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Study on the instantaneous protection reliability of low voltage circuit breakers*

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Abstract: This paper outlines the significance of enhancing the instantaneous protection reliability of low voltage circuit breakers and describes their main failure modes. The instantaneous failure mechanism of low voltage circuit breakers was analyzed so that measures to improve instantaneous protection reliability can be determined. Furthermore, the theory of the instantaneous characteristics calibration device for low voltage circuit breakers and the method of eliminating the non-periodic component of test current are given in detail. Finally, the test results are presented.

Key words: Low voltage circuit breakers, Instantaneous protection reliability, Non-periodic component of current, Phase selective closing
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INTRODUCTION

Low voltage apparatus usually refers to electrical equipments which work as switching, controlling, protecting and detecting elements in low voltage distribution and control systems. Low voltage circuit breakers are the most important low voltage apparatus used for carrying, loading and cutting off current under normal or non-normal conditions (i.e., operating current or overload current and short-circuit current) in the low voltage distribution system or power supply system (National Standard GB14048.2-2001, 2002).

With the development of technology, the electric energy consumption in industry and household living is highly demanding. According to statistics, the distribution and power supply system of a 0.3 million kilowatts generating set generally requires approximately 6900 conventional circuit breakers and 66000 moulded case circuit breakers. At present, in China, the accessorial generator capacity is about tens of millions of kilowatts yearly. The demand of low voltage conventional circuit breakers is about hundreds of thousands per year, and that of low voltage moulded case circuit breakers is about several million.

In addition to the growing demand for low voltage circuit breakers, the performance and quality requirements are increasingly high, especially the requirement for high reliability (O'Donnell *et al.*, 1997; Norris, 1989).

Generally, the major failure modes of low voltage circuit breakers in service can be mainly divided into three types as follows (Schoen, 1989a; 1989b; Hanna, 1995; Chen *et al.*, 2001):

(1) Operational failure: low voltage circuit breakers do not close or open on command of manual /power closing or opening operation, and then cannot connect or break current correctly.

(2) Overload protection failure: the unexpected operation of time-delay trip unit that causes automatic breaking of low voltage circuit breakers without over-load current being present (misoperation); or trip unit of low voltage circuit breakers not being able to reliably break overload current within a defined pe-

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riod of time (refuse operation).

(3) Instantaneous protection failure: the unexpected operation of instantaneous trip unit in automatic breaking of low voltage circuit breakers without short-circuit current being present (misoperation), or the trip unit of low voltage circuit breakers cannot break short-circuit current instantaneously (refuse operation).

This shows that the reliability of low voltage circuit breakers includes the reliability of operation, overload protection and instantaneous protection, in which the reliability of instantaneous protection is the most important. If the reliability of low voltage circuit breakers is not high, and when the short-circuit failure of circuits or equipments occurs, the low voltage circuit breaker cannot cut off short-circuit current; this may lead to burning of circuits and equipments. The power cut in factories or workshops could result in major economic loss. Besides, the reliability of low voltage circuit breakers has also aroused the concern of the international academic world. Reliability work group of low voltage circuit breakers in IEEE Power Systems Technical Committee carried out an international survey on low voltage circuit breakers. The survey results showed that the failure probability of trip unit calibration of low voltage circuit breakers was the highest rate, and was twice that of other failure modes (mechanical malfunction and electrical malfunction). Therefore, study on the instantaneous protection reliability of low voltage circuit breakers is of great significance.

INSTANTANEOUS FAILURE MECHANISM OF LOW VOLTAGE CIRCUIT BREAKERS

Problem of instantaneous characteristics calibration for low voltage circuit breakers

At present, calibration stand is commonly used for instantaneous characteristics calibration of low voltage circuit breakers. The circuit diagram of instantaneous characteristics calibration stand is shown in Fig.1.

The calibration stand's imprecision in instantaneous characteristics of low voltage circuit breakers is due to the following factors:

(1) Voltage fluctuations.

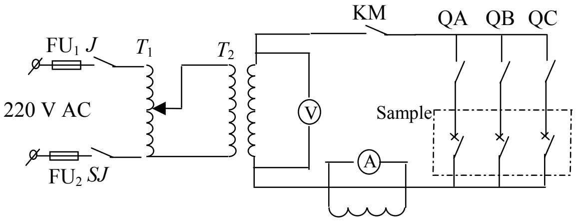


Fig.1 Circuit diagram of calibration stand

It can be seen from Fig.1 that the test current will change with voltage fluctuations, leading to the calibration errors.

(2) Dispersive internal resistance of test samples, the changes of environmental temperature.

The conventional method of calibration is only for detecting the test current of the first test sample with the same product specifications. This kind of calibration method is inappropriate. The internal resistance of different circuit breakers or even different circuit breaker poles is different due to the materials and production process, especially for breakers whose rated current is low. Besides, it cannot be ignored that the environmental temperature changes or the temperature rise of wires in test circuits has impact on the test current (Chen, 1989). Thus, in Fig.1, even the supply voltage is invariable, so that the test current through the circuit breaker will not be constant, leading to the instantaneous characteristics error of circuit breakers.

(3) Different closing phase angle.

During the instantaneous characteristics calibration, the supply voltage in Fig.1 is randomly imposed, thus the current through the release coil includes the non-periodic current component. The non-periodic component of current is related to the closing voltage phase angle ψ. The random changes with different closing phase angle of the test current lead to inaccuracy of instantaneous characteristics calibration.

The first two factors are easy to understand, the analysis of the third factor is given in detail as follows.

Analysis of transient process of instantaneous characteristics calibration for circuit breakers

The National Standard GB14048.2 (IEC60947-2) provides the requirements of instantaneous characteristics calibration for low voltage circuit breakers: for circuit breakers in distribution system, the instantaneous characteristics calibration current is $10I_N$, error is ±20%; for circuit breakers controlling motor, the instantaneous characteristics calibration current is $12I_N$, error is ±20%. And the test circuit should have the function of timely breaking. The circuit diagram of instantaneous characteristics calibration device for moulded case circuit breakers is shown in Fig.1.

The test circuit is composed of auto-transformer T_1, heavy current transformer T_2, contactor K_1, and time relay J. The timely breaking of test circuit can be accomplished by the normally closed contacts of time relay J.

According to the requirements of moulded case circuit breakers, the detective standard of qualified products is shown in Table 1, in which t_T is the limit of release time, 100~200 ms in general.

Table 1 Requirements of instantaneous characteristics for circuit breakers

Applied current	Release time
$8I_N$	$\geq t_T$
$12I_N$	$\leq t_T$

The detailed test method is as follows:

(1) Connect test sample, close K_1, make the test current equal to I_N by adjusting the voltage regulator, then record the output voltage of voltage regulator U_N, break K_1;

(2) Adjust the voltage regulator, make output voltage of voltage regulator to be $8kU_N$, $k>1$ (determined according to experiences in order to ensure the test current to be $8I_N$), close J, meanwhile, make SJ break on time, observe whether the test sample trips;

(3) Adjust voltage regulator, make its output voltage $12kU_N$, $k>1$, close J, meanwhile, make SJ break in proper time, observe whether the test sample trips.

The equivalent circuit diagram of Fig.1 is Fig.2.

In the closing moments of switch K, the voltage balance equation is:

$$u = Ri + L\frac{\mathrm{d}i}{\mathrm{d}t}, \tag{1}$$

where u is applied voltage.

Assume that the applied voltage in the closing moments is:

$$u = U_\mathrm{m}\sin(\omega t + \psi). \tag{2}$$

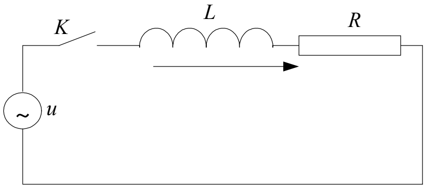


Fig.2 The equivalent circuit diagram of test circuit (Fig.1)

If Eq.(2) is incorporated into Eq.(1), Eq.(3) can be obtained:

$$\begin{aligned} i &= \frac{U_\mathrm{m}}{Z}\sin(\omega t + \psi - \varphi) - \frac{U_\mathrm{m}}{Z}\sin(\psi - \varphi)\mathrm{e}^{-t/T} \\ &= I_\mathrm{m}\sin(\omega t + \psi - \varphi) - I_\mathrm{m}\sin(\psi - \varphi)\mathrm{e}^{-t/T}, \end{aligned} \tag{3}$$

where $Z = \sqrt{R^2 + (\omega L)^2}$ is loop resistance; φ=arccos(R/Z) is power factor angle; $T=R/L$ is circuit time constant.

Assume that $i_1=I_\mathrm{m}\sin(\omega t+\psi-\varphi)$, $i_2=-I_\mathrm{m}\sin(\psi-\varphi)\mathrm{e}^{-(t/T)}$.

Then Eq.(2) can be written as:

$$i = i_1 + i_2. \tag{4}$$

Eq.(4) shows that i_2 is the component exponentially decaying with time, which is called non-periodic component (or transient component). With the extension of time, its value tended gradually to zero; i_1 is a periodic function of time, which is the expected test current and whose effective value is $I_1 = U_\mathrm{m}/(\sqrt{2}Z)$; I_m is the peak value of periodic component. i_2, the transient component during the test, should be eliminated. The following analysis yields the influence of non-periodic component on the test current.

First, the extreme case is discussed:

$$\psi - \varphi = -\pi/2. \tag{5}$$

If Eq.(5) is incorporated into i_1, i_2 and i, the following can be obtained:

$$i_1 = -I_\mathrm{m}\cos\omega t, \tag{6}$$

$$i_2 = I_\mathrm{m}\mathrm{e}^{-t/T}, \tag{7}$$

$$i = I_\mathrm{m}(\mathrm{e}^{-t/T} - \cos\omega t). \tag{8}$$

In Fig.3, the solid line shows the waveform of i, the dashed line that of i_1.

It can be seen from Fig.3 that the peak of i is 60% larger than the peak of i_1. That is to say, the experimental test current is 1.6 times the current needed. According to this ratio, if $12I_N$ is needed, the actual current value is $19.2I_N$. Thus, the circuit breakers, qualified by the current calibration through this actual current, may not operate when short-circuit current occurs in service and at the same time the non-periodic components are very small, or even non-existent due to the random closing phase angle.

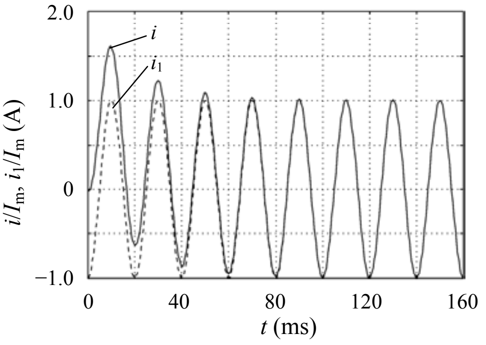


Fig.3 Test current waveform

Fig.4 gives the relationship of closing phase angle and the current peak, in which the abscissa denotes $\psi-\varphi$, radian unit; the ordinate denotes the ratio of i_m to I_m. When $\psi-\varphi=\pm(\pi/2)$, the difference between the actual current value and the expected current value will be the biggest. When $\psi-\varphi=0$, the two current values are the same. It can be deduced from Eq.(4) that when $\psi-\varphi=0$, $i_2=0$; $i=i_1=-I_m\sin\omega t$.

It can be concluded from the above analysis that: during the instantaneous characteristics calibration of moulded case circuit breakers, the non-periodic components of current on closing is related to the supply voltage phase, i.e. the closing phase angle. The non-periodic components of current will be equal to zero when the closing phase angle is the same as that of the power factor angle.

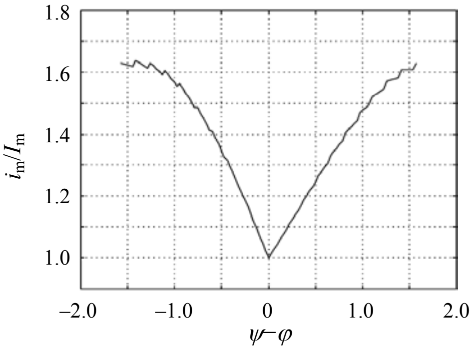


Fig.4 Relationship between $\psi-\varphi$ and i_m/I_m

MEASURE FOR IMPROVING INSTANTANEOUS PROTECTION RELIABILITY OF CIRCUIT BREAKERS

Elimination of calibration error due to factors such as voltage fluctuations, dispersive internal resistance of test samples and the environmental temperature changes

Each instantaneous characteristics calibration is divided into two steps: first, every test sample is calibrated by the rated current I_N, and then by $8I_N$ or $12I_N$. Such complicated calibration should be accomplished efficiently by the computer controlled instantaneous characteristics calibration test device instead of the manual methods currently used.

Elimination of calibration error due to the factors of different closing phase angle

During the instantaneous characteristics calibration of circuit breakers, the non-periodic components of test current should be eliminated. According to the previous analysis, we can see that the non-periodic components of test current can be eliminated when $\psi-\varphi=0$. Therefore, the first thing we should do is to calculate the power factor angle φ of test circuit rapidly, and the second is to make the closing phase angle ψ be equal to φ by the phase selective closing method.

The above analysis shows that such instantaneous characteristics calibration test device can improve the accuracy of calibration and increase the instantaneous protection reliability of circuit breakers. The principle of the instantaneous characteristics calibration test device we developed will be detailedly discussed in the next section.

INSTANTANEOUS CHARACTERISTICS CALIBRATION TEST DEVICE

Technical performance of calibration test device

The main technical performances of instantaneous characteristics calibration test device of circuit breakers are as follows:

(1) Eliminate the calibration error due to the non-periodic components of test current produced by the traditional calibration test device, and thus improve the quality and reliability of moulded case circuit breakers;

(2) The range of current rating is 6~225 A, the maximum of current is 3500 A;

(3) The test device has four installation positions on which the rated currents of test samples are different, seen in Table 2.

(4) Users can input such test parameters as rated current of test samples, the releasing time according to the actual test requirements;

(5) Perfect data protection function: data will not be lost when power is cut off accidentally;

(6) Record the test results automatically and print the test data and waveform;

(7) Easy to use with good man-machine interface.

Table 2 Current range of calibration test device

Installation position	Rated current of test samples (A)
1	100~225
2	40~100
3	16~40
4	6~16

Hardware design of test device

The instantaneous characteristics calibration test device of moulded case circuit breakers (MCCB) is mainly composed of two parts: the control cabinet and detection cabinet. The diagram of the test device is shown in Fig.5.

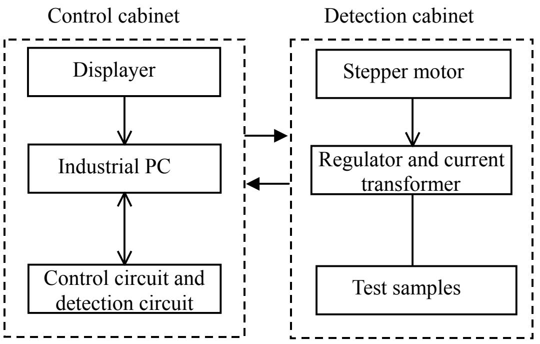


Fig.5 Diagram of instantaneous characteristics calibration test device

1. Control cabinet

The control cabinet is composed of industrial PC, the detection circuit and control circuit. The main function of the detection circuit is to detect the voltage and current in the test loop, the circuit power factor, and voltage phase. The control circuit is made of 6 contactors, 2 relays and 1 solid state relay. Two relays are used to control the rotation of stepper motor so as to increase or decrease the test current.

2. Detection cabinet

The main circuit diagram of the detection cabinet is shown in Fig.6.

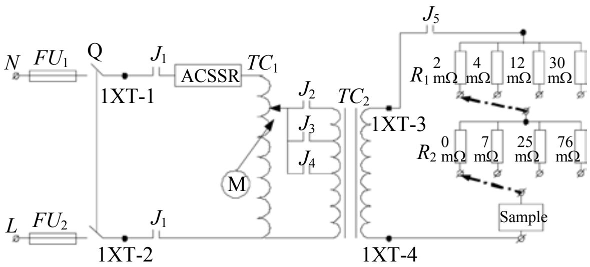


Fig.6 The main circuit diagram of detection cabinet

The main circuit is composed of electric auto regulator TC_1, AC solid relay (ACSSR), transformer TC_2, Frederick resistor R_1, balance resistance R_2 and the contactors J_1~J_5. The electric auto regulator is used to adjust the test current, which is controlled by relays K_1 and K_2. When K_1 is closed, the stepper motor rotates positively and the voltage increases; when K_2 is closed, the stepper motor rotates reversely and the voltage decreases. When the original voltage of TC_1 remains unchanged, and the contactors J_2,J_3, J_4 are closed respectively, we can obtain three vice voltages U_N, $8U_N$, $12U_N$ and the needed test current is produced correspondingly. Thus, we can obtain the accurate test current rapidly with the regulation of electric voltage regulator (Rieder and Strof, 1990; Lu *et al*., 1990).

Software design of test device

The software of test device mainly includes two technical key points: one is regularly interrupted technology which is used for timing control and data acquisition; another is graphic technology which is used for drawing the real-time dynamic curve of test parameters.

The main functions of the applied software are as follows:

(1) To modify such test parameters as the name of test samples, rated current and release time;

(2) To control the test: producing the rated current or the upper/lower limit current users set; acquisition of the voltage and current values; confirming the qualified state of test samples; calculating the power factor angle; phase selective closing; controlling the on/off state of contactor J_2, J_3 and J_4 by timing operation technology;

(3) Printing and displaying the test data.

Through the above analysis on the system's requirements, the software should be made of four levels of functional modules shown in Fig.7.

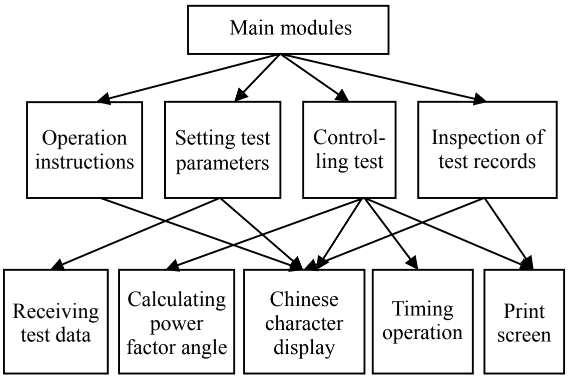


Fig.7 The call relations of three levels of functional modules

Principles and methods of eliminating the non-periodic components of test current

It can be seen from the above analysis that the non-periodic components of test current can be eliminated when $\psi-\varphi=0$. Therefore, the most important thing is to rapidly obtain the accurate value of power factor angle φ of test circuit. It is accomplished by the Fast Fourier Transform (FFT) method.

1. Fast Fourier Transform method

There are two methods of signal analysis: time-domain analysis and frequency domain analysis. FFT is used to convert the time-domain signal into a frequency domain signal.

FFT is shown in Eqs.(9) and (10), where $h(t)$ is the time-domain signal, $H(f)$ is the frequency domain signal.

$$H(f)=FT(h(t))=\int_{-\infty}^{+\infty}h(t)\mathrm{e}^{-\mathrm{j}2\pi ft}\mathrm{d}t, \tag{9}$$

$$h(t)=FT^{-1}(H(f))=\int_{-\infty}^{+\infty}H(f)\mathrm{e}^{\mathrm{j}2\pi ft}\mathrm{d}f. \tag{10}$$

The above shows the mutual conversion between the time-domain signal and the frequency domain signal. This method can be used to analyze the spectrum of the time-domain signal and similarly, represent the time-domain signal according to the signal spectrum.

$H(f)$ is a complex function, which contains real and imaginary parts: $H(f)=\mathrm{Re}H(\mathrm{e}^{\mathrm{j}\omega})+\mathrm{Im}H(\mathrm{e}^{\mathrm{j}\omega})$. It can be also expressed in amplitude and phase: $H(f)=|H(f)|\mathrm{e}^{\mathrm{j}\phi(f)}$, where, $|H(f)|=[(\mathrm{Re}H(\mathrm{e}^{\mathrm{j}\omega}))^2+(\mathrm{Im}H(\mathrm{e}^{\mathrm{j}\omega}))^2]^{1/2}$, $\phi(f)=\arctan[\mathrm{Im}H(\mathrm{e}^{\mathrm{j}\omega})/\mathrm{Re}H(\mathrm{e}^{\mathrm{j}\omega})]$.

In fact, the sampling of the signal is always conducted in a limited time interval, which is called as time window. Fig.8 shows the available sampling data and the spectral characteristics of their counterparts in the limited time.

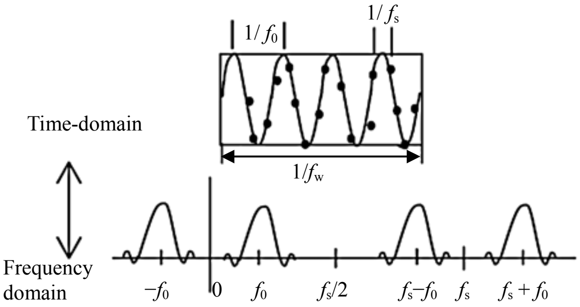


Fig.8 The sampling data and the spectral characteristics in time window

There are several definitions of time intervals: the given component cycle of the spectrum $1/f_0$, the cycle of time window $1/f_w$, the sampling cycle $1/f_s$.

Their radio frequency domain characteristics are: spectrum frequency f_0, peak width f_w, spectrum cycle interval f_s.

By the Z Transform of Eqs.(9) and (10), the Discrete Fourier Transform (DFT) can be obtained:

$$X(k)=\sum_{n=0}^{N-1}x(n)\mathrm{e}^{-\mathrm{j}2\pi nk/N},\ k=0,1,\cdots,N-1, \tag{11}$$

$$x(n)=\frac{1}{N}\sum_{k=0}^{N-1}X(k)e^{\mathrm{j}2\pi nk/N},\ n=0,1,\cdots,N-1, \tag{12}$$

where N is the number of data acquisition in time window in the time domain, i.e.,

$$N=f_s/f_w, \tag{13}$$

$x(n)$ is N sampling data in the time domain, $X(k)$ is K data in the discrete spectrum.

The number of discrete spectrum is determined by the number of sampling points in the time domain, i.e., the resolution of spectrum v is:

$$v=f_s/N=f_w. \tag{14}$$

2. Calculation of power frequency

The power frequency should be calculated first in order to obtain the early phase angle of the test voltage and current signals. The specific methods of calculating the frequency is: put N sampling data of voltage into arrays $x(n,1)$, FFT, then put the real part of results into arrays $x(n,1)$, and the imaginary part into arrays $x(n,2)$; identify the absolute best location k of the real and imaginary parts. The power frequency can be calculated by the following formula: $f_0=(k-1)f_s/N$.

3. Calculation of power factor angle

The power factor angle is the phase difference between voltage and current in the same loop. Thus, the power factor angle can be obtained by calculating the early phase angle based on the analysis of sampling data of voltage and current.

The voltage and current signal can be expressed as:

$$h(t)=\sin(2\pi f_0 t+\alpha), \tag{15}$$

where α is the early phase angle of voltage or current signal.

If $f_0=Mf_w$ is not valid, the approximate calculation method of the early phase angle is:

Supposed that $t_W=Mt_0+t_\Delta$, i.e. t_Δ is the remainder of t_0 in addition to t_W.

Assume that $\theta=2\pi f_0 t_\Delta$, FFT is equivalent to:

$$H(f_0)=\int_{-t_W/2}^{t_W/2}\sin(2\pi f_0 t+\alpha+\theta/2)\mathrm{e}^{-\mathrm{j}2\pi f_0 t}\mathrm{d}t. \tag{16}$$

Assume that $\beta=\alpha+\theta/2$, then Eq.(16) will be:

$$\begin{aligned}H(f_0)&=\int_{-t_W/2}^{t_W/2}\sin(2\pi f_0 t+\beta)\left[\cos(2\pi f_0 t)-\mathrm{j}\sin(2\pi f_0 t)\right]\mathrm{d}t\\&=\frac{1}{4\pi f_0}\{\sin\theta\sin\beta+(2\pi M+\theta)\sin\beta\\&\quad-\mathrm{j}[\sin\theta\cos\beta+(2\pi M+\theta)\cos\beta]\}.\end{aligned}$$

Because $(2\pi M+\theta)>>\sin\theta$, the above formula can be approximated to:

$$H(f_0)\approx\frac{2\pi M+\theta}{4\pi f_0}(\sin\beta-\mathrm{j}\cos\beta). \tag{17}$$

It can be concluded from Eq.(17) that the ratio of real and imaginary parts of spectrum in f_0 is:

$$\frac{\mathrm{Re}\,H(f_0)}{\mathrm{Im}\,H(f_0)}=-\mathrm{tg}\beta. \tag{18}$$

Because $\beta=\alpha+\theta/2$, then

$$\alpha=-\arctan\frac{\mathrm{Re}\,H(f_0)}{\mathrm{Im}\,H(f_0)}-\frac{\theta}{2}. \tag{19}$$

When $f_0=Mf_w$ is valid, then $t_W=Mt_0$, $\theta=0$,

$$H(f_0)=\frac{M}{2f_0}(\sin\alpha-\mathrm{j}\cos\alpha). \tag{20}$$

The early phase angle is:

$$\alpha=-\arctan\frac{\mathrm{Re}\,H(f_0)}{\mathrm{Im}\,H(f_0)}. \tag{21}$$

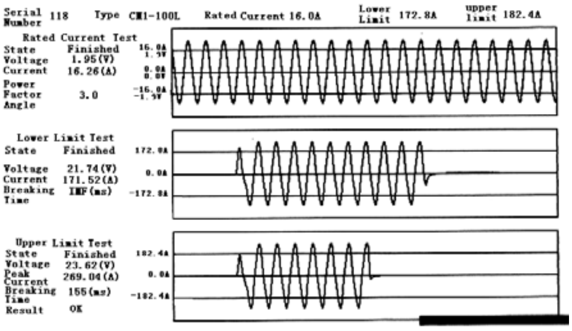
Thus, the power factor angle φ can be obtained by calculating the early phase angle of voltage and current.

TEST RESULTS

The waveform of test current during the instantaneous characteristics calibration test is shown in Fig.9.

CONCLUSION

Low voltage circuit breaker is a major category of electrical apparatus, which has an important role in the national economy due to its production capacity and wide use. It is of great theoretical and practical value to study and improve the instantaneous char-


Serial Number 118 Type CM1-100L Rated Current 16.0A Lower Limit 172.8A upper limit 182.4A

Rated Current Test
State Finished
Voltage 1.95(V)
Current 16.26(A)
Power Factor Angle 3.0

Lower Limit Test
State Finished
Voltage 21.74(V)
Current 171.52(A)
Breaking Time INF(ms)

Upper Limit Test
State Finished
Voltage 23.62(V)
Peak Current 269.04(A)
Breaking Time 155(ms)
Result OK

Fig.9 Waveform of test current

acteristics calibration technology of MCCB because it is related to the quality and reliability of MCCB. This paper provides the following:

(1) Research of the phase selective closing technology to eliminate the calibration error due to the non-periodic components of test current.

In the closing moment, the test current through the contacts includes the periodic and non-periodic component. The current peak increase as the non-period components affects the instantaneous characteristics calibration accuracy of circuit breakers. FFT method was used for calculating the power frequency and power factor angle, so that the calibration error can be eliminated by such calculation method and the phase selective closing technology.

(2) Research of computer control and detection technology.

In addition to the main circuit design, the computer control and detection technology is also the core. The main functions of this part are: timing control, detection of test parameters, waveform display of test data, parameters modification, confirmation of qualified state of test samples, and data storage and processing.

(3) Development of instantaneous characteristics calibration test device for moulded case circuit breakers.

The instantaneous characteristics calibration test device of MCCB includes a main circuit, the control and detection modules and the hosts. The test current for calibration is generated by controlling the output voltage of electric regulator with the PID control algorithm. The current detection is achieved by the acquisition of voltage drop on the sampling resistor. In short, reasonable hardware and software are designed to meet the functional requirements of the test device.

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