Design of Voltage Source for Step Response Calibration System of DC Voltage Transformer

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Abstract: Aiming at the lack of the theory and test methods for the transient characteristics of DC (direct-current) transformers and the difficulty of the existing test power supply to meet the test requirements, the step response characteristics of the transformers are studied by designing the step voltage source system of the DC voltage transformers. Capacitor energy storage technology design capacitor energy storage square wave power supply. At the same time, the control loop uses voltage feedback to improve the output voltage stability. The simulation results show that the top of the waveform of the step voltage source system is very flat, there is no obvious overshoot at the leading edge of the output voltage waveform, the stabilization time is much less than 100 μs, and the leading edge rise time is less than 10 μs, which meets the system requirements.

1. Introduction

At present, with the development of power electronic technology and the maturity of related technologies of flexible DC (direct-current) transmission system, electronic current transformer is widely used because of its high measurement accuracy, digital and intelligent characteristics. For the flexible DC transmission system, the error characteristics and step response characteristics of electronic DC current transformer in a wide dynamic range have higher requirements with the deepening of research [1], especially in the stability and accuracy of the test power supply. However, the existing test equipment and detection methods mainly focus on the test and measurement of DC transformer's steady-state characteristics. Due to the difference of performance indexes, it is difficult to meet the requirements of field test and verification of transient characteristics. However, due to the lack of relevant theories and detection equipment for its transient characteristics, the relevant test methods and national standards need to be further improved [2-4].

According to the definition of the step response time of the DC voltage transformer [5] and the requirements of “DC Voltage Measurement Device for HVDC (High Voltage Direct Current) Transmission System”(GB/T 26217-2010), a step voltage of more than 10% of the measuring range is applied at the high voltage end of DC voltage transformer, and the transient response characteristics are measured at the output end, and the step response time $T_{SR} \leq 250 \mu s$ [6]. Square wave power supply is the key factor for step response test of DC voltage transformer. The main technology of pulse forming circuit of square wave power supply includes energy storage technology and switch technology. According to the requirements of DC voltage transformer step response time $T_{SR} \leq 250 \mu s$, in order to meet the test requirements, the step response rise time of square wave power supply and standard
transient voltage divider shall not be greater than 50μs, the rise time of square wave power supply shall not be greater than 20μs and the overshoot amplitude shall not be greater than 5% of the test voltage. According to this requirement, the rising edge of the required voltage curve of the test power supply is very steep.

2. Step response calibration system of DC voltage transformer

In the DC transmission system, the signal measured by DC transformer is mainly used for control and protection. Compared with the AC transmission system, the DC transmission system has the requirements of faster sampling speed and wider frequency band width for the protection signal, especially in the flexible DC transmission system. In order to improve the response speed of the flexible DC system, restrain the fault current and improve the safety and stability of the power system, it is necessary to control and protect the signal sampling with faster sampling speed and faster sampling speed. Wider frequency band width, for example, in ±500kV flexible DC transmission, the signal transmission delay of DC current transformer is required to be less than 100μs, and the sampling frequency is up to 50KHz. Generally speaking, if the DC transformer does not meet the requirements of transient characteristics, it will lead to poor stability of DC control and protection system and affect the safe and stable operation of the system, which is of great significance for the safe operation of DC system.

According to the requirements of “DC Voltage Measurement Device for HVDC Transmission System” (GB/T 26217-2010), DC voltage transformer should carry out step response test in type test and routine test. At present, there is lack of test means and test equipment in China. In recent years, scholars at home and abroad have carried out a series of research on field calibration and calibration test of DC transformer based on remote synchronous measurement The standards and field test specifications of the voltage and DC transformers are gradually improved[7]. At present, the field calibration mainly aims at the verification test and measurement calibration of DC current transformer's steady-state characteristics. The existing test power supply and technical means are difficult to support the field test and detection of DC current transformer's transient steady-state characteristics. For DC current transformer, steady-state measurement calibration and transient characteristics related tests are carried out, which greatly improves the stability, convenience and applicability of field use and transportation.

In order to verify the step response time of DC voltage transformer, this paper proposes a verification system of DC voltage transformer step response test system based on closed-loop comparison method. The schematic diagram of the verification system is shown in Figure 1. The calibration system is mainly composed of square wave voltage source, standard transient voltage divider and DC voltage transformer calibrator. The square wave voltage source provides step input signals for the calibrated DC voltage transformer and standard transient voltage divider. The output signals of the two are respectively transmitted to the DC transformer step response calibrator by digital signal conversion unit and analog signal conversion unit, and are calculated Step response time of DC voltage transformer. In order to meet the step response time $T_{sr} \leq 250\mu s$ test of DC voltage transformer, the step response time $T_{sr}$ of square wave power supply and standard transient voltage divider shall be less than 1/5 of rated step response time of DC voltage transformer under test, that is $T_{sr} \leq 50\mu s$. 

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3. Step voltage source system schematic

The square wave voltage source is an important part of the step response verification system for DC voltage transformers, and its performance parameters directly affect its test results. However, pulse power technology is the core technology of square wave voltage source. Pulse power technology has a history of more than 50 years. Since the first generation of X-rays, it has attracted more and more attention from scientists. At the IEEE International Conference in 1976, the development and significance of pulse power technology were discussed, and the term "pulse power technology" was determined. With the continuous development of technology, pulse power technology has gradually developed from the military field to the industrial and civilian fields, and has become one of the contemporary high-tech. Generally, the pulse power generator includes a primary energy system, an intermediate energy storage system, and a pulse generation system.

In the 1970s, the introduction of a pulse-width modulation DC/DC converter with a switching frequency of 20kHz greatly reduced the size of the power supply and improved the efficiency. It is known as the “20kHz revolution” of power supply technology. In the 1980s, the successful development of GTR (Giant Transistor), GTO (gate turn-off thyristor) and other self-shutdown fully-controlled second-generation power electronic devices marked the entry of the magnetron power supply into the era of high-frequency switching power supplies. In the 1990s, the third generation of power electronic devices represented by IGBTs (insulated gate bipolar transistors) and power MOSFETs (Metal-Oxide-Semiconductor Field-Effect Transistor) promoted the development of magnetron power supplies in the direction of high frequency, low loss, and high reliability. Ulrike Hahn and others at the University of Virginia developed a four-stage miniature Marx nanosecond pulse generator[8]. In order to reduce the loop stray inductance and the rise time, a low-inductance ceramic capacitor is selected. In order to reduce the trigger voltage, a MOSFET (40N160, IXYS) is selected as the controllable initial trigger switch. The spark gap switch is selected as the discharge switch. It works under atmospheric pressure. The electrode is a needle-to-needle electrode with a distance of about 0.5mm. The distance between the electrodes can be adjusted to adjust the breakdown voltage to achieve different amplitude output. The spark gap SGIV is connected at both ends of the load to quickly cut off the wave tail.

Domestic research in this area is in its infancy, with weak research strength and slow progress. Fudan University Liu Kefu and others made some attempts on the all-solid-state Marx generator technology, and designed a set of fast pulse source device with high repetition frequency[9]. This device is based on the traditional Marx circuit, combining MOSFET devices are innovative by superimposing four output voltages to increase the amplitude of the output voltage. The power supply can output positive and negative bi-directional pulses, the pulse frequency and pulse width are adjustable, and the dead time between positive and negative pulses can be changed.

In the pulse voltage forming circuit, there are two important components, namely energy storage element and switching element. According to the difference of energy storage principle, the pulse power circuit is divided into capacitance type and inductance type[10]. As shown in Figure 2, the basic
structure and output pulse voltage waveform of the capacitor energy storage type pulse power circuit. Figure 3 shows the structure and output pulse voltage waveform of the inductive energy storage pulse power circuit. The former stores the energy in the capacitance $C$, the latter stores the energy in the inductance $L$, and the two generate the pulse voltage by controlling the switch $s$. Among them, the pulse voltage of capacitor energy storage type is related to the stray inductance in the loop and the RC network time constant composed of capacitance and resistance in [11,12]. The pulse voltage of the inductive energy storage type is related to the switching speed of the switching element and the energy storage density and internal resistance of the energy storage inductance [13].

![Figure 2. Capacitive energy storage pulse power circuit](image)

![Figure 3. Inductive energy storage pulse power circuit](image)

At present, although the inductive energy storage technology has been improved to a certain extent, the inductor with high energy storage density and transmission power has been designed. Considering that the manufacturing process of the energy storage inductor requires high requirements, and it can not solve the problem of huge current generated when the inductor is interrupted in the working process [14,15]. Compared with the capacitor energy storage technology, the capacitor energy storage technology is mature, flexible and operable. Because of its strong characteristics, capacitor is selected as energy storage element. A square wave power supply for step response test of DC current transformer is designed by means of capacitor energy storage. The basic structure of capacitor energy storage square wave power supply circuit is shown in Figure 4. First, switch $S1$ is closed, $S2$ is open, and the power supply charges capacitor $C$; then switch $S1$ is open, switch $S2$ is closed, and capacitor $C$ is discharged to generate pulse voltage, where $l$ is the stray inductance in the circuit.

![Figure 4. Capacitive energy storage square wave power circuit](image)

Switching elements are important devices in pulse-forming circuits. Among them, commonly used switching elements are trigger vacuum switches, spark gaps, thyristors and semiconductor switches. Since the switching speed of semiconductor switches can reach nanoseconds, they can withstand several
kilowatts. Power above and above has great advantages in terms of service life, repetition frequency, high integration, etc. Therefore, the switching device of this system uses semiconductor switching tubes.

The system shown in Figure 3 is a typical second-order RLC circuit, and the critical starting value \( R = \frac{L}{\sqrt{LC}} \) of the second-order RLC circuit. According to the parameters of inductance and capacitance, the critical value of resistance is 310. When \( R < 310 \Omega \), the system is in underdamped state, and the system response is fast, but the waveform leading edge oscillation is large, that is, the voltage overshoot amplitude is too large; when \( R > 310 \Omega \), the system is in over damped state, the waveform leading edge rises smoothly, and the voltage waveform has no overshoot. Because the voltage overshoot is required to be less than 5%, the resistance value is set to make the system in the state of over damping, which fully meets the requirements. The capacitance of the energy storage module affects the charging speed, and the rise time of the system is required to be less than \( 10 \mu s \). In fact, it is generally considered that the capacitor charging and discharging end after 3RC time. Therefore, the resistance \( R \) is 1kΩ, and the capacitance is 0.06μF. Matlab simulation software is used to establish its simulation model, as shown in Figure 5.

The resistance \( R \) value is 1kΩ, the capacitance value is 0.06μF, the simulation time is set to 20ms, and the system overshoot amplitude is required to be less than 5%, that is, the output voltage overshoot is less than 10kV. When the energy storage capacitor is 0.06μF, the output waveform at both ends of the load is as shown in Figure 6. From the simulation results, it can be seen that the waveform is flat and meets the system index requirements. The rising edge time and stabilization time of the test output waveform are shown in Figure 7.
Figure 7. Waveform stabilization time

It can be seen from the image that, because the system is in an overdamped state, there is no overshoot at the leading edge of the output voltage waveform, the top of the waveform is very flat, and the stabilization time is far less than $10\mu s$, which meets the system index requirements. The width of the rising time of the waveform is reduced, and the rising time of the waveform is measured. The rising time of the leading edge is less than $10\mu s$, which meets the requirements of the system index.

4. Conclusion

This paper adopts capacitor energy storage technology to design a capacitor energy storage square wave power supply, and uses voltage feedback to improve the output voltage stability. The squared results show that the step voltage source system can meet the technical requirements of the step response test of DC voltage transformers. The error characteristics and step response characteristics of the electronic DC transformer are its most critical performance. When considering the overall error performance of the transformer, the measurement error caused by the step voltage source in the step response process and the quantization error caused by the delay time and step rise time of the transformer need to be further analyzed.

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