System Realization of CASHIPS DC High Power Test Facility

Xiaojiao Chen, Liansheng Huang, Peng Fu, Ge Gao, Zhiquan Song, Liuwei Xu, Shiying He, and Xiuqing Zhang

***Abstract*—Aims to complete the test of the International Thermonuclear Experimental Reactor (ITER) poloidal field (PF) converter system, and to meet future continuous upgrading needs of a modern industrial power system and scientific research, direct current (DC) high-power test facility of Hefei Institutes from Physics science, Chinese Academy of Sciences (CASHIPS) is built in 2011. As the largest DC high-power test facility in China, the rated steady state DC current is 120 kA and the pulse peak current is 500 kA. Four thyristor-based AC/DC converter modules are paralleled to handle this huge current. In May 2017, 15 testing items are accredited by the China National Accreditation Service (CNAS) for Conformity Assessment . Up to now, the test for 17 devices of 16 companies and manufacturers in the world have been completed. In this paper, the topology and the control of DC High-Power test facility are presented. In addition, the testing capability and the completed tests of DC high-power test facility are illustrated.**

***Index Terms*—120 kA steady state DC current, 500 kA pulse peak current, DC high-power test facility.**

I. Introduction

With the development of modern industrial power systems, scientific research, the capacity of the high-power electrical equipment test facility is expanded and upgraded continuously to satisfy the needs of economic and social development. At present, there are more than 10 well-known power labs with DC high-power test facility all over the world. Most of the leading electric companies have their own high-power labs, in addition to some independent high-power laboratory. According to the investigation, the biggest DC testing voltage is 7 kV and the largest DC testing current is up to 320 kA before 2011 [1].

International Thermonuclear Experimental Reactor (ITER) is an international collaboration project located in south France to demonstrate the scientific and technological feasibility of fusion energy for peaceful purposes [2], [3]. The ITER poloidal field (PF) AC/DC converter system mainly provides the controlled current thereby implementing the plasma shape and position control, which is one of the key systems for ITER [4], [5]. The ITER PF AC/DC converter Procurement Arrangement (PA) was signed between China Domestic Agency (DA) and ITER Organization (IO) in April 2011. The Institute of Plasma Physics, Chinese Academy of Science (ASIPP) takes the responsibility of ITER PF AC/DC converter PA. The PF AC/DC converter system is a major AC/DC converter system, and the total installation power is 1.2 GVA. The ITER PF AC/DC converter system required DC short-circuit impulse test current is 400 kA and the DC steady state testing current is up to 100 kA for type test [6]. Hence, the existing test facilities cannot satisfy the test requirements of the ITER PF AC/DC converter system.

Considering the testing requirements of ITER PF AC/DC converter system components and continuous upgrading capacity of high-power test capability, the steady-state current of DC high-power test facility is rated at 120 kA and the pulse current is 500 kA. 120 kA steady-state current make it the largest steady state DC current test facility in China until now. The DC high-power test facility of Hefei Institutes of Physics science, Chinese Academy of Sciences (CASHIPS) is a professional test facility. 15 testing items are accredited by the China National Accreditation Service (CNAS) for Conformity Assessment in May 2017. The relevant reports are accredited by 35 countries including France, Germany, Italy, United Kingdom, United States, etc.

Designed and constructed by ASIPP, co-phase counter parallel connection topology structure is selected on account of the low voltage and the high current of DC high power test facility. In this paper, the characters, parameters and operation modes of DC high power test facility are presented. In addition, the configuration of the control system, hardware and software of the local controller is illustrated in detail. Moreover, the relevant qualification experiments including the testing capability and some completed tests are also provided. The paper is organized as follows. The topology and the control of DC high-power test facility is presented in Section II and Section III respectively. The qualification experiments are performed in Section IV. In this part, the experiment of 120 kA rated steady state DC current and 500 kA pulse current is carried out to demonstrate the testing capabilities. Moreover, some typically completed tests are also provided in this part. At last, the conclusion is drawn in Section V.

II. Topology of the DC High-Power Test Facility

A. Topology Structure

Four AC/DC converter modules are paralleled to handle

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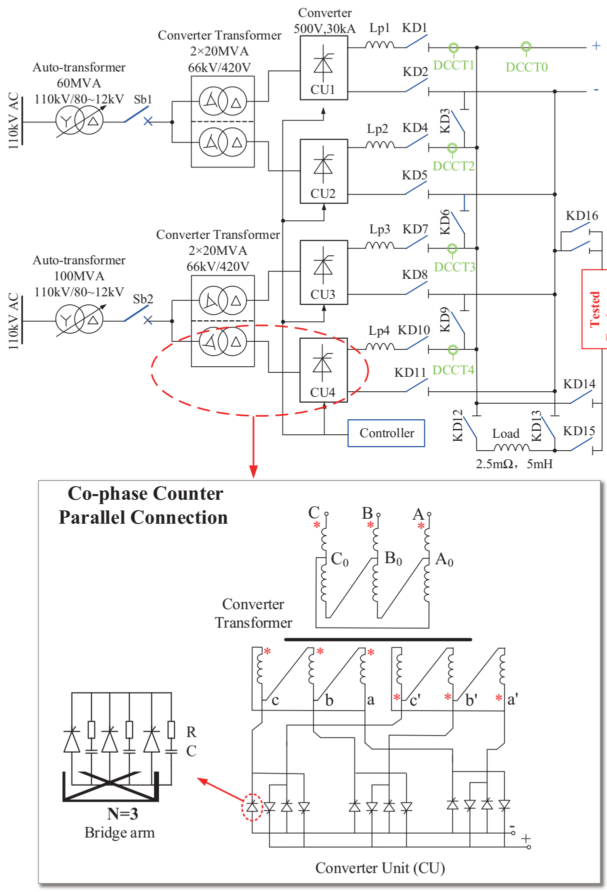


Fig. 1. DC high-power test facility scheme.

120 kA steady-state DC current and 500 kA pulse current. 30 kA rated steady-state DC current and 0.5 kV rated DC voltage of each converter module make the co-phase counter parallel connection topology structure the suitable choice for DC high power test facility as Fig. 1. Co-phase counter parallel connection topology structure not only reduces the current carrying load of transformer individual windings, but also reduces the eddy power loss and heat generation of the transformer because the adjacent two-phase windings currents are reversed. In addition, the magnetic flux density in the converter cabinet is near to zero, which improve the operating environment of the semiconductor component [7].

IGBT, IGCT and other semiconductor is wildly studied and used in high power electronic field [8], [9], [10]. However, with the outstanding advantages that heavy current, high voltage, relatively small heat dissipation density and low cost, the thyristor-based AC/DC converter module is chosen and each bridge arm is paralleled with 3 thyristors and RC snubber circuit. The type of thyristor is ABB 5STP 50Q1800.

As shown in Fig. 1, the DC high-power test facility is composed by 110/66 kV 100 MVA and 115/66 kV 60 MVA autotransformers, four 20 MVA converter transformers, four 30 kA/0.5 kV converters, four DC reactors (50 uH), load (2.5 mΩ, 5 mH) and sixteen DC disconnectors. Each thyristor-based AC/DC converter module is connected to a converter transformer. The converter transformers are phase shifting to each other in order to implement the 24 pulses output in DC terminal thereby eliminating harmonics at specific frequencies on the AC side and reducing current ripple in DC side. The DC high-power test facility scheme and parameters are shown as Fig. 1 [11]. CU1–CU4 are the four AC/DC converter modules, KD1–KD16 are the DC disconnectors, Lp1–Lp4 are the DC reactors, DCCT0–DCCT4 are the current sensors [12]. The DC high-power test facility is shown as Fig. 2.

Fig. 2. DC high-power test facility.

TABLE I
OPERATION MODES

Operation Mode	Operation Converter Module	Parameter
Single converter operating	CU1 / CU2 / CU3 / CU4	30 kA, 0.5 kV
Two converters in parallel	CU1&CU2 / CU3&CU4	60 kA, 0.5 kV
Four converters in parallel	CU1&CU2&CU3&CU4	120 kA, 0.5 kV
Two converters in series	CU1&CU2 / CU3&CU4	30 kA, 1.0 kV
Four converters in series	CU1&CU2&CU3&CU4	30 kA, 2.0 kV

B. Operation Modes

The converters can operate in different operation modes to satisfy the different test requirements. As shown in Table I, the operating modes include single converter operating mode, converters in parallel operating mode, and converters in series operating mode. DC disconnector array is designed to change the circuit connection to implement multiple operating modes according to the different test requirements. The autotransformers are set in different position according to the required maximum voltage and

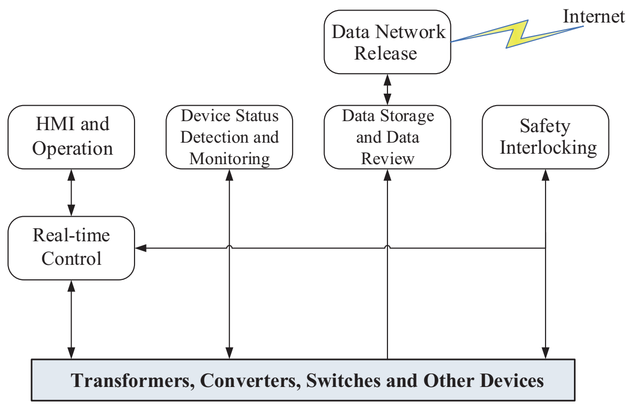


Fig. 3. The structure of the control system.

current ripple, and which is helpful to reduce the current ripple in some case.

III. The Control System of DC High-Power Test Facility

A. The Configuration of Control System

The test facility control system is divided into the following different parts according to the functions: human machine interface (HMI) and operation, real-time control, device status detection and monitoring, data storage and data review, data network release, and interlock. The structure of the control system is shown in Fig. 3.

- HMI and operation: to set the operation parameters such as waveform preset, converter operation mode, converter control mode, and to operate the converter state machine.
- Real-time control: to complete voltage open-loop and current closed-loop control operation, and to change the operation mode in real time according to the rectifier operating parameters, and to act the interlock action.
- Device status detection and monitoring: to detect the status of transformers, rectifiers and switchgears periodically, and to monitor the status. And to act the remote operation of switches.
- Data storage and data review: to measure the circuit voltage, current of transformer and converters. To store the data and review the data.
- Safety interlock: to act the occupation safety function.

Each part of the control system is interconnected through the network. According to the different performance and function requirements, the control network is divided into two types: shared memory real-time network and Ethernet. Each network is independent, and all devices are in the same network layer to ensure data transmission efficiency. As the core controller of the DC high-power test facility, the real-time controller is also called the local controller.

B. The Local Controller

The local controller is based on Compact PCI computer [13], and the Compact PCI chassis is 12V18OPX98Y5VQ2X/ELMA; According to the real-time reference voltage, the trigger angle is calculated by CPU and the CPU board type is CP6005; Then, the converter bridge control and the trigger pulses generating is implemented by the alpha controller. Alpha controller outputs and modulates the trigger signal into a 15 kHz pulse to reduce the amplifier power and send the trigger pulse at the corresponding time to the thyristors by optical fiber, and the alpha controller type is CPCI-2008. Each converter module is controlled by an independent alpha controller. The configuration of the local controller is shown in Fig. 4. The AD board type is CPCI-9116 for analog signal input and the DIO board type is CPCI-7432 for digital signal input and output. The control block of local controller is shown in Fig. 5.

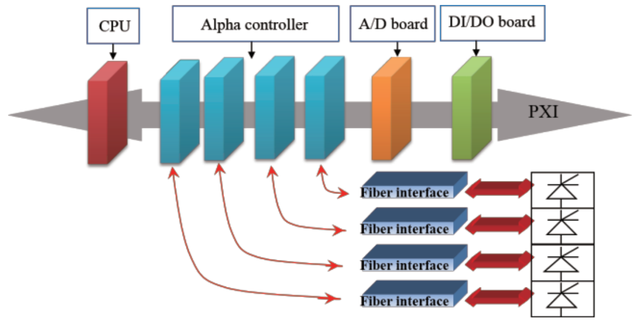


Fig. 4. The configuration of loacl controller.

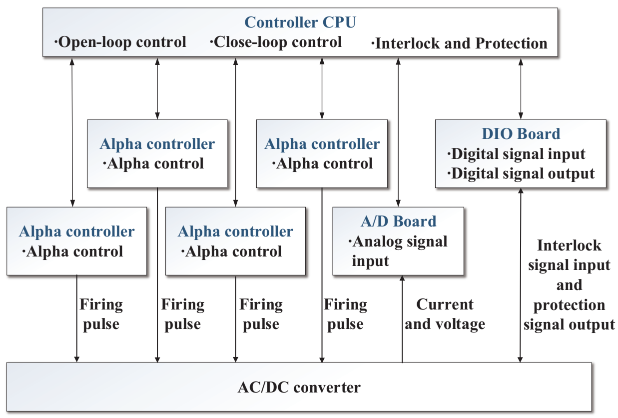


Fig. 5. The control block of local controller.

Fig. 6 shows the cubicle configuration of the local controller. The synchronization board is used to obtain the synchronization signal. The synchronization signal is delivered to the local controller to provide an accurate phase synchronization and frequency synchronization for the trigger time. The feedback signal and protection signal is collected by fast A/D.

IV. Testing Capability

A. 120 kA Steady State DC Current

The DC test facility is composed of four 30 kA/0.5 kV

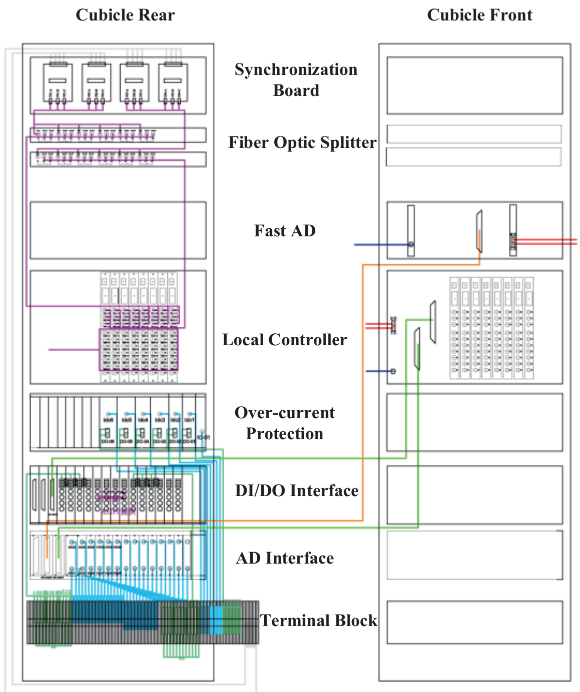


Fig. 6. The cubicle configuration of local controller.

converters. These converters could be operated in different modes to implement different required output. The output performance of different operation mode is shown in Table II.

When the four converter modules are in parallel, the steady state output current is rated to 120 kA. The huge DC continues current could be outputted to implement superconducting coil test, high temperature current lead test, DC disconnect test, etc. During steady state operation, the current closed loop control is adopted. The typical experiment results that rated current of 120 kA is shown as Fig. 7.

B. 500 kA Pulse Current

1) The Output Capability Calculation Based on System Parameters

Based on the analysis of the system parameters, the pulse current test capability of DC test platform is calculated. The equivalent circuit of four paralleled converter units is shown in Fig. 8. The U_{d0} is the no-load voltage of the converter; R_{S4} is the internal resistance of the four paralleled converter units; L_p is the inductance of DC reactor; L_d is the inductance of DC circuit; R_d is the DC resistance; R_1 is the resistance of the stainless steel resistor.

According to Fig. 8, the (1) can be obtained as:

$$\begin{cases} U_{d0} - R_{S4} i_d - \dfrac{L_p}{4} \times \dfrac{di_d}{dt} = (R_d + R_1) i_d + L_d \dfrac{di_d}{dt} \\ U_{d0} = 1.35 U_2 \cos\alpha \end{cases} \tag{1}$$

TABLE II
Operation Parameters of DC High-Power Test Facility

Operation Mode	Parameter	Value	Ripple
Single converter operating	Rated DC voltage	500 V	-
	Rated DC current	30 kA	≤1%
Two converters in parallel	Rated DC voltage	500 V	-
	Rated DC current	60 kA	≤1%
Four converters in parallel	Rated DC voltage	500 V	-
	Rated DC current	120 kA	≤1%
	Short pulse current	500 kA	-
Two converters in series	Rated DC voltage	1.0 kV	-
	Rated DC current	30 kA	-
Four converters in series	Rated DC voltage	2.0 kV	-
	Rated DC current	30 kA	-

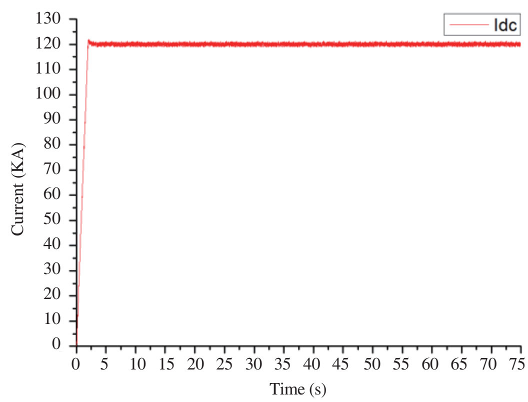


Fig. 7. The 120 kA steady state current profile (I_{dc} is the dc terminal current).

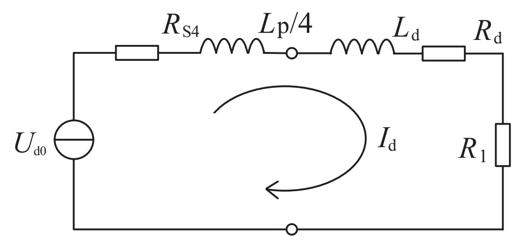


Fig. 8. The equivalent circuit of four paralleled converter units.

The U_2 is the secondary phase to phase voltage of the converter transformer. Then (1) can be equivalent to (2).

$$(R_{S4} + R_d + R_1) i_d + \left(L_d + \frac{L_p}{4}\right) \frac{di_d}{dt} = 1.35 U_2 \cos\alpha \tag{2}$$

The I_d can be calculated:

$$I_d = \frac{1.35 U_2 \cos\alpha}{R_{S4} + R_d + R_1} \left(1 - e^{-t/\tau_4}\right) \tag{3}$$

$$\tau = \frac{L_d + L_p/4}{R_d + R_1 + R_{S4}} \tag{4}$$

Different transformer tap position corresponds to the

TABLE III
OUTPUT CAPABILITY OF FOUR PARALLELED CONVERTER UNITS

	U_2 (V)	R_{S4} (mΩ)	R_Σ (mΩ)	τ (ms)	I_d^* (kA)
115/80	487	0.48	0.88	59.7	721.7
115/42	256	0.27	0.67	78.4	498.3
115/12	73	0.20	0.60	87.5	158.7

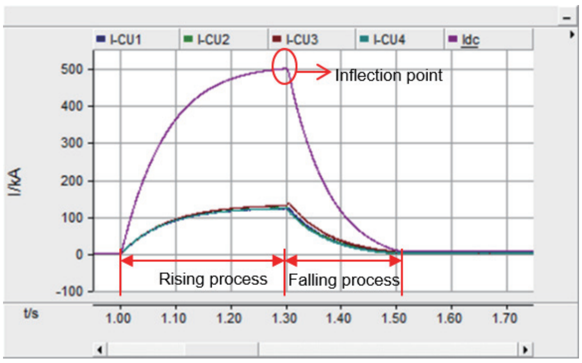


Fig. 9. The simulation of 500 kA peak pulse current output.

different parameters. The internal resistance of the four paralleled converter units R_{S4}, the total resistance R_Σ, the (3) and (4) can be obtained as Table III.

The calculated output capability of the DC current in Table III is not the experiment current that the converter can withstand. The experiment peak current and its pulse width is limited by the thyristor limiting load integral parameter, the thyristor internal silicon temperature, and should be with some safety margins.

2) The 500 kA Output Capability Experiment

For the pulse current operation, the whole process of the pulse can be divided into three stages, rising process, inflection point and falling process as Fig. 9. All of these three stages current control is required very fast dynamic response within milliseconds.

During the rising process, the converters work in the converter model. Because of the AC and DC loop impedance difference between each paralleled converter, the control purpose is not the same DC average voltage but the same current for each paralleled converter. During inflection point, it is, in fact, in a transient process, the converters should be changed from converter model to inverter model. Because of the phase shifting between each converter transformer, the DC voltage transient values of each converter is different, the DC output transient current is hard to be controlled. And any current overshoot could lead the converter failure because of the huge transient current. While during the falling process, the converters work in the inverter model. Because of the inherent characteristics commutation failure of thyristor-based converter when in inverter model, this process should be controlled carefully according to each converter DC current. And in this phase, the current sharing control is a very important task to make sure the system safe.

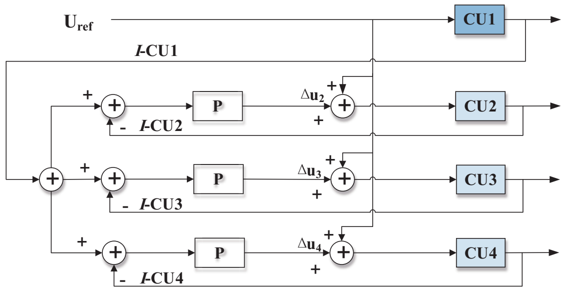


Fig. 10. Dynamic current sharing control strategy of 500 kA pulse current. (*I*-CU1: CU1 converter current; *I*-CU2: CU2 converter current; *I*-CU3: CU3 converter current; *I*-CU4: CU4 converter current; I_{dc}: the dc terminal current).

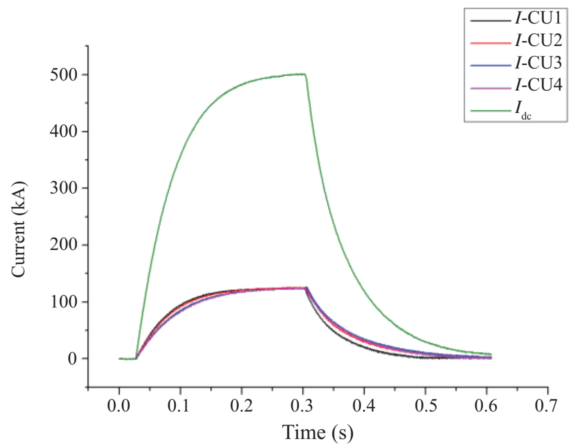


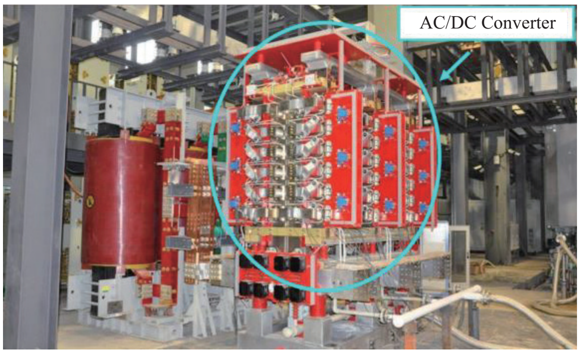
Fig. 11. The 500 kA Peak Pulse Current Profile (*I*-CU1: CU1 converter current; *I*-CU2: CU2 converter current; *I*-CU3: CU3 converter current; *I*-CU4: CU4 converter current; I_{dc} is the dc terminal current).

As the key technology of DC high power test facility, the dynamic current sharing control strategy of 500 kA pulse current is shown as Fig. 10.

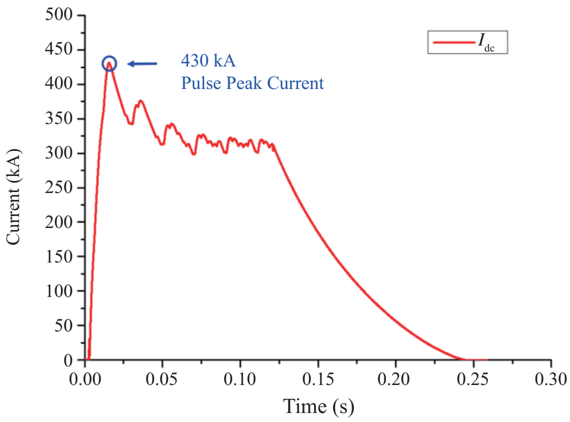
The proportional control with the incremental control algorithm is adopted to ensure the dynamic characteristics and the system stability [14], [15]. U_{ref} is the control reference voltage. The *P* controller parameters are designed carefully to ensure the short response time, and to avoid overshoot or shock in operation. $\Delta u1$, $\Delta u2$ and $\Delta u3$ are the incremental voltage.

With the characteristics that short pulse time, large output current and fast current rising, the voltage open loop and current closed loop are adopted for the pulse output operation. One of the paralleled converter CU1 is selected as the master module, and the other ones (CU2 to CU4) are treated as the slave modules, each slave module will perform current sharing adjustment according to the current of the master module *I*-CU1.

The experiment is carried out on DC high power test facility to verify the effectiveness and the feasibility of this control strategy. The 500 kA pulse peak current output is shown as Fig. 11. In pulse operation, the output peak current is 500 kA within 0.3 s, the profile is shown in Fig. 11. These



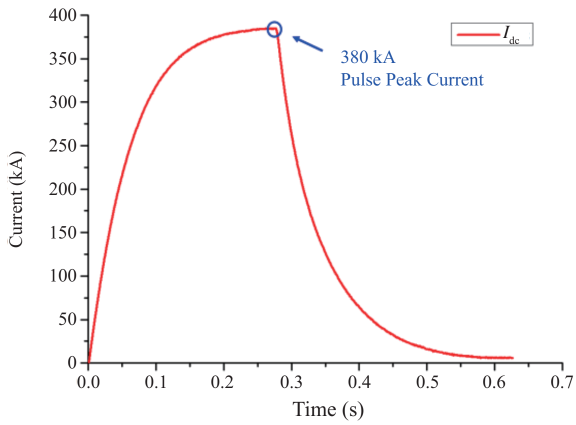
(a)



(b)

Fig. 12. AC/DC converter type test. (a) Test photo. (b) Test profile (I_{dc} is the dc terminal current).

(a)



(b)

Fig. 13. DC Line Disconnector type test. (a) Test photo. (b) Test profile (I_{dc} is the dc terminal current).

performance could be used for DC high-power equipment type test.

C. The Completed Test

Until now, 17 devices type test of 16 companies and manufacturers have been done, including AC/DC converter type test, bypass the type test, DC reactor type test, feeder type test, DC line disconnector type test, and traction distribution DC switchgear type test, etc.

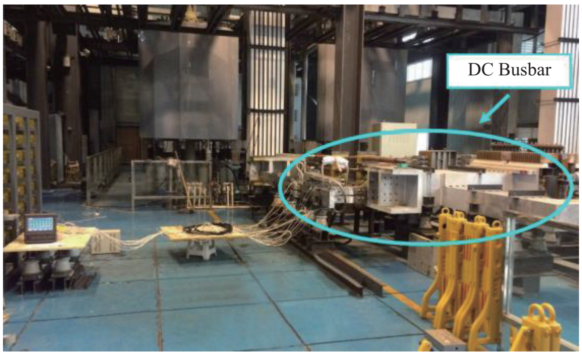
AC/DC converter is implemented the type test, in order to verify the converter structural strength in case of the converter reactor upstream short. The thyristors were all replaced by high power diodes in order to achieve the peak current without control. In this test, the converter bridge was subjected to 430 kA peak short current test. There is no deformation or damage to the structure, and the test results showed that the structural strength of the converter meets the design requirements. The test photo and the current profile is shown in Fig. 12.

DC line disconnector type test is realized in the pulse mode to verify mechanical stability and thermal stability under shock current conditions of 380 kA peak current. The DC line disconnector is not deformed or damaged, and the test results showed that the designed disconnector meets the design requirements. The test photo and the current profile is shown in Fig. 13.

DC busbar type test is realized in the steady state current mode to verify the thermal stability. The steady state current is 27.5 kA, the test continues until the bus temperature reaches equilibrium. The test results showed that design of the DC busbar meets the design requirements. The test photo and the current profile is shown in Fig. 14.

V. Conclusion

The DC high-power test facility is designed and constructed by ASIPP which aims to perform the test of ITER PF AC/DC converter system and meets the future continuous upgrading needs of the modern industrial power system and scientific research. Certified by CNAS in May 2017, 15 test reports are accepted by 35 countries in the world. The steady-state current of DC high-power test facility is rated at 120 kA. The pulse peak current is 500 kA. The DC high-power test facility is developed into a high-power electrical professional test facility, which is capable of the type test and routine test of the components in industry, rail traffic and electric power. In this paper, the topology and the control of the DC high-power test facility are presented. Then the performance results from the experiments of



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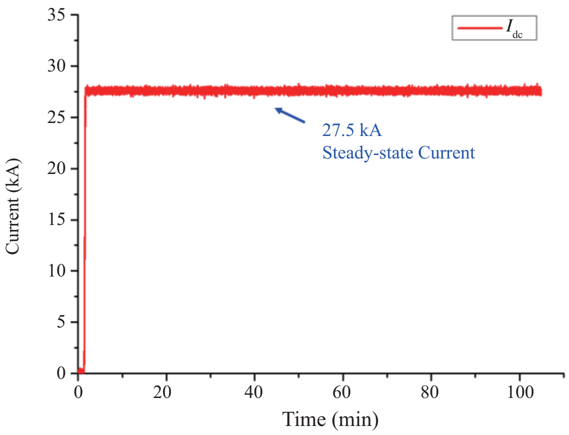

(b)

Fig. 14. DC Busbar type test. (a) Test photo. (b) Test profile (I_d is the dc busbar current).

its testing capability are reported. The experiment results illustrated that the testing capability that 120 kA steady-state continuous current and 500 kA pulse current of DC high-power test facility is qualified.

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