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Study and Equipment Development on Transient Characteristics Test on Electronic Current Transformer

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SUMMARY

With the increasing capacity and the rising voltage level of power grid, the breakers will cut out the fault of short circuit in very short time. This requires the transient characteristics of the current transformers to be good enough to reflect the short circuit current signal. The system short circuit current of the 500kV and above voltage class grid exceeds tens of kA, with time constant even 100ms above. However ECT has a large deviation in detecting different primary time constants of the system.
As for ECT transient characteristic test method, Researchers have done a lot of work of ECT transient characteristic in the laboratory. It is difficult to realize the transient high current for the transient characteristic test, so shat indirect method is used.
This paper proposes a transient characteristic test of ECT on various time scale, which is based on the modular combination, meeting the requirements of peak currents. The transient large current test source are designed as follows: AC component peak current 20kA, frequency 50±5Hz; transient offset current peak 20kA, full DC component offset 40ms-120ms time constant. In addition, through the combination of DC transient controllable current source module and DC impulse current source module, DC surge transient current test and a square wave current test of 20 kA and below for 40 ms-1 min of a DC current transformer can be realized with the current rise rate of 20 kA/800 us and flexible setting of a wide range of time constants.
The experiment results show that the requirements of test technology and the transient test of protective ECT are met, that is realized by providing an overall solution and test equipment for the transient test of current transformers for protection.

KEYWORDS
Electronic current transformer; transient characteristic; primary time constant; modular combination; transient current power supply

1. INTRODUCTION

With the continuous increase of power system capacity and the up-grading of power grid voltage level, once the short circuit fault occurs in the system, the power grid protectors and the breakers will cut out the fault in a very short time, which requires that the transient characteristics of transformers to be good enough to quickly reflect a high-voltage fault signal. As the new generation of smart substation demonstration stations is successfully completed and put into operation, electronic transformer is fully applied in new generation of smart substations [1].

In 110kV smart substations, electronic current transformer (ECT) rated current is generally 600A. According to the protection factor of 20 times, the test current reaches 12kA. The system short circuit current of the 500kV and above voltage class grid is even higher to tens of kA. At the primary side, system time constant generally exceeds 100ms. As far as the technical level of existing test equipment is concerned, it is rather difficult to realize transient high-current power supplies for transient characteristics test [2-3]. Traditional transient characteristics test of current transformer adopts equal ampere-turn method to reduce the overall requirements of test power system. There are still some difficulties in applying this method. As for shunt type current transformer, the ampere-turn method is even hard to perform Due to the structure of ETC itself , the transient characteristic test can only be performed by the direct method, so a current source with sufficient capacity, phase-selective closing function and a primary circuit time constant is required to meet the standard requirements. And it has difficulty in adjusting the time constant and peak current [4-5]. Secondly, limited by the test power equipment, the transfer test after installation of electronic transformers has not been effectively implemented. Consequently, the performance of protection ETC that will be put into operation will not be assessed. Moreover, the primary part of the electronic transformer and the merging unit are often required to be measured as a whole, to realize the digital output of the measurement result [6].

Regarding the issue above, this paper, starting from the transient characteristic test of the protective electronic current transformer (ECT), proposes a transient characteristic test of the protective electronic current transformer technology based on various time scale. And the transient great current test source of protective electronic current transformer is proposed based on the modular combination technology of DC plus current source, DC controlled transient current source and AC transient current source, meeting the requirements of peak current of AC component and DC component's full bias. The transient characteristic test of protective ECT uses the transient great current test device without AC primary current adjuster inductances, which achieves the rapid rise of plus current of DC bias component, and aperiodic component with wide range of time constants is set flexibly. By this way, the problem that the output capacity of AC current and the DC bias current cannot be adjusted separately is solved greatly, and it is taken into account simultaneously. At the same time, the power capacity and volume of test source are reduced greatly, so that the requirements of test technology and the transient test of protective ECT are met.

2. PRINCIPLE ANALYSIS

Firstly, calculate the system short circuit current theoretically. Illustrated in Fig.1, when the system occurs short circuit fault, the fault point is F.

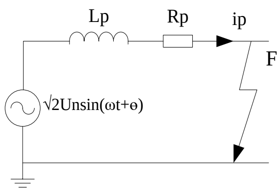


Fig.1 Principle of system short-circuit current

The primary current's instantaneous value is $i_p = \frac{\sqrt{2}\cdot U_n}{\sqrt{R_p{}^2+(\omega L_p)^2}}[\sin(\omega t+\theta-\varphi) - e^{-\frac{R_p}{L_p}}\cdot\sin(\theta-\varphi)]$ (1)

Considering $\varphi = \pi/2$ eq.1 can be expressed as $i_p = \sqrt{2}I_{psc}[e^{-\frac{t}{\tau}}\cos\theta - \cos(\omega t+\theta)]$ (2)

Now, the primary circuit current instantaneous value includes AC component and aperiodic component (or called DC component) decaying by the primary circuit time constant τ two parts. When θ=0, two parts' amplitudes are equal, that is the short circuit current bias 100%, illustrated in Fig.2.

The primary circuit current can be expressed as $i_p = \sqrt{\sqrt{2}I_{psc}[e^{-\frac{t}{\tau}} - \cos(\omega t)]}$ (3)

In the equation, Un is the rated system voltage. Lp and Rp are system equivalent inductance and resistance respectively, and its impedance angle is $\varphi = \tan^{-1}\left(\omega L_p / R_p\right)$ (4)

Ipsc is the RMS of short circuit current steady value, $I_{psc} = \frac{U_n}{\sqrt{R_p{}^2 + (\omega L_p)^2}}$ (5)

τ is the system primary circuit time constant, $\tau = \frac{L_p}{R_p}$ (6)

θ is the angle between initial short circuit voltage and initial short circuit current. Cosθ is the bias degree of short circuit current.

When t=0, the aperiodic component's initial value is greater than any other time which is equal to the amplitude of periodic component and the DC component offsets fully. In IEC standard and national standard, the transient characteristic is calculated mostly in the case that the short circuit current offsets fully. This paper analyzes according to full offset of DC component in the following content [7-8].

Transient characteristic test requires the transient power source meets the following conditions [9-10]:

a) Output current is not less than primary circuit short circuit rate current;

b) Phase selection closing control to realize the rate primary short-circuit current with maximum offset.

c) The primary time constant of the test system meets the current transformer requirements for TP protection, i.e. the deviation is not more than 10%.

d) Realize program control according to the setting request, finish C-O or C-O-C-O work cycle mode.

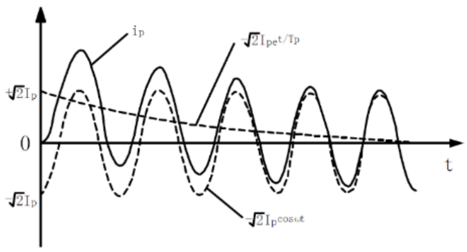


Fig. 2 100% offset current waveform

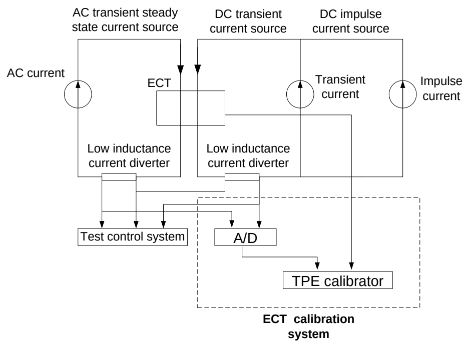


Fig. 3 Schematic diagram of transient characteristic test

3. TRANSIENT CHARACTER TEST METHOD AND SYSTEM ANALYSIS

3.1 Technical Scheme

The design and development of transient character test source is the core of protective CT transient character test system. The primary short circuit current consists of sinusoidal periodic component and exponentially decaying non-periodic components where the sinusoidal periodic component current is generated by AC power frequency inrush current source and the aperiodic component currents are generated by DC inrush current sources and DC transient controllable current sources.

This project proposes synthetic test loop method consisting of a DC inrush current source, transient controllable current source and AC transient test source based on the modular technology. On this basis, the developed transient characteristic test source comprises AC power frequency transient current source, DC inrush current source and DC transient controllable current source. The DC inrush current source decides the current rising edge response time of aperiodic component and outputs the current that decays by the fixed primary time constant. The difference between the total DC transient output current and DC inrush output current is provided by DC transient controllable current source, which greatly reduces the dynamic stability requirements of DC transient controllable current source.

3.2 Technical Parameter Requirements

Protective CT transient characteristic test source system principle is illustrated in Fig.3. Taking the maximum 40kA peak current test power source consisting of a 20kA AC transient current source and a 20kA DC transient current source as an example, its specific functions and technical requirements are as follows:

a) Through the DC transient controllable current source module to achieve 5kA and below the DC current transformer long-term steady-state series of tests, within 1 minute 20kA DC transient current output, the maximum transient output current response speed 10kA/10ms;
b) Through the combination of a DC transient controllable current source module and a DC inrush current source module, a DC surge transient current test and a square wave current test of 20 kA and below for 40 ms-1 min of a DC current transformer can be realized, and an impact current rise rate of 20 kA/800 us, flexible setting of a wide range of time constants can be realized;
c) Because the alternating current transient current source module has no loop adjustable inductance, zero switching and reactive power compensation of the thyristor are adopted, so the power test capacity of the AC transient current module is greatly reduced;
d) Through the combination of the AC transient current source module, the DC transient current source module and the DC inrush current source module, a transient large current test for the transient characteristic test of the protection ECT is realized, and the AC component peak current is met: 20 kA/single turn; The DC output adopts the electrical parallel connection method, the DC component is fully offset, the time constant is 40ms~1min, and the setting of the DC offset inrush current rise rate and a wide range of time constants are flexible;
e) Modular combination design. Through the parallel combination of multiple types of AC and DC currents, AC/DC transients of different types controlled current can be output under all operating conditions.

3.3 Simulation Analysis

According to the technical requirements of the protective ECT transient characteristic test, the technical parameters of the transient large current test source are determined as follows: Primary circuit AC component peak current 20kA, frequency 50±5Hz; transient offset current peak 20kA, full DC component offset, Time constant: 40ms-120ms, arbitrarily adjustable time constant. Based on the DC inrush current source circuit parameters as shown in Table 1, the simulation model is established. The simulation waveforms of each module and the composite transient current are shown in Fig.4.

Table 1 Circuit parameters of test power supply

	Parameter	Value
DC inrush current source	Maximum peak current	20kA
	Primary time constant	23ms
	Current rising time	800us
DC controllable current source	Maximum output current	20kA
	Maximum output voltage	10V
	Maximum current change rate	1kA/ms
AC transient current source	Maximum peak current	20kA
	Maximum output voltage	28V
	Frequency	50Hz
Compounded current source	AC component peak current	20kA
	Transient offset peak current	20kA
	Time constant	120ms

From the simulation results, it can be seen that the overall performance index of the test power system and each source combination meet the system design requirements. The parameters of each combined source module are designed rationally. The dynamic current regulating ability of DC transient controllable current source is 1kA/ms, which is much bigger than the maximum output current change rate of 0.5kA/ms required by DC transient controllable current source to meet the rate regulation requirement of DC transient controllable current, greatly reducing the capacity and dynamic performance requirements of the controllable current source itself.

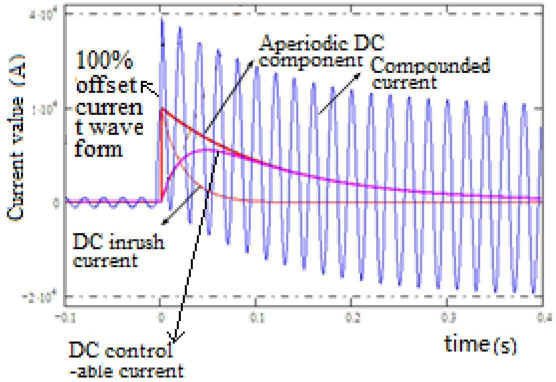


Fig.4 Simulation waveforms of transient characteristic test system

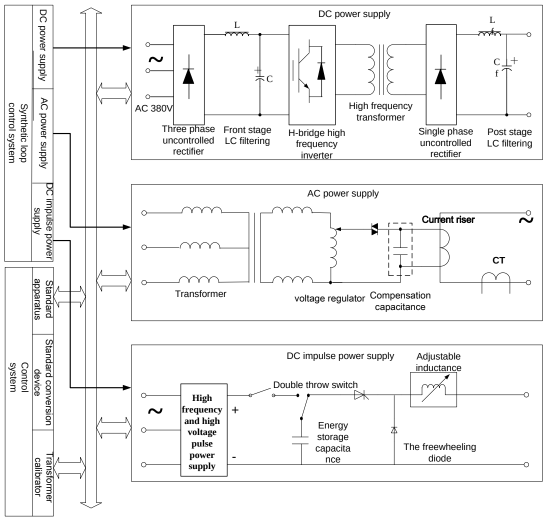


Fig.5 Schematic diagram of transient characteristic test system

4. KEY TECHNOLOGY AND DEVICE DEVELOPMENT

4.1 Modular Design

Based on the system theory analysis, this paper adopts the modular design ideas [8,11-13]. The combination test method of multiple types of different time scales source module is used to realize the modular composition of the transient character test power system for the protection current transformer. The specific implementation of the system is shown in Fig.5.

The transient characteristic test system cancels the tunable inductance of the overall traditional test circuit and uses a fixed small inductor as the rising edge modulation test inductor in the DC inrush current module, thus ensuring the inrush current rise rate and the minimum discharge time constant requirement. The overall test system adopts a modular combination design and integrated control technology to realize the non-inductance or micro-adjustable inductance design of the whole system and the phase selection switching control based on reactive power compensation. Compared with the traditional test scheme, the requirements for energy storage and test power supply are greatly reduced.

4.2 DC Transient Controllable Current Source

The main circuit topology of the modular DC transient controllable high-current source adopts a DC power module based on a phase-shifted full-bridge structure, and the secondary side adopts self-driven synchronous rectification. High-frequency main transformer primary winding, secondary winding and self-driven transformer winding adopts integrated design, which makes full use of the leakage inductance parameters of the primary and secondary sides of the transformer and makes full use of aluminum alloy shell for high current output and heat dissipation. Based on the above, this paper proposes an interleaved and parallel modular control technology based on locked synchronization. The power switches of each module work in a time-series manner. The drive signals have the same frequency, and the phase angles are staggered and alternately turned on, which effectively suppresses the output current ripple of the converter, reduces the filter capacity, and improves the overall efficiency and current quality [14].

The DC transient controllable current source also has the following characteristics:

a) Modular design, which can realize multi-parallel connection to meet the requirements of high peak test current;
b) It has good dynamic performance and accuracy to meet the follow-up performance index of the protective CT transient characteristic test source and the maximum transient output current response speed approaches 10kA/10ms.

4.3 DC Impulse Current Source

This project puts forward higher requirements on the transient characteristics of the test current, which needs to reach a rising dynamic speed of 20kA/800us. The structure of the capacitor energy storage type impact power supply based on pulse shaping network (PFN) is adopted [15-16], which is shown in Fig. 6.

The source mainly consists of high-frequency high-press impulse source, high-press energy storage capacitor, power output inductance, discharge switch, diodes etc. The main work are mainly separated into three phases:

a) Charging phase. In this phase the high-frequency high-pressure impulse source charges the capacitor until the voltage reaches the setting value.
b) Discharging phase. The energy storage capacitor discharges through discharge diode, output inductance and load. At this time the circuit is the typical RLC two orders circuit, and the output current will rise to the peak in a short time.
c) Freewheeling phase. Output current starts to drop after reaching peak. The output inductance produces invers electromotive force which makes the end voltage of freewheeling diode flipped positive and conducting free flow. At this point, the circuit converts to RL one order circuit, and the output current gradually drops to 0.

The rising and falling edges of DC inrush current source output current are respectively shown in eq.7 and eq.8.

$$i_1 = \frac{U_0}{\omega L} e^{-\delta t} sin(\omega t) \quad (0 \le t \le \pi/2\omega) \tag{7}$$

$$i_2 = i_{max} e^{-\frac{t}{\tau}} \qquad (t > \pi/2\omega) \tag{8}$$

Here, $i_{max} = \frac{U_0}{L\sqrt{\delta^2+\omega^2}} e^{-\delta\beta/\omega}$, $\omega = \sqrt{\frac{1}{LC} - \left(\frac{R}{2L}\right)^2}$, $\delta = R/2L$, $\beta = arctan(\omega/\delta)$.

U0 is the charging voltage of capacitor. C is the capacity of energy storage capacitor. L is the system equivalent output inductance. R is the output load impedance.

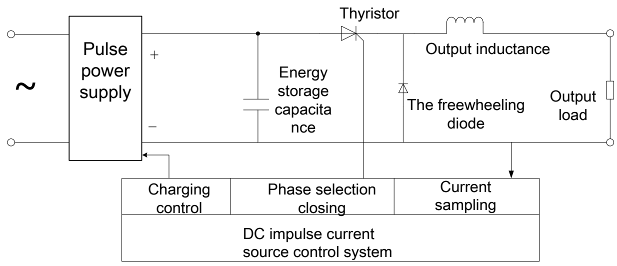


Fig.6 Diagram of DC impulse current source

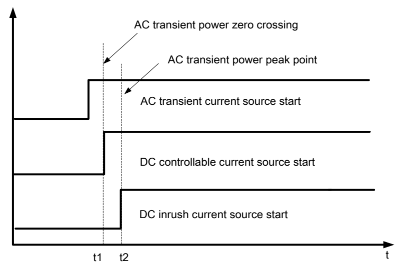


Fig.7 Time sequence of control on transient characteristic test system

4.4 Synchronous Collaborative System Control

As shown in Fig. 7, the difficulty in controlling the power module based on different time scales in this project lies in the synchronous and cooperative control of the system.

The main process is as follows: First, a trigger signal is sent at the zero crossing point of the AC voltage to start the AC transient current; then a DC transient controllable current source is started, and the controllable current source enters the output current adjustment phase; when the transient AC source output current is at the peak current point, a synchronous trigger signal is generated from impact source to produce DC inrush current. When DC inrush current is in freewheeling phase of falling edge, the output current of transient controllable current source is controlled according to preset current curve, and the impulse current source is in coordination with waveform control. A non-periodic DC bias current with a full offset of the DC component is generated, and a desired full offset current is generated based on the output current of the transient AC source.

5. EXPERIMENTAL STUDIES AND RESULTS ANALYSIS

5.1 Test Conditions

Referring to the requirements of national standard GB 20840.2-2014 and GB/T 20840.8-2007 [7-8], the test power supply of the CT transient characteristic detection test system adopts the combination of DC inrush current source, DC controllable current source and AC transient current source, and adopts a 0.05-level high-accuracy shunt meter as the current standard, a high-accuracy 6-digit half-table (HP3456A) as a traceability verification device, and TPY-class CT are used as the tested CT to conduct high-current, large current errors, and transient performance tests [10-16].

5.2 Transient Characteristic Test of DC Controlled Source

The DC controlled current source has two working modes: Steady-state through-flow and transient upwelling flow. Direct method is used to test the stability of the output current of the power supply of DC calibration system. 10%, 20%, 50%, 80%, and 100% of the rated current are injected at the primary side. In steady-state through-flow mode, when the long-term rated current is 5kA, the output current stability and ripple are less than 0.1%, and the high-current output precision is better than 0.2%. In transient upwelling flow mode, at the range of 50% or more transient rated current, the accuracy rate of DC transient controllable current can be within 0.2%, the maximum transient output current is between 10 kA and 20 kA, full range of current response time is faster than 15 to 25ms. Short connect the output end of DC current transient test power supply with high current cable, and the test waveform is measured by the HAZ20000-SB LEM hall sensor, and the output current data are converted from hall sensor output through the measurement of Agilent 6-bit semi-digital voltmeter 34410A. Transient dynamic characteristics of the output current are shown in Table 2, and the step output current waveform of its 20kA DC transient controllable source is shown in Fig. 8.

Table 2Output dynamic performance of DC transient test power source

Initial current(A)	Step current(A)	Termination current (A)	Step time(ms)
400	2000	400	17.4
400	5000	400	19.6
400	10000	400	21.6
400	16000	400	23.4
400	20000	400	25.2

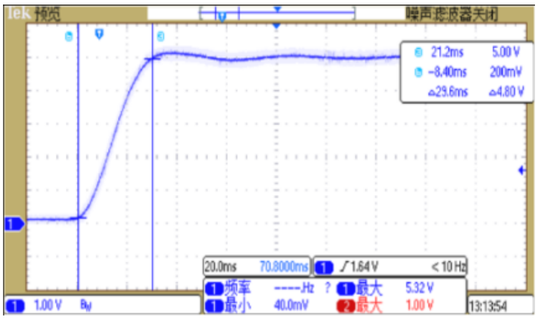


Fig.8 Experimental waveform of DC transient step current

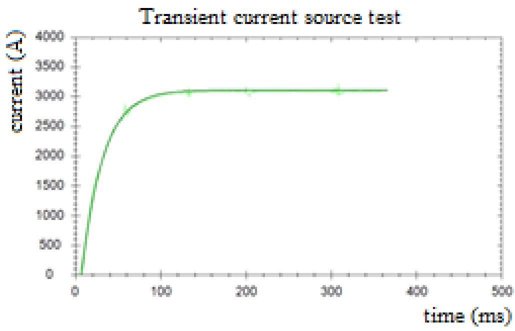


Fig.9 Output current and quasi-step instruction of DC controlled current source

The test results of transient characteristics of DC current are shown in Fig. 10 and it can be obtained that the maximum transient output current is 20 KA, the rising time of current is 29.6 ms. The step-up rate of transient controllable current is better than 6×105A/S. The dynamic tracking performance of DC transient controllable current source is represented as the output current of the step instruction following the performance comparison waveform, as shown in Fig. 11. From the above test results, it can be seen that the output current of DC transient controlled current source has a good dynamic following performance and response speed. It can meet the technical requirements for dynamic performance index of DC controlled current source by the transient characteristic test system of dc current transformer.

5.2 Dynamic Characteristic Test of Impulse Current Source

The DC impulse current source has a range of 0~20kA, which can realize the maximum dynamic response rate of 20kA/800us. The actual current waveform of DC impulse current source can also be divided into two stages: Rapid current uplift and descending phase. The dynamic performance test waveforms of the DC impulse current source output current rising and falling are shown in Fig. 11 and

Figure. 12

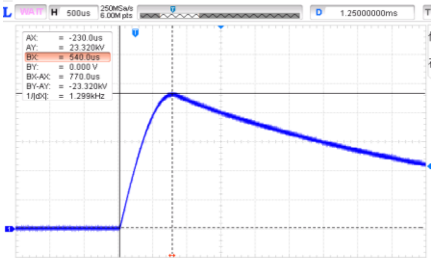


Fig.10 Rising edge waveform of dynamic current on DC impact current source

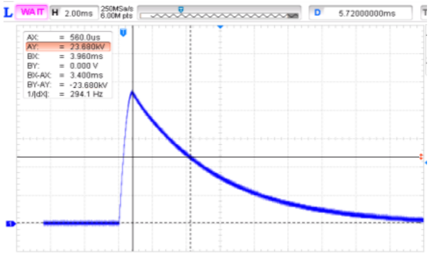


Fig.11 Falling edge waveform of dynamic current on DC impact current source

Fig.10 shows the current rising dynamic waveform of the peak 20kA shock current source. It can be seen that the shock current has reached the dynamic rising speed of 20kA/770us, which meets the test requirements of the transient characteristics of the CT. Fig. 11 shows the current drop dynamic waveform at the peak of 20kA. It can be seen that based on the circuit parameters in Table 1, the descending time constant is compensated to 40ms~120ms by the transient controllable current source, which meets the requirements of the descending time constant of the transient characteristic test.

5.3 Repeatability Test of Synthetic Power

The stability and repeatability of DC impact big current source and controlled DC current source is the basis of the synthetic power test. Based on the power supply module and system, this paper repeats test based on maximum deviation. Five groups of repeated upwelling tests are conducted in four values of 2000 A, 5000 A, 8000 A, 10000A. The average curve of each group of tests is calculated based on the wave data recorded in each group, and the positive maximum deviation point and negative maximum deviation point of each group test are calculated. In all two sets of deviation points, the maximum deviation value is divided by the amplitude of each updraft to obtain the repeatability based on maximum deviation. The test results are shown in Table 3.

TABLE T3 REPETITION TEST OF DC TRANSIENT CURRENT SOURCE

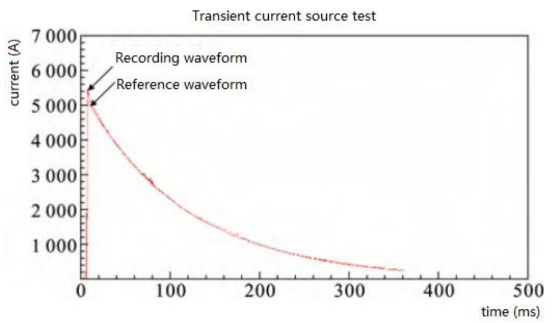
Table 3 Repetition test of DC transient current source

Source / Rising type	2000A	5000A	8000A	10000A
Impulse source	0.77%	0.19%	0.10%	0.12%
Controllable source	2.3%	2%	1%	1.5%
Compound source	2.0%	2.1%	1.7%	1%

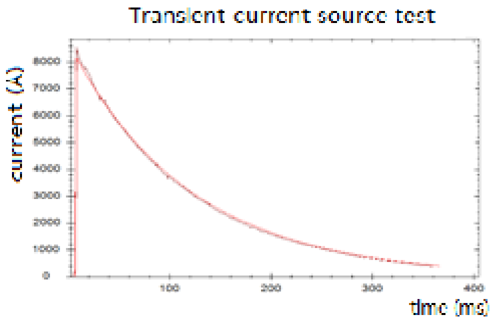
It can be seen from Table 5 that the transient repeatability of DC impulse current source is better than 1%, and the transient repeatability of output current over 10% range is better than 0.2%. The transient repeatability of DC transient controllable current source is better than 2.3%, and that of aperiodic component synthetic current is better than 2.1%.

5.3 Transient Test of Synthetic Power Supply

The main output current based on a synthesis of power supply includes the DC controlled current source and DC impact current source. Precise transient large current control is realized through the multi-dimensional waveform control technology based on time scale and amplitude, and intelligent repetitive control technology based on non-dependent model.. The exponential failure output current waveform of its DC transient synthetic power is shown in Fig. 12.



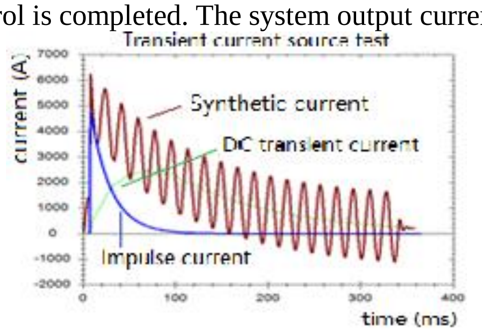
(a) Test with maximum peak current of 5000A



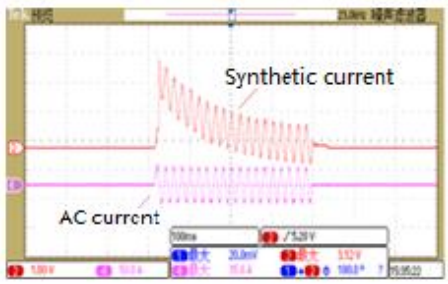
(b) Test with maximum peak current of 8000A

Fig.12 Output current and index instruction of DC transient current source

After the completion of functional debugging and synthesis test, this paper makes the AC synthetic transient test power supply realize the synchronous control of time and amplitude matching between AC transient target current waveform and DC transient target current waveform in the manner of AC/DC time synchronization. Realizing that in AC source implementation after zero quarter cycle time, DC transient current rise to the target in impact current mode, and the corresponding waveform control is completed. The system output current waveform is shown in Fig. 13.



(a) Waveform of output current



(b) Oscilloscope waveform of output current （2:2000A/div；4:2500A/div）

Fig.13 Output current of transient characteristic test system

As shown in Fig. 16, AC transient synthesis output current (including non-periodic DC offset component) reaches its maximum value at the peak of AC transient current sine when combined with DC biasing component current, DC bias current component decays exponentially with time. It simulates the test output current of the primary fault current of the transformer, among which the peak value of periodic AC component is 2000A, the maximum peak current of non-periodic DC component is 3000A, and the maximum peak current of synthetic output is 5000A.

6. CONCLUSION

1）Develop a modular combined AC/DC transient test power supply based on different time scales, including DC impulse current source, DC transient controllable current source, DC transient current source, detection unit, system synchronization and control unit, etc. Large current test of transient characteristics of current transformer for protection is realized by using controllable output, eliminating the conventional primary time constant inductance, realizing the analog output of wide range of one time constant of the whole working condition fault large current, providing an overall solution and test equipment for the transient test of current transformers for protection.

2) The developed protection current transformer transient testing power supply is designed with module combination based on soft switch technology, pulse power technology, waveform control technology, etc. The output precision of the half range and above of output current is better than 0.2%. Under the condition of 20% and above rated current, the overall dynamic repeatability of DC impact current source is better than 0.2%, and that of DC controllable current source is better than 2%. The overall dynamic repeatability of the synthesized total output current is better than 2.1% under the condition of 10% and above rated current conditions, and is better than 1% under the condition of half range and above conditions.

3)The rise velocity of the aperiodic component of the synthesized large current output in the transient test of the current transformer for protection is better than 20kA/800us. The primary time constant is adjustable from 40ms to 120ms and above. The technical performance indexes that meet the transient characteristics test of current transformer for protection have been completed, and the test capability of the protection current transformer of the transient large current test power supply is verified.

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BIBLIOGRAPHY

[1] Yan Shaojun. *Electronic Transformer Technology of GIS Smart Substation* [M]. Beijing: China Electric power Press, 2015.

[2] ZHANG Renyu, CHEN Changyu, Wang Changchang. *High Voltage Testing Technology* [M]. Beijing: China Electric power Press, 2011.

[3] XU Zheng, LIU Gaoren, ZHANG Zheren. *Research on Fault Protection Principle of DC Grids* [J]". High Voltage Engineering, 2017, 43(1) : pages 1-8.

[4] LI Feng, FAN Qinghua, XU Bingyin, et al. *Development of High-Voltage Surge Signal Generator for Cable Test Van* [J]". High Voltage Engineering, 2016, 42(2) : pages 528-534.

[5] SONG Tao. *Technical Research of Accurate Digital Integrators for Rogowski Coil Current Transformer* [J]. High Voltage Engineering, 2015, 41(1):pages 237-244.

[6] Wang Ling, WANG Benjin, Wu Shipu, Chen Xiaoming, Sun Chenjun, et al. *Study on Transient Characteristics Test Method of Electronic Current Transformer* [J]. (High Voltage Apparatus, 2014, 50(11): pages 86-91).

[7] Transformer, part II: *Electronic Additional requirements for Current Transformers*: GB/T 20840.2-2014[S], 2014.

[8] Instrument transformers, part VIII: *Electronic Current Transformer*: GB/T 20840.8-2007[S], 2007.

[9] *The Guide for Selection and Calculation of Current Transformer and Voltage Transformers*: GB/T 20840.8-2007[S], 2012.

[10] Wang Zhenhao, Li Guoqin, et al. *Analysis of Simulation and Experiment on the Characteristic of the Current Transformer Used for Protection Affected by DC Magnetic Bias* [J]. Power System protect and control, 2015, 43(13): pages 15-22.

[11] XIONG Lan, ZHOU Jianyao, SONG Daojun, et al. *Modeling and Experimental Analysis of Current Transformer Based on Modified J-A Hysteretic Model* [J]. High Voltage Engineering, 2014, 40(2): pages 482-488.

[12] WANG Liming, DU Zhen'an. *Double Air-gap Current Transformer Applied to High Voltage Transmission Line On-Site Mobile Comparison System* [J]. High Voltage Engineering, 2015, 41(1): pages 106-114.

[13] LI Yang, ZHAO Min, LIU Xiaoting, et al. "*Optimal Design on Power Synthesis of Ultra-Wide Band Dual-Expotential Pulser with Fast Edge*[J]". (High Voltage Engineering, 2016, 42(5): pages 1422-1428).

[14] ZhANG Jie, Hu Yuanyuan, Liu Fei, et al. *Critical Technology of On-Site Calibration System for DC Electronic Instrument Transformer*[J]. High Voltage Engineering, 2016, 42(9): pages 3003-3010.

[15] CHEN Gang, WANG Zhongdong, BAI Hao, et al. *DC Method for Measuring Parameters of Remanence of Current Transformer* [J]. High Voltage Engineering, 2014, 40(8) : pages 2416-2421.

[16] TANG Yi, LI Zhenhua, JIANG Bo, et al. *On-Site Calibration System for Electronic Transformers Based on IEC 61850-9* [J]. High Voltage Engineering, 2014, 40(8) : pages 2353-2359.