Prototype Design and Test of ITER PF Converter Unit

Zhiquan Song, Peng Fu, Jinchao Li, Peng Wang, Xiuqing Zhang, Chuan Li, Yong Yang, and Ling Dong

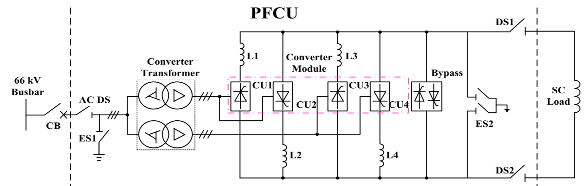
***Abstract*— This paper presents the design and testing of the full scale prototype of the international thermonuclear experimental reactor (ITER) poloidial field converter unit (PFCU), which is mainly composed of converter transformer, converter module, external bypass, and dc reactors with a rated capacity of 82 MVA and a rated dc current of 55 kA. Considering the space limitation, the high safety and reliability requirements, the nonsame-phase antiparallel connection structure, and the fault suppression capability criterion are applied in the prototype design. After the completion of the preliminary design of the PFCU in summer 2012, the detailed prototype structure design and the manufacturing of the PFCU were launched and completed at the end of 2013, then the following main type tests, including short circuit current test and temperature rise test on the main components of the PFCU, have been done on the ITER power supply test platform at ASIPP site. In addition, the PFCU integration test has also been done to verify the system operation performance. The prototype test results are well in compliance with the design requirements of the ITER PF converter system. It indicates that the full scale prototype research and development of PFCU has been accomplished successfully.**

***Index Terms*— Fault suppression capability (FSC), poloidial field converter unit (PFCU), prototype design, type test.**

I. Introduction

THE poloidial field converter unit (PFCU), as an important part of the international thermonuclear experimental reactor (ITER) PF coil power supply system, plays an essential role in plasma current shape and position control in vertical and horizontal directions [1].

The ITER PF coil power supply system is composed of 14 PFCUs to be provided by China Domestic Agency, each PFCU is with a rated capacity of 82 MVA and a rated dc current of 55 kA. Fig. 1 shows its main circuit topology. It mainly comprises four off-identical 6-pulse bridges (one converter module), which are decoupled by dc reactors at dc side and in four-quadrant operation, and the converter bridges are supplied by a common converter transformer designed with two secondary and two primary three-phase windings, two windings are shifted by 30° to provide 12-pulse operation. Besides, an external bypass is adopted (pulsed duty) to handle fault conditions and to circulate the load current [2].



CB - Circuit breaker, L1~L4 - DC reactor, CU1~CU4- Six-pulse Bridge, DS - Disconnector Switch, ES - Earthing Switch, SC - Superconducting Coil

Fig. 1. Main circuit topology of the PFCU.

Due to the limitation of the installation space at ITER site and safety concerns for the ITER operation, so the nonsame-phase antiparallel connection structure should be designed and applied in the PFCU. In addition, the prototype components of the PFCU should be designed for the fault suppression capability (FSC) criterion.

According to the procurement arrangement (PA) requirement of ITER PF ac/dc converter, the main task is to perform the full scale prototype research and development (R and D) of the PFCU in the final design phase. After about two years hard work, the detailed structure design, manufacturing, and testing of all the prototype of the PFCU have been accomplished successfully last year.

Due to the high current rating and the controlled dc voltage/current characteristics for the PFCU, it is designed based on thyristor technology and modular approach. Sophisticated structure design and special physical structure are applied in the prototype to ensure good current sharing and high dynamic characteristic. Moreover, the stringent type tests of the prototype and the PFCU integration test are performed to check the design and verify the operation performance.

This paper is focused on the prototype structure design and testing of the PFCU. The design inputs of the prototype are introduced first. Then, the detailed structure design, analysis, and type tests of the main prototype components, including converter module, bypass, and dc reactor, are presented, respectively. Section II is the integration test of the PFCU. In Section VII, the conclusion of this paper will be presented.

II. Design Requirement

According to Annex B and the preliminary design outputs of the PF converter PA [3], the detailed design inputs of

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TABLE I
TECHNICAL PARAMETERS OF MAIN COMPONENTS

Components	Rated value	Dynamic stability value [a]
Converter transformer	66 kV/1.05 kV, 82 MVA, 16%	350 kA/250 ms
Converter module	± 1.42 kV/55 kA	350 kA/80 ms
External bypass	± 1.42 kV/55 kA, 1s	350 kA/80 ms
DC reactor	27.5 kA/200 μH	190 kA/80ms
DC disconnector	2 kV/55 kA	350 kA/80 ms

[a] Peak short circuit current value and duration time

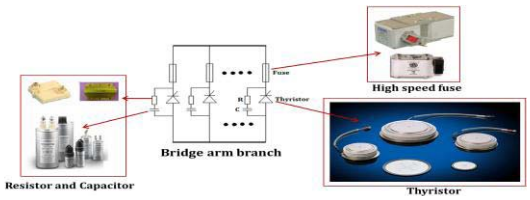


Fig. 2. Electrical structure of a bridge arm.

the prototype R and D of the PFCU are summarized as follows.

A. Electrical Parameter Requirement

The electrical parameter requirements of the prototype component design are obtained from the results of the normal operation and the fault analysis of the PF converter system [4], [5].

A summary of the technical requirements is shown in Table I. And the insulation level of the PFCU is 12 kV (rms). The maximum current unbalance coefficient (K_{unb}) of the PF converter shall be no more than 1.4.

B. Structure Requirement

The FSC criterion is the special requirement for the ITER ac/dc converter, and it should be applied in the structure design of the PFCU. The FSC criterion is that the converter should withstand the electrical stress and the mechanical stress due to two worst short circuit conditions before tripping off the CB. The electrical stress and mechanical stress should be satisfied when the peak withstanding current is up to 175 and 350 kA, respectively, and the duration time is 80 ms.

III. CONVERTER MODULE R AND D

Converter module is a key component of the PFCU to provide the controlled large dc power to the superconducting coil. It contains four identical six-pulse bridges.

A. Electrical Design

Thyristors, fuses, resistors, and capacitors used in a snubber circuit are the most important four components, which directly influence the performance of the converter module. It is the premise and basis of the structure design. The electrical structure of a bridge arm is shown in Fig. 2. Each thyristor is in series with a fuse and in parallel with an RC snubber circuit.

Using the transient thermal impedance model of the thyristor and fault analysis results, two types of thyristors with similar characteristics are chosen and used half and half in the converter module prototype. And the parallel number of each bridge arm is 12 [6].

TABLE II
ELECTRICAL DESIGN RESULT

Components	Type	Parameters	Value
Thyristor	ABB 5STP 52U5200, CSR KP_D 5000-52	V_{DRM}	5200 V
		$I_{T(AV)M}$	5060 A, 5000 A
		N_P	12
High Speed Fuse	12 URD 284 PLAF 3000	Rated voltage	1200 V
		Rated current	3000 A
RC snubber	UXM600-8R-J-150PPM	Resistance	8 Ω
	E62.M17-222CRO	Capacitance	2.2 μF

High-speed fuse is to prevent the thyristor from exploding and cut off the fault branch to avoid fault propagation. The proper Mersen (former Ferraz) fuse is selected by the fault analysis and combining with the characteristics of the fuse [7].

The RC snubber circuit is to protect the thyristor from being damaged by commutating overvoltage. The RC snubber circuit is designed through the built turn-OFF model of the multiparallel thyristors and the commutating overvoltage circuit model [8].

The electrical design result of the main components can be listed in Table II.

B. Prototype Structure Design

The nonsame-phase antiparallel connection structure is applied on the converter bridges. Furthermore, in order to fulfill the FSC requirement, a new bridge structure is designed and developed to achieve a good current sharing and high dynamic characteristic for high current rating and large short circuit current.

1) Current Sharing Structure: Bridge arm is the basic and core structure of a six-pulse bridge. Current sharing among the multiparallel thyristors in the bridge arm is influenced by many factors, and the arm structure is the main factor [9].

a) Current sharing analysis: The current sharing analysis of the bridges is based on the current sharing equation. For an arbitrary arm in the PF converter bridge, a current sharing equation can be built for its current sharing analysis, as shown in the following:

$$U_0 = \boldsymbol{M}_0 \frac{d\boldsymbol{I}_B}{dt} + \boldsymbol{R}\boldsymbol{I}_B + U(\boldsymbol{I}_B) + \sum_k \boldsymbol{M}_k \frac{dIt_k}{dt}. \quad (1)$$

It is actually a set of differential equations regarding the thyristor currents of the analyzed arm. The thyristor currents are contained in the current matrix $\boldsymbol{I_B}$. $\boldsymbol{M_0}$ is the inductive coupling coefficient matrix, which includes the coupling between different branches (B1∼B12) and bus segments (S1∼S12), as shown in Fig. 3.

The coupling between the internal structure of the arm and its ac and dc busbars is also included in the matrix. $\boldsymbol{R}$ is the resistance matrix, which contains the resistance information of the branches and the bus segments. Considering the nonlinear behavior of the thyristors, the U–I characteristic

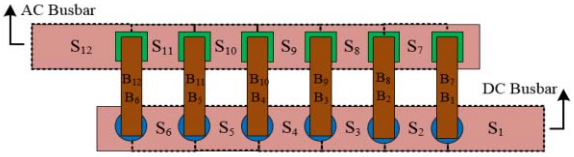
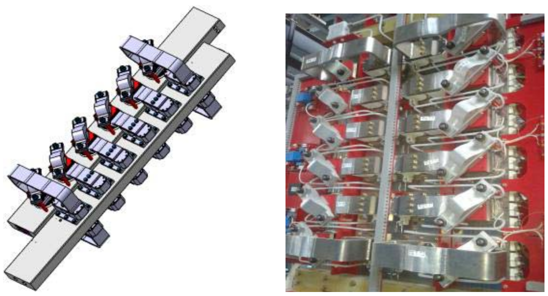


Fig. 3. Schematic of the bridge arm.



(a) (b)

Fig. 4. Design structure of the bridge arm. (a) 3-D model. (b) Application in the prototype.

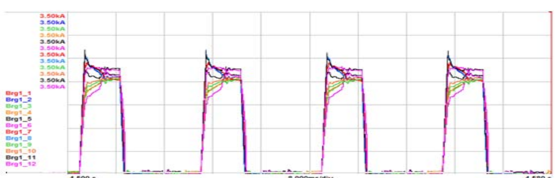


Fig. 5. Thyristor current waveforms of the arm1 in the CU3.

curve provided by the manufacturer is adopted to represent the voltage drop on a thyristor regarding to its current. And it is expressed in the form of a nonlinear function $U(\boldsymbol{I_B})$. The last portion of the equation builds the coupling from adjacent arms and their associative busbars. Solving the equation, the current waveforms of the parallel thyristors, which contain the current sharing information, can be obtained. As coupling from busbars, adjacent arms and the nonlinear behavior of the thyristors are fully considered, and the bridge arm designed in this method will have high current sharing coefficient.

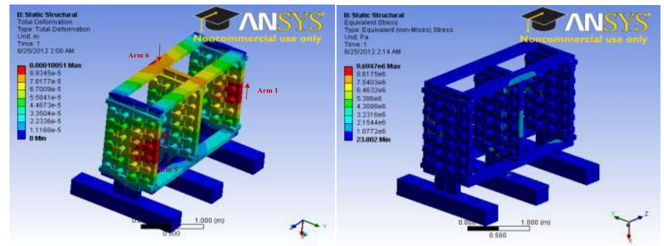
b) Bridge arm structure: Using current sharing equation (1), a new bridge arm structure with good current sharing characteristic is designed and applied in the prototype, as shown in Fig. 4. The maximum current unbalance coefficient is no more than 1.25 for 12 thyristors in parallel connection in one arm.

c) Current sharing test: Current sharing test is performed on each bridge prototype under a rated current of 27.5 kA. The typical thyristor current waveforms of arm1 in the bridge CU3 are shown in Fig. 5. A summary of the current sharing test results is shown in Table III. It indicates that four bridge prototypes have good current sharing, and the max unbalance factor is 1.22, better than the design requirement ($K_{\text{unb}} \leq 1.4$).

2) Mechanical Structure: In order to meet the FSC criterion, the PF converter prototype should have sufficient strength to survive under a peak short current up to 350 kA without any damage or permanent deformation in the mechanical structure.

TABLE III
CURRENT SHARING TEST RESULT

Bridge	Current unbalance coefficient of each bridge arm					
	Arm1	*Arm2*	*Arm3*	*Arm4*	*Arm5*	*Arm6*
CU1	1.10	1.16	1.18	1.20	1.12	1.19
CU2	1.20	1.13	1.15	1.15	1.15	1.14
CU3	1.10	1.19	1.22	1.16	1.12	1.13
CU4	1.13	1.11	1.15	1.16	1.19	1.20



(a) (b)

Fig. 6. Deformation and stress distributions of the bridge structure. (a) Deformation distribution. (b) Stress distribution.

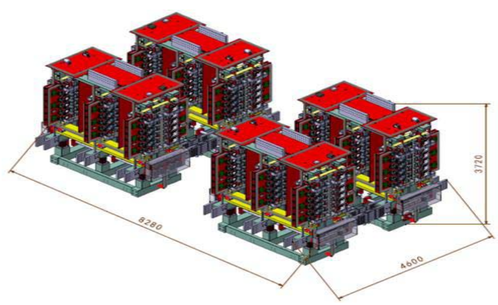


Fig. 7. Design structure and layout of the converter module prototype.

a) Electromagnetic analysis: Based on the arm structure designed and using ANSYS Workbench software, the framework structure analysis of the whole bridge is carried out. And the deformation and the stress distributions of the bridge structure are shown in Fig. 6.

It can be seen from Fig. 6 that the maximum deformation of the bridge is no more than 100 μm under a peak short current of 350 kA. And the maximum stress (9.7 MPa) is much less than the yield strength (193 MPa) of the material.

b) Prototype structure: A new framework bridge structure with high mechanical strength is designed and developed. And two antiparallel bridges are in series connection. The prototype design structure and the layout of the converter module are shown in Fig. 7.

C. Prototype Tests

After completing the prototype manufacturing, the routine and type tests, mainly including insulation voltage test, current sharing test, temperature rise test, and FSC test, are performed to verify the design and performance of the prototype. Finally, these required tests have been accomplished successfully in several months. Especially, it has passed short circuit withstand (FSC) test initially successfully. This test was performed on ITER ac test platform at ASIPP site, as shown in Fig. 8.

Fig. 8. Short circuit withstand test at ASIPP site.

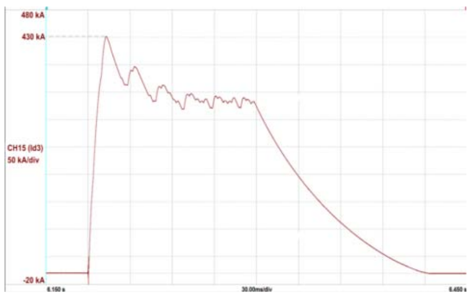


Fig. 9. Test waveform of short circuit current (430 kA/100 ms).

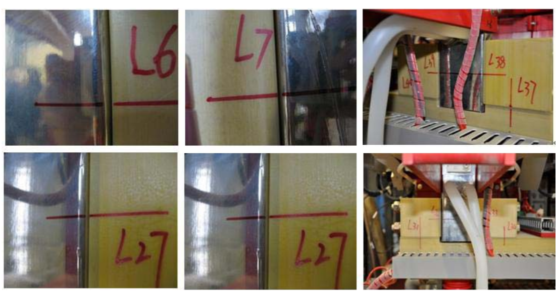


Fig. 10. Some inspecting marks of the bridge in the test.

This test was performed six times in total, and each phase has two times short circuit impulse current test. As shown in Fig. 9, the maximum peak short circuit current is up to 430 kA.

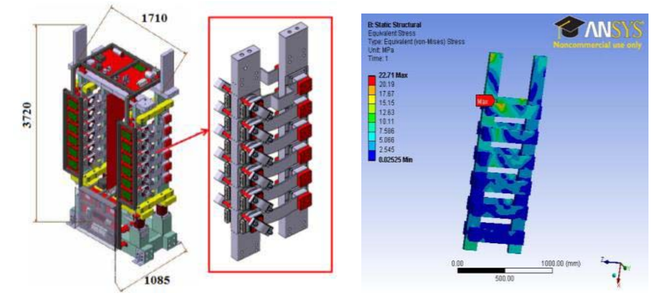
In addition, the duration time of the short circuit current above 350 kA is more than 100 ms; there is no visible deformations occurred on the mechanical structure by checking the inspecting marks made before the test, as shown in Fig. 10. It indicates that the converter bridge prototype can fully meet the FSC requirement.

IV. External Bypass R and D

External bypass is located at the downstream of the dc reactor, providing the protection of PF converter and magnets in fault conditions.

A. Prototype Structure Design

In order to satisfy the FSC criterion, the bypass is designed to survive with the electronic protection from the converter under the external or internal faults, and to avoid damaging the mechanical structure under a peak short current of 350 kA.



(a) (b)

Fig. 11. 3-D design structure and stress distribution of the bypass. (a) 3-D design structure. (b) Stress distribution.

Fig. 12. Type test site of the bypass at ASIPP site.

The 3-D design structure of the external bypass is shown in Fig. 11(a). The bypass consists of two bridge arms. The 12 thyristor branches are designed in parallel for one bridge arm. And they are distributed on both sides of the water cooled aluminum busbar. Each thyristor is in series with a resistor made by many stainless steel sheets, which can improve the conducting condition of the parallel thyristors and current sharing characteristic of the bypass.

The simulation model of the bridge arm is built to verify the mechanical strength of the bypass. The stress distribution of bypass arm is shown in Fig. 11(b). It can be seen that the maximum stress (22.7 MPa) is much less than the yield strength (193 MPa) of the aluminum material [10].

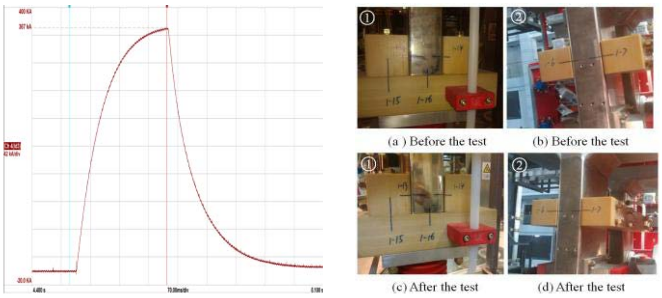
B. Prototype Tests

After finishing the bypass manufacturing, the routine and type tests have been completed successfully in the following several months. All the type tests were performed on the ITER dc test platform at ASIPP site, as shown in Fig. 12.

The main test results are shown in Fig. 13(a). The peak short current is up to 367 kA, and the duration time of the short circuit current above 350 kA is up to 100 ms; there is no fault propagation and deformations of the mechanical structure by checking the inspecting marks, as shown in Fig. 13(b). It shows that the bypass prototype can fully meet the FSC requirements.

V. DC Reactor R and D

DC reactor is used in the PFCU to restrain ripple current in normal operation, and to limit the dc short circuit current and its increase rate in fault condition. It is also designed to



(a) (b)

Fig. 13. Test results of the short circuit withstand test. (a) Test waveform (367 kA/100 ms). (b) Inspecting marks.

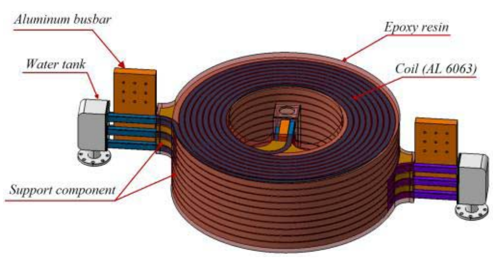
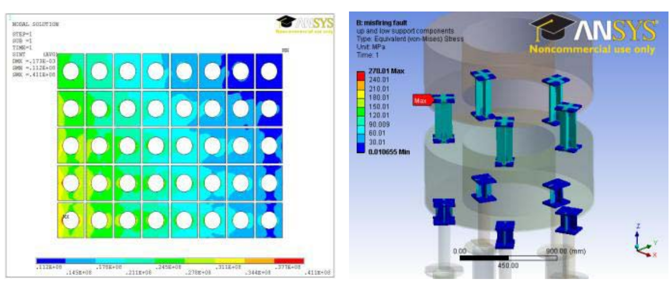


Fig. 14. 3-D design structure of the dc reactor.



(a) (b)

Fig. 15. Stress distribution of the coils and supports of the dc reactors. (a) Coils. (b) Supports.

survive in the worst short circuit fault without damaging the mechanical structure for the FSC criterion.

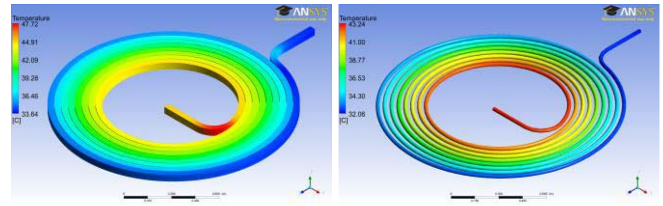
A. Structure Design and Analysis

The basic design structure of the dc reactor is shown in Fig. 14, which consists of two identical parts in series.

Each part has five coils in parallel with the average diameter of 1.21 m. Each coil is a square cross-sectional hollow aluminum pipe with the dimensions of 50 mm × 40 mm and a diameter of 25-mm center hole for cooling water.

Based on the finite-element method, the structure analysis and the thermal analysis are adopted to verify the prototype design of the dc reactor. As shown in Fig. 15, under peak short circuit fault current of 190 kA, the maximum stress of aluminum pipe and the supports are ∼41.1 and 270 MPa, respectively, which are less than the yield strength of the used materials [11].

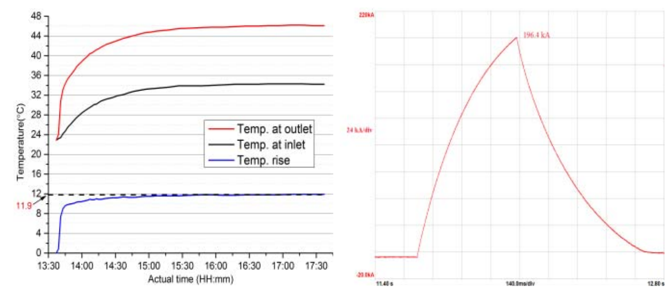
Under the condition of 32 °C inlet temperature, 1 m/s water velocity (17.6-m^3/h water flow) and a rated current



(a) (b)

Fig. 16. Temperature distribution of the coil and cooling water. (a) One coil. (b) Cooling water.

Fig. 17. Type tests site of the dc reactor at ASIPP site.



(a) (b)

Fig. 18. Two type test results of the dc reactor. (a) Water temperature rise curve. (b) Transient fault current waveform.

of 27.5 kA, the temperature distribution of the coil is shown in Fig. 16. The maximum temperature of the coil is ∼47.7 °C, and the temperature difference of the inlet and outlet water is ∼11.2 °C [12].

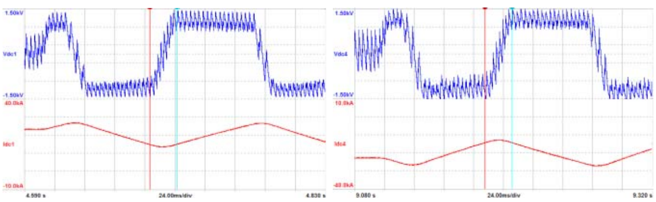
B. Prototype Tests

The required type tests, including temperature rise test and transient fault current test, were also carried out on the ITER dc test platform at ASIPP site, as shown in Fig. 17.

The results of two type tests are shown in Fig. 18. It can be seen that the steady temperature rise of the cooling water is 11.9 °C under a water flow of 17.4 m^3/h, which is less than the requirement of 20 °C temperature rise. For the transient fault current test, the peak short current is up to 196 kA, and the duration time of the short current above 175 kA is up to 145 ms. And there is no fault propagation and no deformation of the mechanical structure after the test. It shows that the dc reactor prototype can also fully satisfy the FSC requirements [13].

(a) (b)

Fig. 19. Integration test of the PFCU prototype at ASIPP site. (a) Outside prototype. (b) Inside prototype.



(a) (b)

Fig. 20. Voltage response waveforms of bridges CU1 and CU4. (a) Bridge CU1. (b) Bridge CU4.

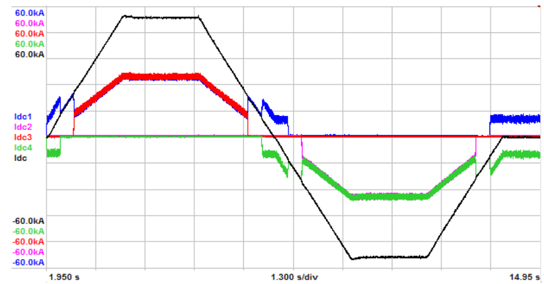
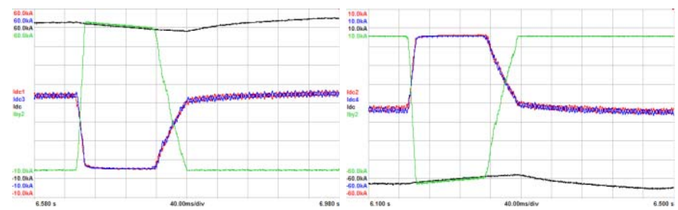


Fig. 21. Four-quadrant operation capability test waveform.



(a) (b)

Fig. 22. Test waveforms of protective test with bypass triggering. (a) Bypass forward bridge triggering. (b) Bypass reverse bridge triggering.

VI. PFCU Integration Test

Integration performance test of the PFCU is performed to verify whether all of the components, as well as the installation and assembly procedures, can meet the system requirements. The PFCU will be tested under different operating modes, with an input voltage of ac 66 kV, variable output current and voltage according to the requirements of ITER operation.

This test is a test combination, mainly including circulating current test, parallel operation test, voltage response test, four-quadrant operation test, protective test with bypass triggering, and so on. The integration test is performed on the PFCU prototype test platform at ASIPP site, as shown in Fig. 19. It is accomplished successfully. The main test results are as follows.

A. Voltage Response Test

Voltage response test is intended to verify the dynamic response of the PF converter during the voltage step. The voltage response waveforms of bridge CU1 and CU4 are shown in Fig. 20. For bridge CU3 and CU2, it is similar with the ones of CU1 and CU4. And the voltage response of each bridge for full-scale change is $\sim$22 ms, which fully satisfy the requirement of within 40 ms.

B. Four-Quadrant Operation Capability Test

Four-Quadrant operation capability test is used to verify the steady-state operation performance of single bridge mode, circulating current mode, and parallel mode of the PFCU. The test waveform is shown in Fig. 21. And the PFCU can operate normally under circulating current operation mode, parallel operation mode, and single bridge operation mode. It indicates that the PFCU can meet the system operation requirement.

C. Protective Test With Bypass Triggering

Protective test with bypass triggering is used to check whether the bypass can be triggered or not in case of some kinds of fault. This test result is shown in Fig. 22. When the bridges CU1 and CU3 operate in inverter under a load current of 55 kA, the forward bridge of the bypass is triggered normally and flow through the rated load current for 100 ms, and vice versa for the bridges CU2 and CU4. It shows that the PFCU can meet the fault protection requirement.

VII. Conclusion

This paper presents the structure design, analysis, and testing of the main prototype components of the PFCU. The PFCU integration test is also introduced. These test results are well in compliance with the prototype design. And it indicates that the full scale prototype of the PFCU can fully meet the design requirements of the ITER PF converter system. Based on the successfully completion prototype R and D of the PFCU, the following final design review and manufacturing readiness review of PF converter procurement package have also been finished smoothly. And the series production of the PFCUs has been launched now.

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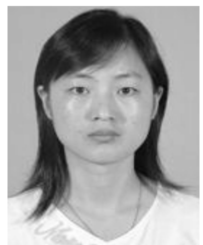

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