Application of Hybrid (混合) Energy Storage Device in High Power Direct-current Power Supply

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***Abstract* - The drop-away (脱扣电流) current of 1500V low-voltage direct-current circuit breaker used in metro DC traction power supply system needs to be checked regularly. The instantaneous power is very high when the detection device is working, and the field power supply is often difficult to meet the requirements. Therefore, an energy storage unit is needed to supply power to the detector. In this paper, a design scheme of high-power DC power supply with supercapacitor and battery as energy storage is proposed, and the energy management and discharge control strategies are studied in theory and simulation, which verify the effectiveness and feasibility of the scheme.**

Index Terms* - *Direct-current circuit breaker. Drop-away current. Supercapacitor. Battery. DC power supply

I. Introduction

The detection of 1500V low-voltage DC circuit breaker is an important measure for safe and reliable operation of subway. The instantaneous trip test of a DC circuit breaker requires the application of (跳闸) a standard rated (额定) short-circuit (短路) current to the circuit breaker in a short period of time, the current value of which is more than ten times of the rated current. The criterion is determined by the tripping time[1]. (决定电流大小) The high-power DC power supply used for testing needs to provide the current above 20000A and the instantaneous output power above 100kW in a short time, but the power supply on the test site is often difficult to meet the power requirements. Therefore, it is necessary to equip the energy storage unit for the high-power DC power supply. Commonly used energy storage components are batteries and supercapacitors. Battery's characteristic of high energy density, short cycle life, low power density is not suitable for short time power output. Supercapacitors have the advantages of high power density, long cycle life and fast charging speed, but the energy density of supercapacitors is low and the sustainable discharge time is short[2]. Therefore, batteries and supercapacitors are highly complementary, which are often connected to form a hybrid energy storage system in a certain way to give full play to their advantages.

Different from the traditional single-source energy storage, hybrid energy storage involves the coordinated management of various energies. However, under the condition of fast dynamic response and large instantaneous power, the energy distribution of the battery and the supercapacitor is not timely and the voltage of the DC bus is unstable. Therefore, reasonable control circuit topology and system voltage control strategy are the key to control the coordination of hybrid energy storage system. In order to solve this problem, a typical dual-ring control strategy is adopted in literature [3] to improve the working performance of the battery, but the hybrid energy storage system needs to control the power flow, and the simple dual-ring control is difficult to meet the control requirements. On this basis, the method of multi-hysteresis control is adopted in literature [4] to optimize the charging and discharging process of the battery and improve the flexibility and practicability of the energy storage link, but the response of the multi-hysteresis control algorithm is slow, which is not suitable for charging and discharging situations with fast dynamic response. In literature [5], the power distribution of battery and supercapacitor is carried out by means of sliding average filtering, so that different energy storage devices can bear different power fluctuations. The effectiveness of the algorithm is verified by simulation, but the problem of output voltage stabilization of supercapacitor and battery is not involved. In view of the above shortcomings, a control strategy for the hybrid energy storage system of supercapacitor and battery under discharge state is proposed in this paper, which basically solves the above problems.

II. Equivalent Circuit Model

A. Overall Structure of the System

The overall block diagram of the system is shown in figure 1. The hybrid energy storage system composed of supercapacitor and battery is connected in parallel to the DC bus, and the current output from the energy storage terminal is input to the high-power DC power supply through the DC bus for DC/DC transformation. The high-power DC power supply required by the detection device needs to be realized by power transformation. Switching power supply with fully controlled power electronic devices adjusts the output voltage by controlling the duty cycle of the switching devices, this kind of power supply has the advantages of small size, light weight, low power consumption and high efficiency [6]. The phase-shifting full-bridge soft switching technology can effectively reduce the switching loss of the power switch tube and improve the work efficiency, so the phase-shifting full-bridge circuit becomes the preferred topology in the high-power DC power supply[7]. As the object under test ACTS as a load on the system, the circuit breaker provides an extremely low impedance resistance load form.

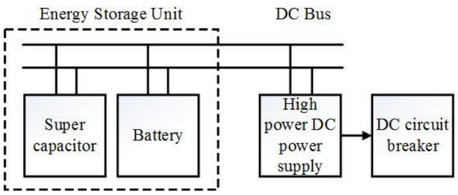

Fig. 1 Overall block diagram of the system

There are three main ways of connection between battery and supercapacitor: 1)passive structure. In this structure, the two are directly connected in parallel. Although the structure is simple, the compensation effect of supercapacitor on the battery is not good enough[8]; 2)Semi-active structure. This structure connects one kind of energy storage element to the power supply bus, Another kind of component is connected to the bus after DC/DC transformation. This structure can only control the energy and power distribution of one kind of energy storage element, which makes the other kind of energy storage element lack of effective management mechanism[9]. 3)Full active structure. The structure connects the two to the power supply bus after DC/DC transformation, which is flexible and can control the charge and discharge of the two respectively, so as to more reasonably configure their respective capacities [10].

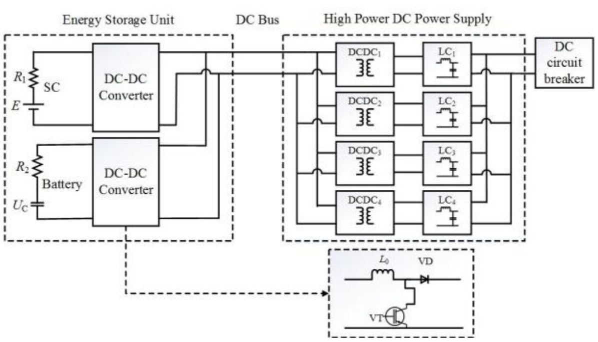

Fig. 2 Circuit structure with hybrid energy storage unit

The circuit structure adopted in this paper is shown in figure 2. The circuit topology is divided into two stages. The first stage is a hybrid energy storage unit, which adopts a fully active structure composite power supply. The equivalent circuit module consists of battery and supercapacitor, which respectively constitute the battery stack and supercapacitor array by means of series and parallel connection. The DC/DC converter is mainly used to realize the discharge control of energy storage and convert the voltage of the energy storage monomer into a higher DC voltage to meet the energy demand of the high-power DC power supply. The rear stage is a high-power DC power supply system. Due to the dual limitation of power electronic devices and transformer power capacity, the single large-capacity power supply technology is not yet mature. Therefore, the multi-module parallel structure is adopted in this paper, which can not only realize the high-power output of the system, but also improve the flexibility, handiness and redundancy [11]. The power supply designed in this paper adopts 4 phase-shifting full-bridge DC/DC circuits with staggered phases. The phase-shifting full-bridge DC/DC circuits include phase-shifting full-bridge DC/DC transform circuit and LC filter circuit. The DC voltage transferred from the energy storage terminal to the DC bus is converted into the low-voltage large current required for detecting the DC circuit breaker, and four output terminals of phase-shifting full-bridge DC/DC circuits are connected in parallel for circuit breaker testing.

B. Supercapacitor Equivalent Circuit Model

The different structures of supercapacitor determine that it has different equivalent models, and its classical model [12] is shown in FIG. 3.

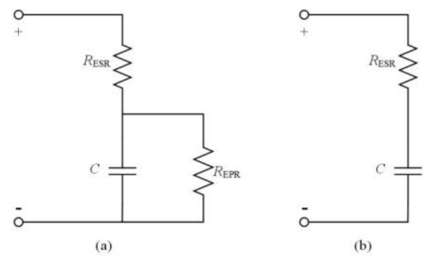

Fig. 3 Supercapacitor equivalent circuit model

R_{EPR} represents equivalent shunt resistance, R_{ESR} represents equivalent series resistance, and C represents equivalent capacitance. R_{EPR} resistance is very small, only a few milliohms, which mainly affects the discharge performance of supercapacitors. R_{ESR} resistance is large, up to tens of thousands of ohms, so its leakage current is very small, only tens of microamperes [13], so in practical application, the influence of R_{EPR} is usually ignored, as shown in FIG. 3(b).

The corresponding mathematical expression is as follows:

The ideal energy storage formula of supercapacitor is

$$W_e=\frac{1}{2}C_F U_F^2 \qquad (1)$$

$$C_F=\varepsilon A/d \qquad (2)$$

The power of the supercapacitor is

$$P=U_0 I=(U-IR)I \qquad (3)$$

The energy output of the supercapacitor is

$$E=\frac{1}{2}CU_{max}^2-\frac{1}{2}CU_{min}^2 \qquad (4)$$

The discharge efficiency of supercapacitor is

$$\eta_d=\frac{\int_0^t I_d\times u(t)dt}{\frac{1}{2}C(U_{d_{max}}^2-U_{d_{min}}^2)} \qquad (5)$$

In these equations, W_e is the electric quantity stored in the supercapacitor, C_F is the ideal capacitor, U_F is the voltage of the supercapacitor, ε is the electrolyte constant, A is the electrode surface area, and d is the electrode spacing. U_0 is the initial voltage; E is the energy output of the supercapacitor, and $U_{\max}$ and $U_{\min}$ are the highest and lowest operating voltages allowed by the supercapacitor. I_d is the discharge current, and $U_{d\max}$ and $U_{d\min}$ are the initial and cut-off voltages when the supercapacitor discharges.

C. Battery Equivalent Circuit Model

There are many equivalent circuit models of batteries, and the classical shepherd model is widely used to describe batteries in new energy generation. The premise of this model is to ignore the influence of temperature and self-discharge of the battery, and consider that its internal resistance R_b remains constant in the energy storage work. The classic equivalent circuit diagram of the battery [14] is shown in FIG. 4.

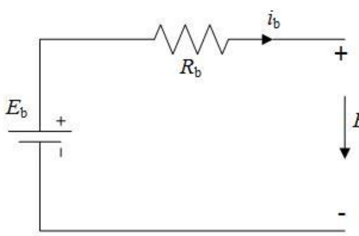

Fig. 4 Classic equivalent model of battery

The battery terminal voltage is expressed as:

$$E_b=E_0+X\exp\left(-Y\cdot\int_0^\tau i\mathrm{d}t\right)-Z\cdot C/\left(C-\int_0^\tau i\mathrm{d}t\right) \tag{6}$$

$$SOC=(C-\int_0^\tau i_b\,\mathrm{d}t)/C \tag{7}$$

In this equation, E_b is the no-load terminal voltage of the battery, E_0 is the initial discharge voltage of the battery, and X is the amplitude of the exponential region to correct the rapid drop of the voltage when the battery starts discharging. Z is the pressure drop coefficient of the electrode plate, and C is the standard capacity of the battery. SOC is the state of charge of the battery, which is used to reflect the degree of its storage capacity.

III. DC/DC Converter Control Strategy And System Parameter Design

A. DC/DC Converter Topology and Small Signal Model

Due to the low voltage of energy storage monomer, if a large number of monomers are used for series and parallel connection, a large amount of materials need to be consumed. At the same time, in order to ensure that the output current ripple of the main circuit of phase shift full bridge is small, HESS DC bus voltage needs to be precisely controlled. Therefore, DC/DC converter is essential. The supercapacitors and batteries are respectively equivalent to ideal capacitors, voltage sources and a simplified model of equivalent series internal resistance. The circuit diagram of the energy storage elements connected to the DC/DC converter is shown in FIG. 5 [15]. C is the equivalent capacitance of the energy storage elements.

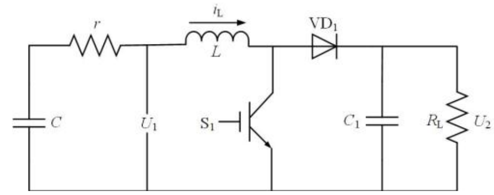

Fig. 5 Circuit structure diagram of DC/DC converter

r is its internal resistance in series, U_1 is the terminal voltage of the energy storage element, that is, the converter's low-voltage terminal voltage, inductance L, switch tube S_1 and output side filter capacitor C_1 constitute the Boost converter, R_L is the equivalent load, U_2 is the output voltage, in fact, U_2 is the DC bus voltage. When the converter runs in Boost stabilized mode, set d as the switching function of S_1, and the small signal model can be obtained as:

$$G_{u_2d}(s)=\frac{\hat{u}_2(s)}{\hat{d}(s)}\bigg|_{\hat{u}_1=0}=\frac{u_2\left(D-\frac{Ls+r}{R_L D}\right)}{LC_1s^2+\left(\frac{L}{R_L}+rC_1\right)s+\frac{r}{R_L}+D^2} \tag{8}$$

$$G_{i_Ld}(s)=\frac{\hat{i}_L(s)}{\hat{d}(s)}\bigg|_{\hat{u}_1=0}=\frac{u_2\left(C_1s+\frac{2}{R_L}\right)}{LC_1s^2+\left(\frac{L}{R_L}+rC_1\right)s+\frac{r}{R_L}+D^2} \tag{9}$$

$$Z(s)=\frac{\hat{u}_1(s)}{\hat{i}_L(s)}\bigg|_{\hat{u}_1(s)=0}=\frac{D^2-\frac{(Ls+r)}{R_L}}{D(C_1s+\frac{2}{R_L})} \tag{10}$$

B. Parameter Design

According to the actual requirements, the switching frequency f_s=10kHz is set, in which the voltage on the low-voltage side of the battery bank is 192V, the voltage on the low-voltage side of the supercapacitor is 160V, and the voltage on the DC bus is 500V.

1) The design of energy-storage inductance

When the circuit works in Boost mode, the critical value L of the inductor when the current is continuous is:

$$L=\frac{R_L d(1-d)^2}{2f} \tag{11}$$

In this equation, f is the switching frequency; d is the duty cycle of the switch; R_L is the equivalent load resistance.

2) The design of filter capacitor

In Boost mode, the calculation formula of voltage regulator capacitance on the side of DC bus is as follows:

$$C=\frac{U_{dc}-E}{\Delta VR_L f} \tag{12}$$

In this equation, E is the terminal voltage of the supercapacitor, ΔV is the ripple size of the high-voltage terminal voltage, and the output voltage ripple is set to be less than 1%.

After calculation, and considering a certain margin, the inductance and capacitance in the DC/DC converter are set as

L_C=5μH, C =5000μF, in order to ensure the current and DC bus remain stable when the supercapacitor and the battery discharge.

3) The design of supercapacitor

The current 2s of 20000A is required to test the trip characteristic of the circuit breaker. After analysis and calculation that the circuit breaker contacts with the output end of the cable resistance is the sum of 250μΩ. Therefore, the output power of low-voltage and high-current DC power supply is 100kW and the total output energy is 200kJ.

Aiming at the problem of supercapacitor overcharge and overdischarge, and according to the requirements of the DC bus voltage grade (500-510V), the maximum charging voltage U_{max} =200V, and the minimum discharging voltage U_{min}=150V. Supercapacitor capacitance satisfies the following relationship:

$$W=\frac{1}{2}C_{sc}\left(U_{max}^2-U_{min}^2\right) \qquad (13)$$

Therefore, the capacitance of super capacitor bank should meet the following requirements:

$$C_{sc}=\frac{2W}{U_{max}^2-U_{min}^2}\approx 23(F) \qquad (14)$$

Based on the above calculation and analysis, the specific parameters of the super capacitor selected in this design are shown in table 1:

TABLE I

SPECIFIC PARAMETERS OF SUPERCAPACITORS

Nominal Voltage（V）	Rated Capacity（F）	DC Equivalent Impedance（mΩ）
2.7	1500	0.47
Maximum Peak Current（A）	Short-Circuit Current（A）	Maximum Continuous Current（A）
1150	6000	140

The supercapacitors selected in this paper: a total of 60 supercapacitors with a capacity of 1500F and rated voltage of 2.7V form a series of 25F supercapacitor Banks with a total voltage of 162V.

Calculation formula of series capacity:

$$\frac{1}{C}=\frac{1}{C_1}+\frac{1}{C_2}+\frac{1}{C_3}+\cdots\cdots+\frac{1}{C_{60}} \qquad (15)$$

C=25F is calculated to meet the actual demand.

4) The design of Lead acid battery :

For the battery cell, the rated voltage of driving high-power DC power supply is 500V, and 12V/200Ah lead acid battery is selected. According to the formula:

$$n_{bser}=\frac{U_m}{U_b} \qquad (16)$$

In this equation: n_{bser} is the number of cells in series, U_m is the rated voltage at the input end of the phase-shifted full-bridge main circuit, and U_b is the nominal voltage of the cells. It can be seen that the number of batteries in series is 16.

C. Energy Management

The primary problem in the energy management of hybrid energy storage system is the real-time power distribution of battery and supercapacitor. Due to the large power fluctuation at the start of the high-power DC power supply, the supercapacitor discharges first to provide the abrupt part of the load. Because the voltage of the supercapacitor drops after discharging for a period of time, the output voltage of the converter is no longer constant and gradually decreases; When the voltage is lower than the set value, the supercapacitor is shut off, and the supercapacitor is replaced by the battery to continue the power supply.

D. Discharge Control Strategy

In this paper, the discharge sequence of supercapacitor and battery is controlled with the DC side voltage U_{dc} as a reference. The control flow chart of the hybrid energy storage unit is shown in FIG. 6.

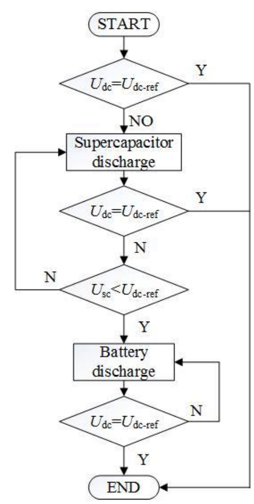

Fig. 6 Control flow chart of hybrid energy storage unit

When the DC side voltage U_{dc} is not equal to its reference value U_{dc-ref}, the supercapacitor starts discharging. When the voltage U_{sc} of the supercapacitor after converter transformation is less than the reference value U_{dc-ref} of the DC side voltage, the supercapacitor stops discharging and the battery starts discharging. When the DC side voltage U_{dc} is equal to the reference value U_{dc-ref}, the discharge stops.

The control structure of the hybrid energy storage unit is shown in figure 7.

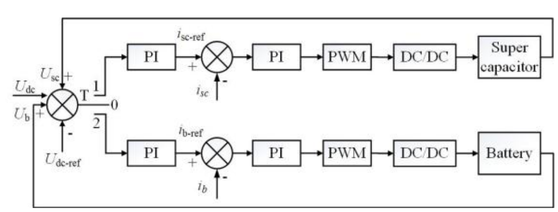

Fig. 7 Control structure diagram of hybrid energy storage unit

The bus voltage on the DC side is collected and compared with the reference voltage to obtain the error signal.

If the bus voltage on the DC side is equal to its reference value, the switch T remains unchanged in the zero state.

If the bus voltage on the DC side is not equal to the reference value, then switch T is connected to node 1, the error signal is obtained after PI regulator to obtain the reference value of the current of the supercapacitor, and the error signal is obtained by comparing the current on the supercapacitor side with the reference value. After PI regulator and PWM modulation, the switch signal is generated and transmitted to DC/DC converter to control the opening and closing of the switch tube.

If the bus voltage on the DC side is not equal to its reference value, and U_{sc} is less than $U_{dc\text{-}ref}$, then switch T is connected to node 2. The reference value of the current of the battery is obtained after the error signal is passed through the PI regulator, and the error signal is obtained by comparing the side current of the battery with its reference value. After PI regulator, the switch signal is generated by PWM modulation and transmitted to the DC/DC converter to control the switch of the battery.

IV. Simulation Results And Analysis

In order to verify the feasibility of the application of the composite power supply topology and control strategy in high-power DC power supply, the topology shown in figure 2 and the control strategy shown in figure 7 were simulated in the MATLAB/Simulink environment, and the voltage and current waveforms were observed. Simulation parameters are as follows: after charging, the supercapacitor voltage is 160V, battery voltage is 200V, the stability of the switch tube switch frequency is 10kHZ, after four phase-shift full bridge main circuit for DC/DC conversion, four phase-shift full bridge module after parallel output to load, hybrid energy storage system output voltage to the DC bus load value is set to 250μΩ. The simulation time of the system is 2s.

The voltage waveform of the super capacitor terminal is shown in Figure 8. The working time of the supercapacitor is 0 ~ 1.15s, the voltage is reduced from 160V to 113V, and the power supply is stopped. Due to the self-discharge phenomenon of the super capacitor, the voltage will continue to drop.

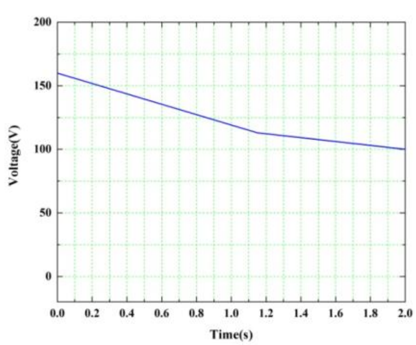

Fig. 8 Voltage waveform of supercapacitor terminal

The voltage waveform at the side of the DC bus is shown in figure 9. At 0~1 s, the output voltage of the converter is stable at 500V. At about 1s, due to the voltage drop of the supercapacitor, it reached the boost limit of the DC/DC converter, and the output voltage began to decrease gradually. At 1.15s, the supercapacitor stopped power supply and was replaced by the battery.

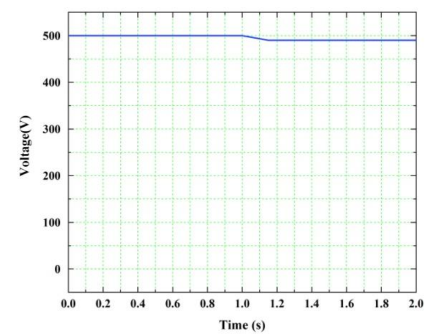

Fig. 9 Voltage waveform on dc bus side

The DC side current waveform of the DC/DC converter is shown in figure 10 when the supercapacitor is supplied. It can be seen that the initial impulse current of the circuit discharge is about 320A, and at this point, the peak power is completely provided by the supercapacitor, the battery is not connected to the power supply. In normal operation, the current is maintained at about 200 A.

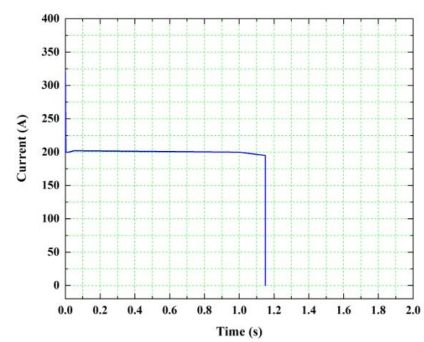

Fig. 10 DC side current waveform of DC/DC converter when supercapacitor is supplied

Figure 11 is the current waveform for the battery when it is operating. After the battery is put into the circuit, there is no impulse current, and the current of the input load is 200A under steady state.

The DC bus side total current waveform is shown in Figure 12. Since the circuit is alternately supplied by supercapacitor and battery, the waveform shown in FIG. 13 can be obtained by adding the two groups of currents in FIG. 10 and FIG. 11, which is basically consistent with the variation of the voltage waveform. The output power of the hybrid energy storage system can be calculated to be about 100kW.

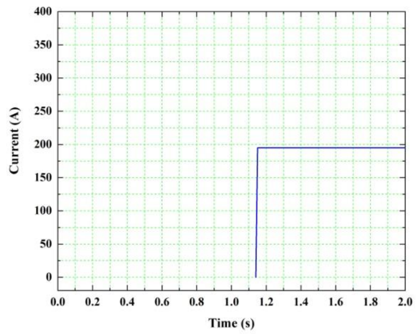

Fig. 11 Current waveform of the battery in operation

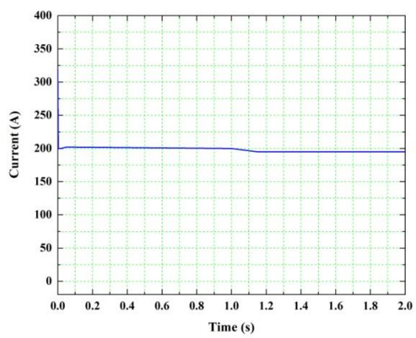

Fig. 12 The total current waveform at the side of the dc bus

Low-voltage high-current DC switching power supply output current waveform as shown in Figures 13. The output result is consistent with the above calculation. The output current can rise rapidly from 0A to 20000A. It can be seen that the combination of battery-supercapactor-hybrid energy storage system and power electronics technology based on phase-shifting full-bridge circuit can meet the output requirements of low-voltage high-current test equipment for circuit breakers.

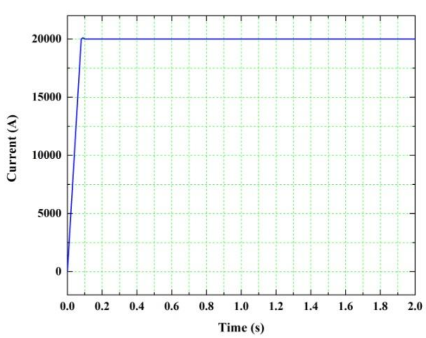

Fig. 13 Current output waveform of low-voltage and high-current dc power supply

V. CONCLUSION

In this paper, a design scheme of low-voltage and high-current DC power supply based on battery-supercapacitor hybrid energy storage is proposed for 1500V DC circuit breaker trip characteristic test equipment used in rail transit. For hybrid energy storage system, a fully active topology structure is adopted to propose a control strategy for hybrid energy storage system in discharge state for high-power DC power supply, and an HESS control model is established. Finally, a simulation model is built on the MATLAB platform for verification. The simulation results show that the hybrid energy storage unit makes full use of the advantages of fast dynamic response of the supercapacitor and high energy density of the battery, and the phase-shifting full-bridge converter can meet the technical requirements of the large-current experimental equipment for DC circuit breakers.

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