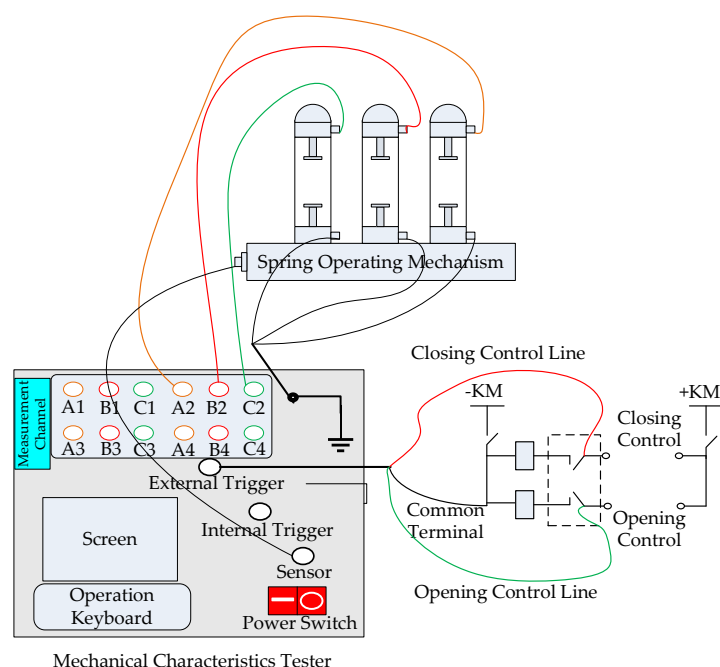


Figure 7. Circuit breaker mechanical characteristics tester test wiring diagram.

The mechanical characteristic test of the vacuum circuit breaker is completed by a digital mechanical characteristic tester. In the process of online monitoring, in order to ensure safety, the background control usually pressurizes the opening and closing coils through an external power supply. When wiring, the auxiliary contacts of the circuit

breaker need to be connected to prevent the coil from burning due to long-term power supply. The time signal is drawn from the upper and lower plum blossom contacts of the circuit breaker.

When the circuit breaker is in the open state, the closing test is performed with the closing signal received as the starting point of the timing, and the timing is stopped when the upper and lower contacts are metal-conducting. This period of time is the closing time. When the circuit breaker is in the closed state, the opening test is performed with the opening signal received as the starting point of the timing, and the timing is stopped when the upper and lower contacts are separated. This period of time is the opening time.

4.2. Self-Calibration Method for Opening and Closing Points

The method adopted in this paper is to calibrate the opening and closing time points of the circuit breaker through transient electrical signals, so as to calculate the opening and closing time. Due to the influence of noise and other factors, there will be certain interference in the acquisition of electrical signals. In order to improve the accuracy of this method, an error compensation link is introduced in the calculation process. Most of the research on error compensation of mechanical and time characteristic parameters of circuit breakers is still at the level of error source modeling, and most of them are offline compensation methods. Based on this, this paper gives an intelligent model-free real-time error compensation method that can effectively process data online, combined with preliminary error mean compensation and further compensation of intelligent compensation module to ensure that the final error meets the expected range. The compensation process is shown in Figure 8.

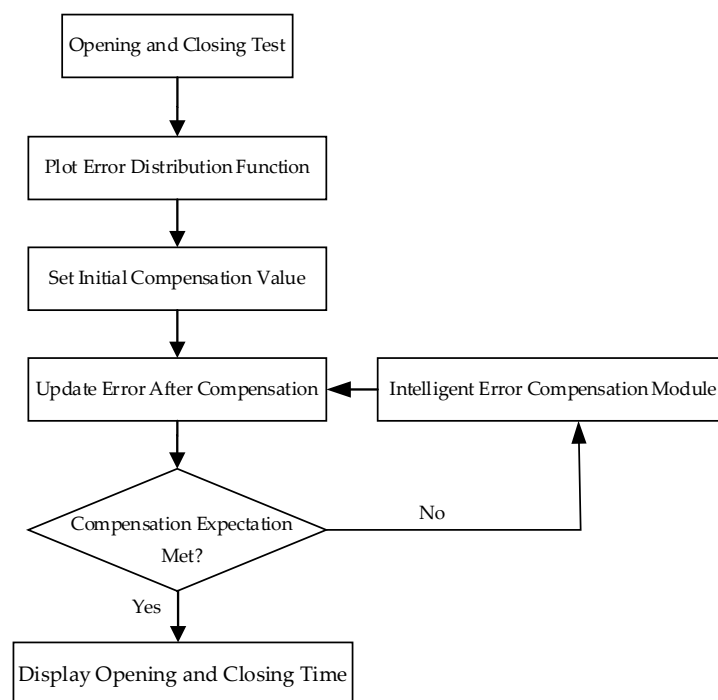


Figure 8. Compensation Flowchart.

A 10 kV opening and closing test platform was built to perform opening and closing operations, and transient electrical signal waveforms were collected. The opening and closing calculation time was obtained by calibrating the opening and closing points. At the same time, the advantage of the circuit breaker mechanical characteristic tester was the stability of the measurement, and the opening and closing time was measured as a benchmark to obtain the calculation error value of the opening and closing time point

based on the transient electrical signal. After multiple groups of tests, the error normal distribution curve was obtained, and the error mean was used as the initial compensation amount. After compensation, it was compared with the benchmark value again, and the intelligent error compensation module was used to compensate until the expected value was met.

The intelligent error compensation module adopts the model-free iterative learning error compensation method, and its structural block diagram is shown in Figure 9. After obtaining the error signal, the LMS (Least Mean Squares) algorithm is used. The LMS algorithm dynamically adjusts the compensation coefficient by minimizing the mean square error between the output signal and the expected signal, so that it can adapt to changes in real time under different environments. After a large number of opening and closing tests, a learning law is obtained to compensate for the error signal. The memory stores historical data of past errors and compensations, and the compensation required for each opening and closing time can be obtained through learning.

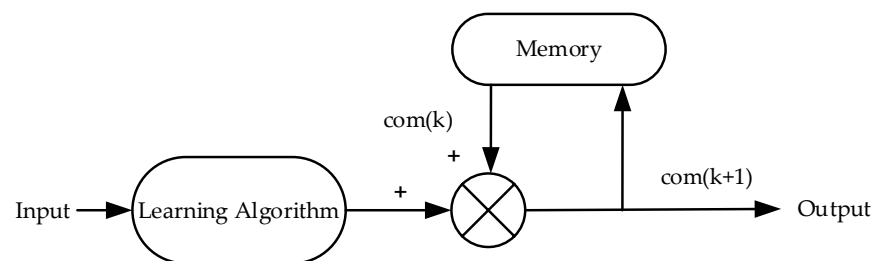


Figure 9. Error compensation iterative learning flow chart.

Assume that the actual measured opening and closing time is t_m , the reference time is t_r , the time error is e_t , the mean error is μ_e , the intelligent compensation amount is τ , and the error is less than the expected value of e_r .

Read the real-time data t_m , and after compensation by the mean error μ_e , the initial compensation opening and closing time t_{c1} can be obtained as:

$$t_{c1} = t_m + \mu_e \quad (8)$$

The initial time error e_t' is:

$$e_t' = t_r - t_{c1} \quad (9)$$

Check whether the error is within the expected range. If so, output t_{c1} . Otherwise, call the intelligent compensation module to compensate for the error. The intelligent compensation amount is τ :

$$\tau = f(\text{Mean Squared Error}, e_t') \quad (10)$$

Calculate the time after final compensation:

$$t_{c2} = t_{c1} + \tau \quad (11)$$

The current measurement and compensation results are stored in the database for the intelligent compensation module to learn and optimize the compensation function.

5. Case Study

This paper takes the ZN28-12 indoor 10 kV vacuum spring energy storage circuit breaker commonly used in power plants as the research object, as shown in Figure 10. An

online monitoring system for circuit breaker opening and closing is built in the laboratory, as shown in Figure 11.

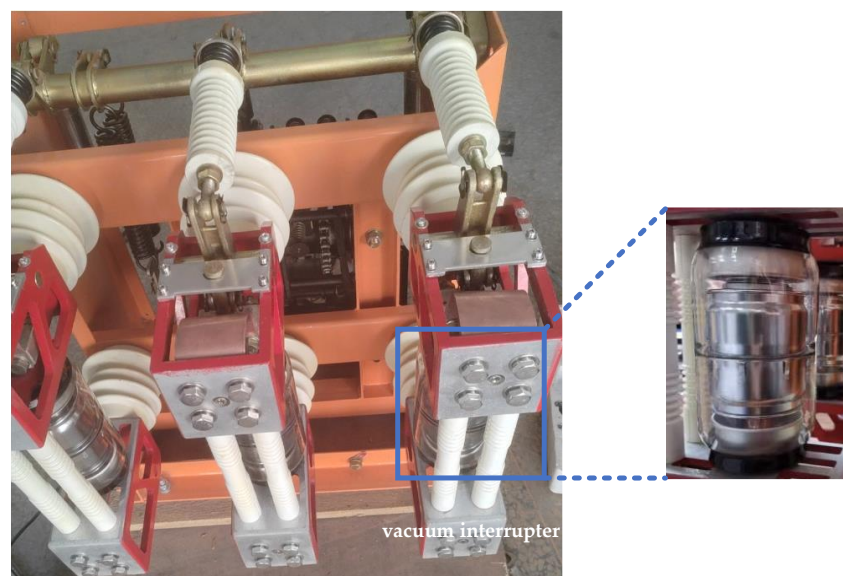


Figure 10. Test the selected circuit breaker.

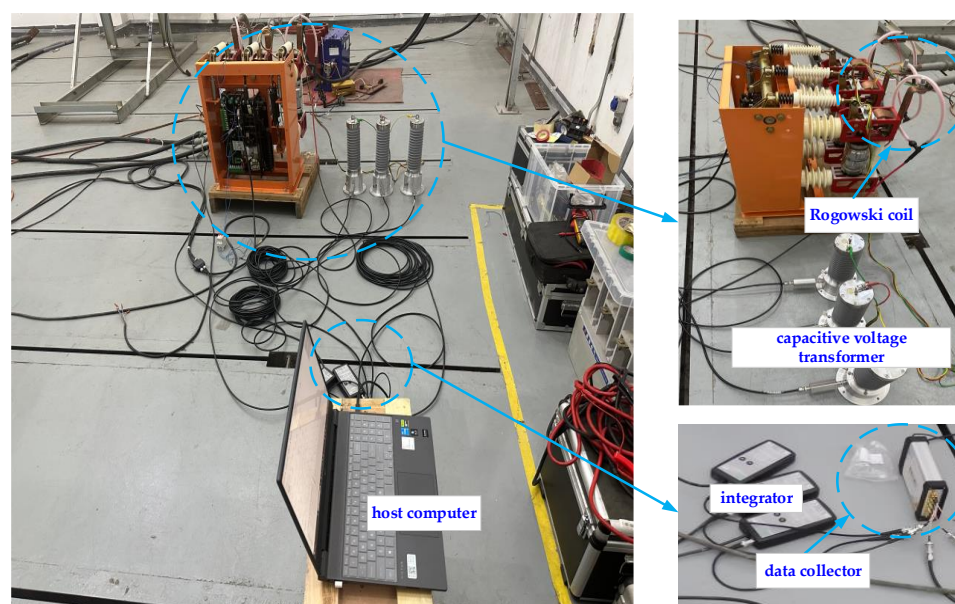


Figure 11. Online monitoring system.

The voltage sensor used in the online monitoring system is a TCF10-300 low-damping high-voltage capacitive voltage divider. After encapsulation, its external insulation is cast with epoxy resin. The overall appearance is similar to that of a lightning arrester. The rated voltage is 10 kV, the voltage division ratio is 1000:1, the sampling rate is 10 MHz, and the accuracy is $\pm 0.5\%$. The current transformer used in the system is a CWT-30B/4/700 Rogowski coil, in which the lead wire is 4 m and the ring circumference is 700 mm. The lead wire length and the ring circumference of the coil have a certain margin, which has good field adaptability, a sampling rate of 10 MHz, and an accuracy of $\pm 0.2\%$. The data acquisition card of this system supports 8-channel synchronous data sampling. While sampling the three-phase current and three-phase voltage, it also leaves a margin of 2 channels for other needs in the later stage. Its sampling rate can reach up to 80 MHz.

Capacitive voltage sensors are installed on both sides of the circuit breaker to measure the transient voltage of the circuit breaker. The Rogowski coil sensor is inserted into one end of the monitoring device to collect the transient current flowing through the circuit during the opening and closing process. The signal is collected by the sensor and transmitted to the acquisition card, which is connected to the upper computer software for analysis and then displays the opening and closing time.

The test conditions in this Section are aimed at measuring transient electrical signals in the closing and opening operating system when the current changes from 13 to 34 A and the power factor angle ($\cos\alpha$) changes from 0.2 to 0.5 when the 400 kVA transformer of the power plant is working at rated state. The main test parameters are shown in Table 2.

Table 2. Test parameter table.

Test Parameter	Opening and Closing Interval Time	Load Parameters
$U_N = 10 \text{ kV}, I_n = 13 \text{ A}$	C-180 ms-O	$R = 88.83 \, \Omega, L = 1385.84 \text{ mH}$ $\cos\alpha = 0.2$
$U_N = 10 \text{ kV}, I_n = 20 \text{ A}$		$R = 86.61, L = 877.03 \text{ mH}$ $\cos\alpha = 0.3$
$U_N = 10 \text{ kV}, I_n = 27 \text{ A}$		$R = 85.54 \, \Omega, L = 624.16 \text{ mH}$ $\cos\alpha = 0.4$
$U_N = 10 \text{ kV}, I_n = 34 \text{ A}$		$R = 84.91 \, \Omega, L = 468.35 \text{ mH}$ $\cos\alpha = 0.5$

5.1. Tests Under Different Working Conditions

Figure 12 shows the transient voltage and current waveforms during the opening and closing process of the circuit breaker. The interval between opening and closing is 180 ms, and the circuit breaker is closed first and then opened. From this waveform, it can be observed that the transient process of opening and closing is only a few dozen milliseconds, and the transient voltage and current waveforms collected by the sensor are complete and obvious.

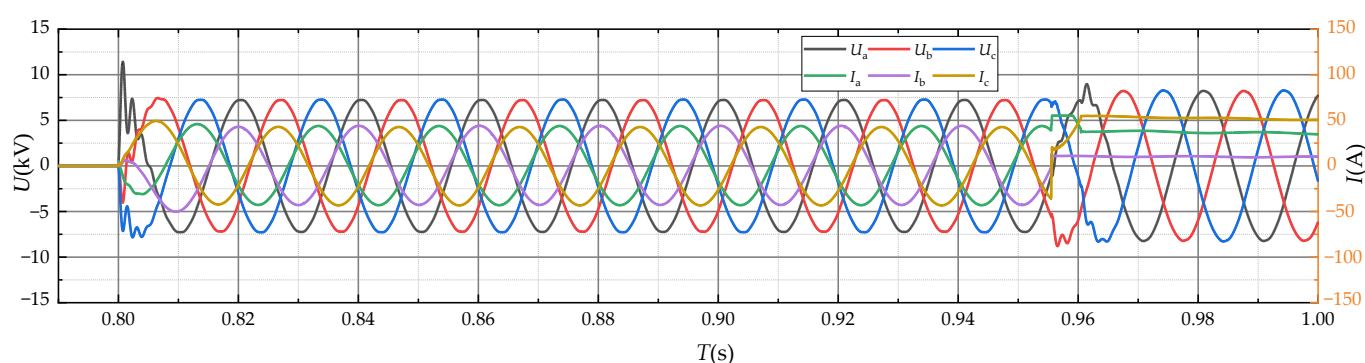


Figure 12. Voltage and current waveforms.

Figure 13 shows the transient voltage and current waveforms in the system during the opening and closing operation when the line voltage is $U_N = 10 \text{ kV}$, $I_n = 13 \text{ A}$, and $\cos\alpha = 0.2$. Figure 14 shows the voltage and current waveforms in the system during the opening and closing operation when the line voltage is $U_N = 10 \text{ kV}$, $I_n = 20 \text{ A}$, and $\cos\alpha = 0.3$. During the opening and closing operation, the transient signal characteristics of the system voltage and current are obvious, and it is easy to mark the opening and closing points.

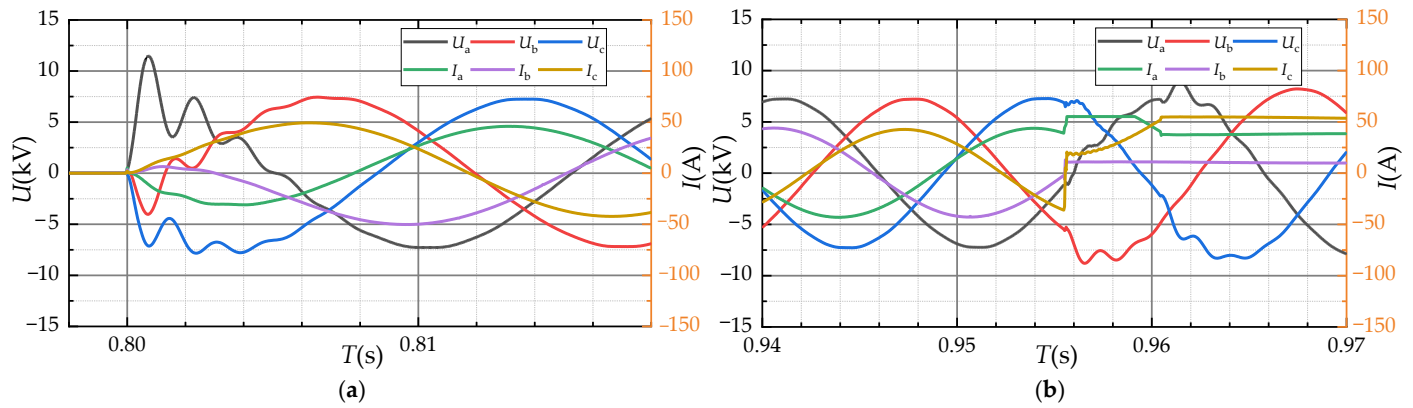


Figure 13. $U_N = 10$ kV, $I_n = 13$ A. Transient voltage and current waveforms in opening and closing test: (a) Closing waveform, (b) Opening waveform.

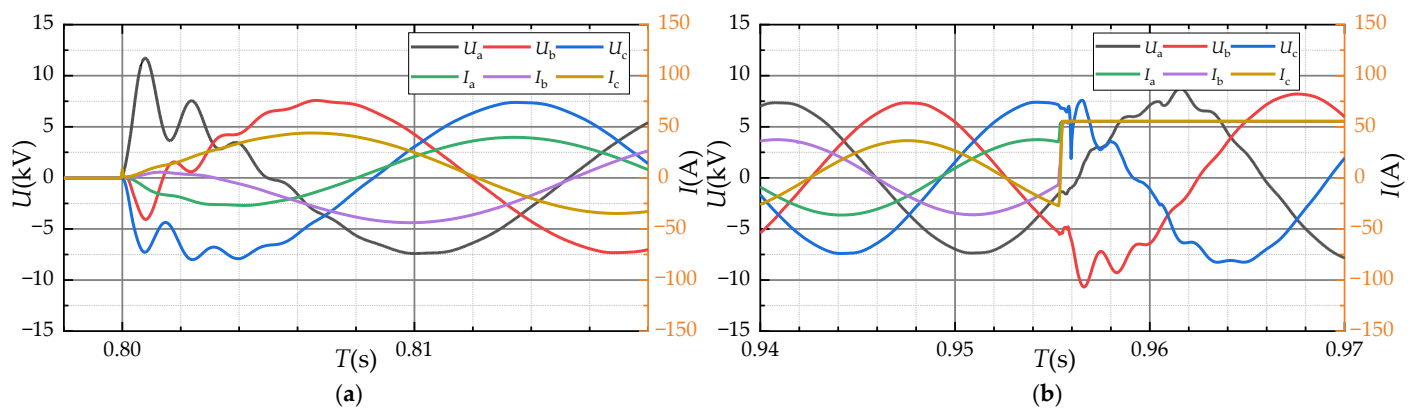


Figure 14. $U_N = 10$ kV, $I_n = 20$ A. Transient voltage and current waveforms in opening and closing test: (a) Closing waveform, (b) Opening waveform.

Figure 15 shows the transient voltage and current waveforms in the system during the opening and closing operation when the line voltage $U_N = 10$ kV, $I_n = 27$ A, and $\cos\alpha = 0.4$. Figure 16 shows the transient voltage and current waveforms in the system during the opening and closing operation when the line voltage $U_N = 10$ kV, $I_n = 34$ A, and $\cos\alpha = 0.5$.

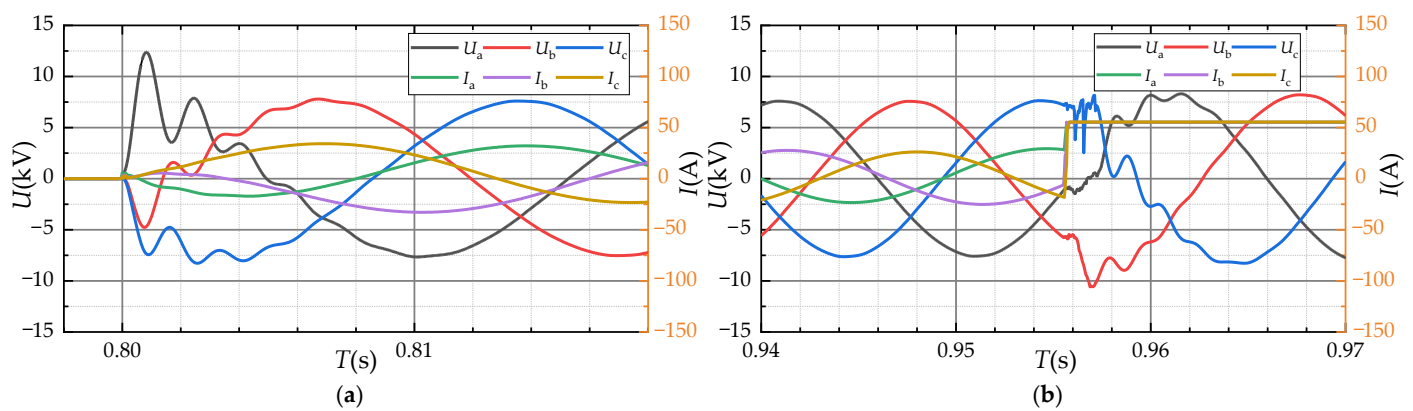


Figure 15. $U_N = 10$ kV, $I_n = 27$ A. Transient voltage and current waveforms in opening and closing test: (a) Closing waveform, (b) Opening waveform.

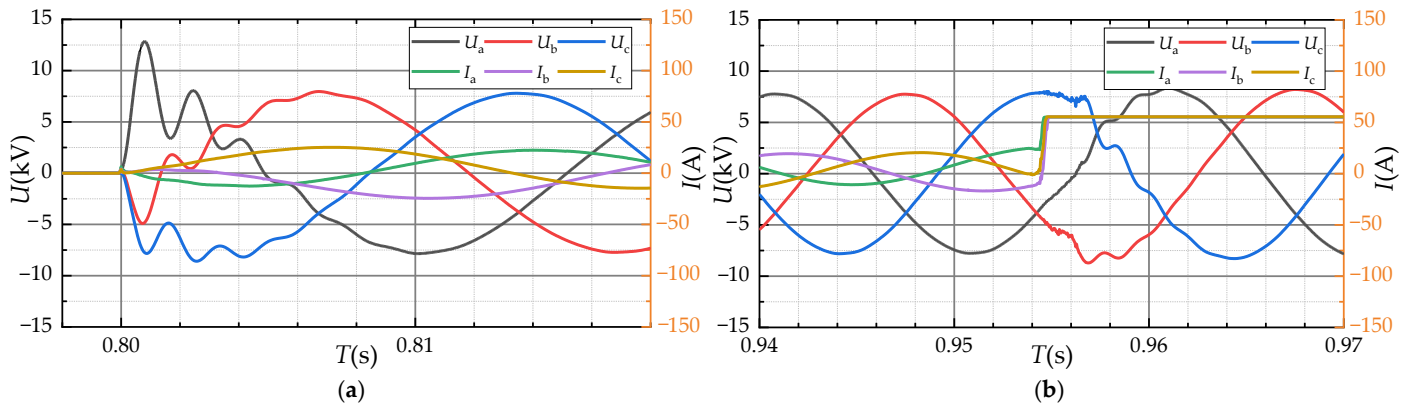


Figure 16. $U_N = 10$ kV, $I_N = 34$ A. Transient voltage and current waveforms in opening and closing test: (a) Closing waveform, (b) Opening waveform.

The purpose of collecting the transient electrical signal waveforms of the circuit breaker opening and closing under different working conditions is to prove that different working conditions have transient electrical signal waveforms that are convenient for opening and closing point calibration. The amplitude of the waveform is accidental and will not decrease with the increase in current. For example, the amplitude of Figure 15b is significantly larger than that of Figure 16b. At the same time, the amplitude of the waveform has nothing to do with $\cos\alpha$, but only with the arc generated by the circuit breaker during the opening and closing process.

During the circuit breaker opening and closing test, the transient current may fluctuate to varying degrees due to factors such as the arc cutoff value. However, this does not affect the calibration of the opening and closing time, because the transient waveform selected for the opening and closing time point calibration is the starting and ending points, not the process quantity. At the same time, the transient voltage waveform can be stably measured, and the transient current only serves as an auxiliary judgment.

The opening and closing time under different working conditions can be calculated by marking the opening and closing start and end points of the opening and closing signals with transient voltage and current waveforms. Transient voltage and current waveforms with obvious opening and closing time feature points are collected under different working conditions. The opening and closing time measurement method based on transient signals is stable, and it can be proved that under different actual working conditions of power plants, the opening and closing time self-calibration can be realized by error compensation, thereby improving the measurement accuracy of the online monitoring system.

5.2. On-Line Measurement of Opening and Closing Time Based on Self-Calibration

In the previous Section, the field test platform was used to prove that the transient voltage and current waveforms can be collected in the circuit breaker opening and closing tests under different working conditions. Phase A of the three-phase circuit breaker with parameters of $U_N = 10$ kV, $I_N = 27$ A, and $\cos\alpha = 0.4$ was selected to carry out a multi-group closing transient electrical signal analysis test.

Before conducting the circuit breaker transient electrical signal test, the circuit breaker mechanical parameter tester was used to measure the closing time–travel curves of multiple groups as shown in Figure 17. The measurement process is to apply a pulse voltage to the opening and closing coils of the circuit breaker through a mechanical stroke tester. The voltage is set to 220 V, and then the displacement–time curve of the moving contact connecting rod is measured by a displacement sensor. The measurement process of each curve is the same, and it is a repeated test under the same parameters. The circuit

breaker mechanical parameter tester can stably measure the closing and opening time, and the closing time was measured to be 44.79 ms and the opening time was 29.84 ms, which were used as the benchmark values of the closing and opening time in this system.

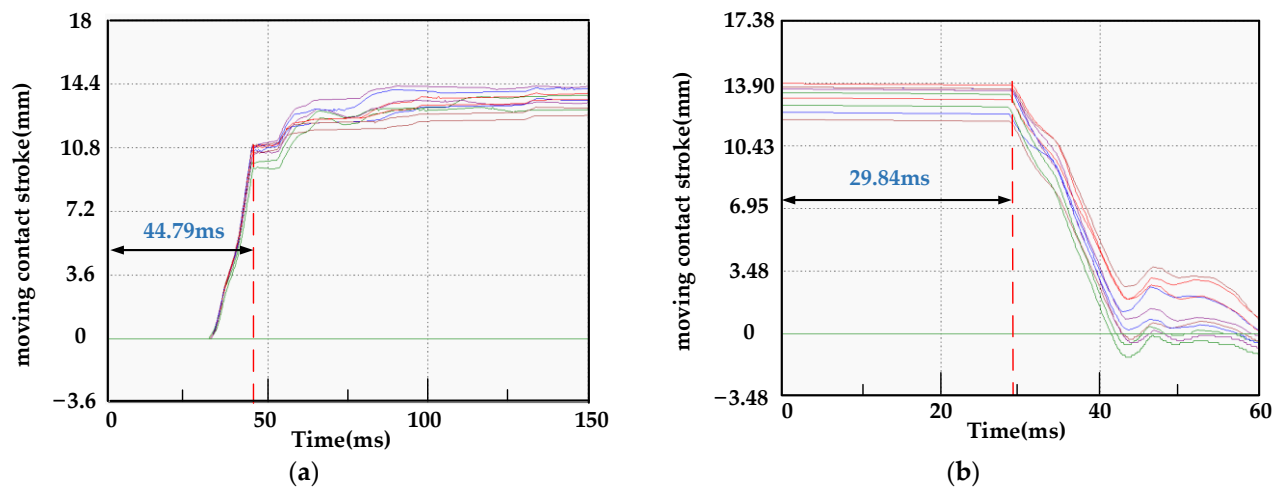


Figure 17. Opening and closing stroke–time curve: (a) Closing stroke curve, (b) Opening stroke curve.

Afterward, through 50 groups of closing tests, multiple groups of transient electrical signal waveforms were obtained. Through the opening and closing point calibration method described in the article, the transient waveform was analyzed to determine the just-opening and just-closing points, and finally, the calculated value of the opening and closing time was obtained. The error value of the opening and closing time is based on the difference between the calculated value of the opening and closing points of the transient electrical signal waveform and the reference value measured by the circuit breaker mechanical characteristic tester. Its normal distribution curve is shown in Figure 18.

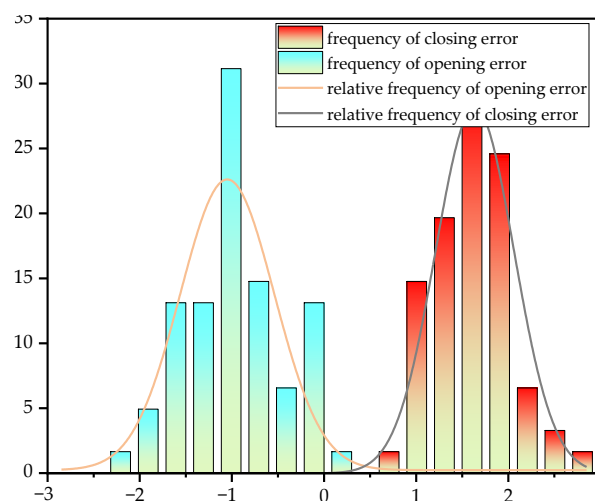


Figure 18. Normal distribution curve of opening and closing time error.

During the opening and closing process, due to certain electromagnetic interference in the environment, there is an impact on the transient electrical signal. The average closing time error is -1.05 ms, and the average opening time error is 1.59 ms.

Then, 30 groups of closing tests were conducted, and the intelligent error compensation module was used for dynamic compensation. The expected value of the closing error was set to 0.5 ms, and the expected value of the opening error was set to 0.5 ms. The LMS

algorithm dynamically adjusted the compensation coefficient by minimizing the mean square error between the output signal and the expected signal, so that it can adapt to changes in real time under different environments. The comparison before and after error compensation is shown in Figure 19.

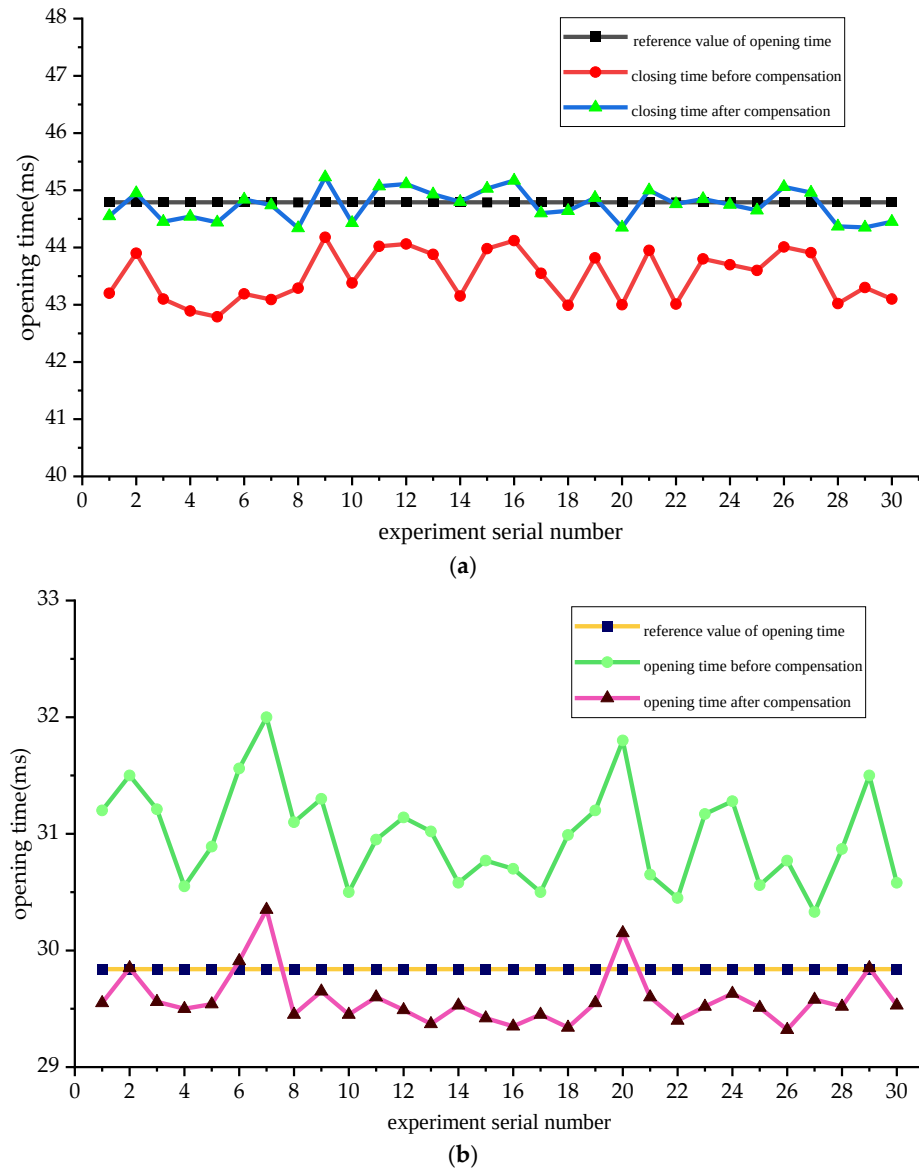


Figure 19. Opening and closing time error compensation: (a) Closing time error compensation, (b) Opening time error compensation.

The reference value of the known closing time measured by the mechanical stroke tester is 44.79 ms, and the reference value of the opening time is 29.84 ms. During the 30-group closing test, the average closing time without error compensation is 43.49 ms, its 95% confidence interval is [43.34 ms, 43.66 ms], and the error range is (0.67 ms, 1.77 ms); the average opening time is 30.98 ms, and its 95% confidence interval is [30.83 ms, 31.14 ms], and the error range is (0.49 ms, 2.16 ms). Without error compensation, the goal of measuring accuracy less than 0.5 ms cannot be achieved.

After error compensation, the average closing time is 44.74 ms, its 95% confidence interval is [44.64 ms, 44.84 ms], and the error range is (0.01 ms, 0.48 ms); the average opening time is 29.34 ms, and its 95% confidence interval is [29.20 ms, 29.46 ms], and the error range is (0.01 ms, 0.43 ms). After error compensation, the error between the closing and

opening time measured by the online monitoring system based on transient electrical signals and the measurement data of the circuit breaker mechanical characteristics tester is less than 0.5 ms. The closing time measurement results of this method are consistent with the measurement results of the mechanical characteristics tester at 98.93%, and the opening time is consistent with 98.56%. This Section simulates the power plant operating conditions and verifies the stability and accuracy of the method in this paper in measuring the closing and opening time of circuit breakers under power plant operating conditions.

6. Conclusions

This paper innovatively proposes a new online monitoring method for calculating the opening and closing time of spring energy storage vacuum circuit breakers during the opening and closing process, breaking the limitation that the traditional method of mechanical and time characteristic detection must be carried out under power outage and maintenance. This method has high stability, reduces the number of circuit breaker operations required for monitoring, increases the operating life of the circuit breaker, and continuously measures data, which is conducive to fault diagnosis and status monitoring of circuit breakers, providing a guarantee for the safe and reliable operation of the power grid.

First, the transient voltage, current, and the motion trajectory of the moving contact during the closing process of the vacuum circuit breaker are analyzed, and based on the analysis, it is found that the opening and closing information can be extracted from the electrical signal waveform, and then the characteristic quantity (the characteristic points of the “appearance and disappearance” of the transient electrical signal) is extracted, and the self-calibration block is introduced into the opening and closing time calculation program for error compensation. Finally, the opening and closing time samples measured by the experiment are compared with the opening and closing time data obtained by the circuit breaker mechanical characteristics tester to verify the stability and accuracy of the method. The comparison of theoretical research and experimental measurement results shows the following:

- The characteristic quantity extracted by the calculation of this method has high reliability. The online monitoring system measures the opening and closing transient electrical signal waveforms of different working conditions in the power plant environment, and the transient voltage and current waveforms with calibrable characteristic points are collected.
- The opening and closing time calculated by this method, after self-calibration, is consistent with the measurement results of the circuit breaker mechanical characteristics tester by more than 99%.
- The opening and closing time calculation method proposed in this paper is directly related to the transient electrical signal generated by the arc during the opening and closing process of the moving and static contacts of the spring energy storage vacuum circuit breaker. This method can be extended to other switching devices with similar mechanisms.

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