Fusion Engineering and Design 138 (2019) 59–67

Contents lists available at ScienceDirect

Fusion Engineering and Design

journal homepage: www.elsevier.com/locate/fusengdes

Design, manufacturing, acceptance testing and quality control of ITER PF AC/DC converters

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ARTICLE INFO

Keywords:
PF converter
Quality control
Design
Manufacture

ABSTRACT

ITER PF converter system is the largest converter system in the world. This special converter has the mutual superconductive coils as load, and requires large scale and rapid response. The institute of plasma physics Chinese academy of sciences (ASIPP) is responsible for this converter's preliminary design, final design, and manufacture. To meet these special requirements, during design and manufacture phase, quality assurance (QA) and quality control (QC) actions are worked out and strictly performed to ensure the validity of the product.

1. Introduction

ITER converter system is the largest converter system in the world with mutual superconductive coils as loads. The output voltage of converter can be adjusted in the range of millisecond according to the plasma control requirement. In the case of system fault, the converter system should respond in real-time and with high reliability to guaranty the safety of the coils and the tokamak machine [1]. The comparisons with common 100 MW class large capacity industrial converters are listed in Table 1.

ITER PF converter system is composed of 14 converter units which should be able to operate in 12-pulse, four-quadrant. Each converter unit provides the rated DC current of 55 kA and the rated on-load voltage of 1050 V [2,3].When the AC supply is between 62 kV and 72 kV, the converter bridge would provide the symmetrical voltage response not more than 2 electrical cycles (40 ms) for full scale change (from 1050 V to -1050 V or vice versa). In terms of the fault suppression capability, the converter structure should not be damaged in the case of short-circuited upstream the DC reactor, while for the short-circuited downstream the DC reactor, neither the converter module nor the electronic device could be damaged [4].

2. Project phases of ITER PF converter

A flow chart is developed to determine the project phases, as shown in Fig. 1. The whole project phases of ITER PF converter include design, manufacturing, FAT and Delivery. For each phase, the quality management, such as the decomposition of PF converter unit tasks, schedule and key nodes are formulated to ensure the successful manufacture of PF converter.

The design is divided into preliminary design, final design, design validation, design optimization and improvement of prototype.

The preliminary design is focused on the PF coil power supply circuit and converter unit level. It includes the characteristic and requirement analysis of ITER coil power supply, topology design and technical specification of main components, the reliability, availability, maintenance and inspectivety analysis of converter and the definition of interface.

The final design is the detailed design at the equipment level. The key issues are the R&D of each component, system integration and installation design.

The design validation is to verify the correctness of final design. It includes prototype development, factory tests and integration test.

The design optimization and improvement of prototype is to make upgrade and improvement on the final design according to the results of design validation and design review.

After manufacturing design review, 14 sets PF converter units are approved to be manufactured. FAT and integration test are the final processes before delivery.

3. Preliminary design of ITER PF converter unit

The 6-pulse bridge technology based on thyristor is employed as the basic module for ITER PF converter unit. For this unit, the key issues

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https://doi.org/10.1016/j.fusengdes.2018.11.004
Received 21 August 2018; Received in revised form 30 September 2018; Accepted 5 November 2018

Table 1
Comparison between ITER PF converter and common 100 MW class large capacity industrial converters.

Items	Illustrations	Load	Control Cycle	Dynamic character	Control and protection
ITER PF Converter	N.A	Mutual inductive coils	In millisecond	Full scale change in the range of millisecond	Special
Common 100 MW class large capacity industrial converters	Standards	Common loads	Minutes or hours	Almost Steady state or pulse	Usual

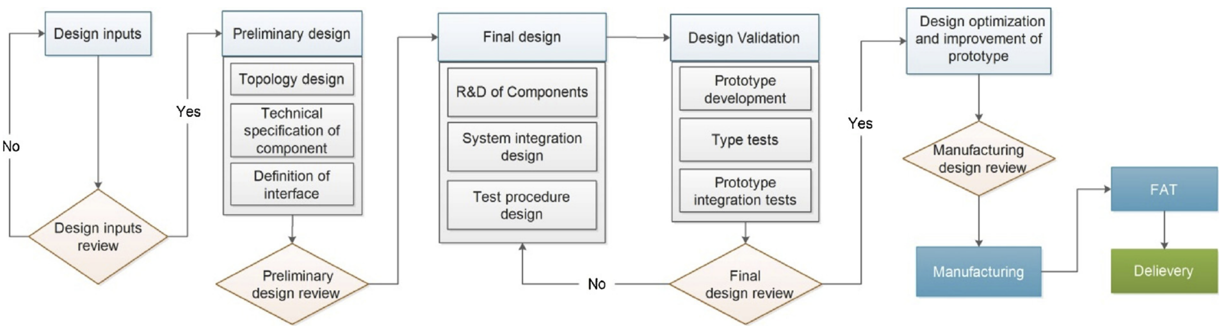


Fig. 1. Flow chart of the project.

arise at the integration design (topology and the technical specification for each component) and the R&D of local controller to meet the special requirement of tokamak operation.

3.1. Topology design

Fig. 2 shows the topology of ITER PF converter unit, which consists of a 300 MVA step-down transformer, two rectifier transformers in one tank, four six-pulse bridges, four DC reactors, AC disconnector, AC Earthing switch, DC disconnector and DC Earthing switches [5,6]. The two rectifier transformers are extendedly connected which leads to 30° phase shift to perform 12-pulse rectification.

As shown in Fig. 3 and Table 2, in region A1 and A2 ($-0.1I_{dN} \leq I_d \leq 0.1I_{dN}$), a circulating current mode is performed. In region B1 ($0.1I_{dN} < I_d \leq 0.3I_{dN}$) and B2 ($-0.3I_{dN} \leq I_d < -0.1I_{dN}$), only one six-pulse bridge carries the load current to perform transition from region A to C, or vice versa. In region C1 ($I_d > 0.3I_{dN}$) and C2 ($I_d < -0.3I_{dN}$), the load current is shared by two parallel six-pulse bridges in the same directions [7].

3.2. Electrical parameters of main components

The main components have been designed and the main electrical parameters are listed in Table 3. The design has taken into account of the influence of the grid, stray parameters, the steady state and dynamic state operation and short-circuit situation. The system must meet the following requirements [8]:

(1) Output the required DC voltage even in the case of the worst grid condition;
(2) The current could not be zero even when the voltage variation with the time constant at 7.5 ms in the circulating current operation;
(3) The unbalance current between two parallel bridges must be less than 10% of the rated current of the bridge.

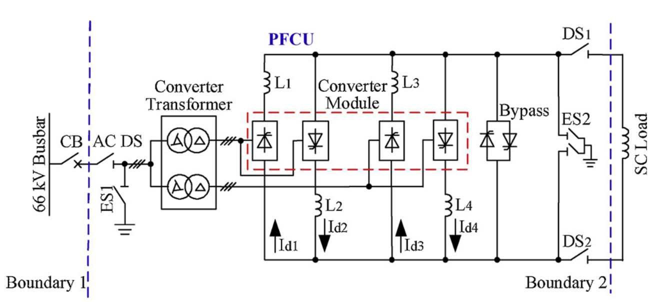


Fig. 2. The topology of ITER PF converter unit.

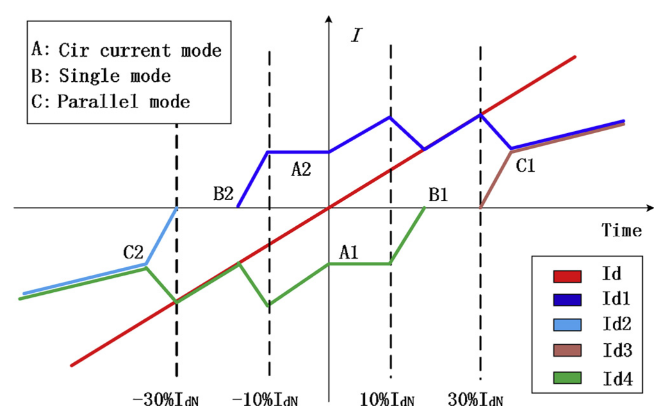


Fig. 3. Division of ITER PF operation modes versus load current.

Table 2
Converter operation modes.

C2	B2	A1, A2	B1	C1
CU3, CU4 Parallel	CU4 Single	CU1, CU4 Circulating	CU1 Single	CU1, CU2 Parallel

4. Final design of ITER PF converter

4.1. R&D of components

Besides the common requirements as in the industrial application, the components must also meet the following requirement:

(1) The converter bridge structure must withstand the short-circuit upstream the DC reactor for 80 ms;
(2) The converter bridge must withstand the short-circuit downstream the DC reactor for 100 ms;

Table 3
Electrical parameters of main components.

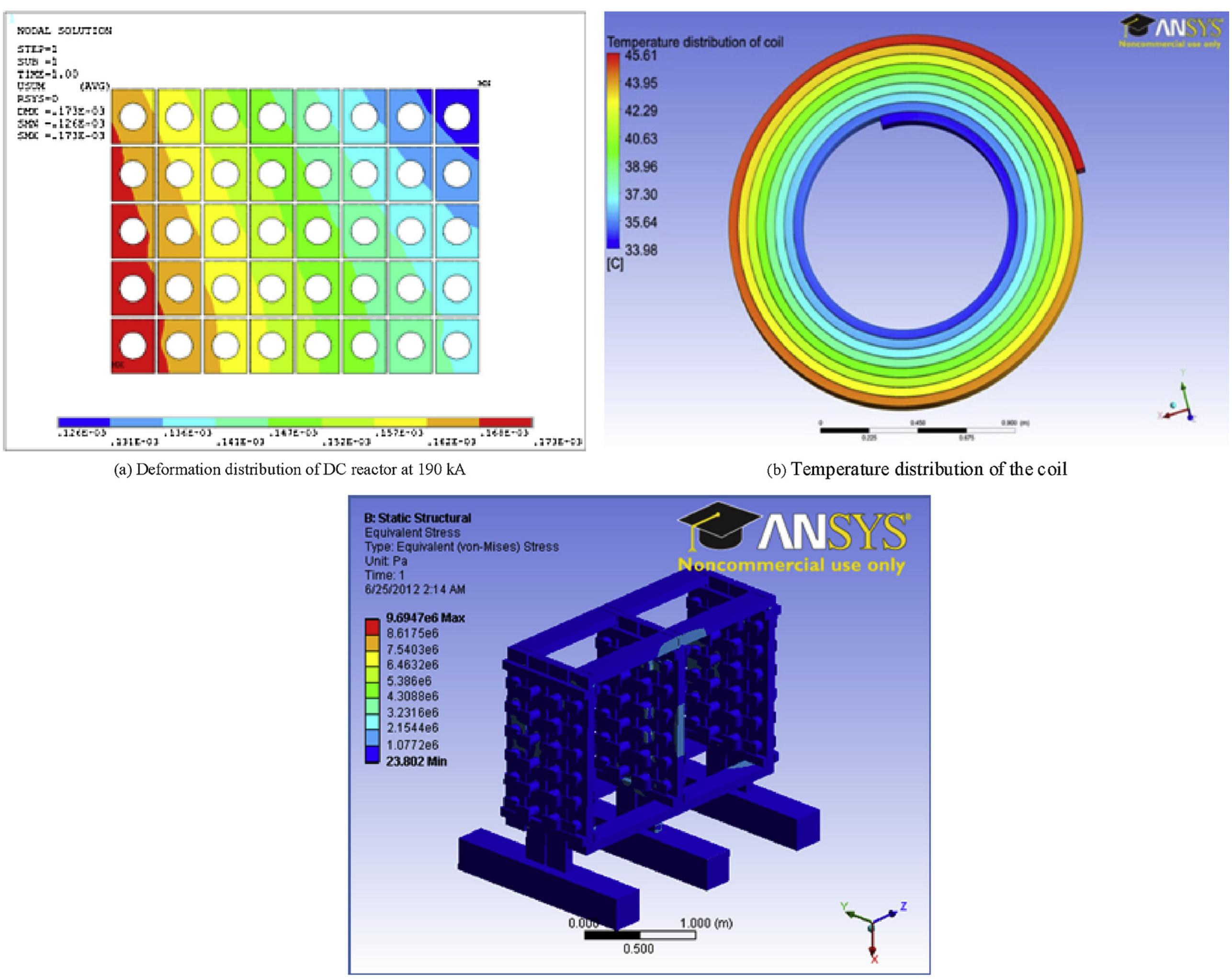
Components	Rated Parameters	Dimension,(L × W × H,mm)	Weight (ton)
AC disconnector& its support	66 kV / 1250 A	3910 × 3855 × 5965	3
Converter transformer	2 × 41 MVA, 16%, 66 kV/1.05 kV	9488 × 5360 × 5710	136
Converter module	1.42 kV / 55 kA	2 × 3030 × 4600 × 3720	2 × 13
External bypass	1.42 kV / 55 kA, 1 s	1700 × 996 × 3720	3
DC reactors assembly	250 μH / 27.5 kA	2955 × 1639 × 3296	2 × 2.5
DC disconnector	2 kV / 55 kA	1497 × 530 × 889	0.5
DC Earthing switch	12 kV	778 × 446 × 491	0.055
AC busbar (IPB)	12 kV / 2 × 22.5 kA	8361 × 3035 × 1500	5
DC busbar	27.5 kA	11498 × 8714 × 4395	3.4
Dummy load	12 kV / 6.73 mH	370 × 3095	10

(3) The external bypass must withstand the short-circuit fault when the electronic protection works;
(4) The structure of external bypass must withstand the short-circuit fault even when the electronic protection fails;
(5) The other components must withstand the short-circuit current downstream the DC reactor.

To meet the above requirements, the electrical model, analysis model for thermal, mechanical and electrical-magnetic field analysis has been set up for design, as shown in Fig. 4.

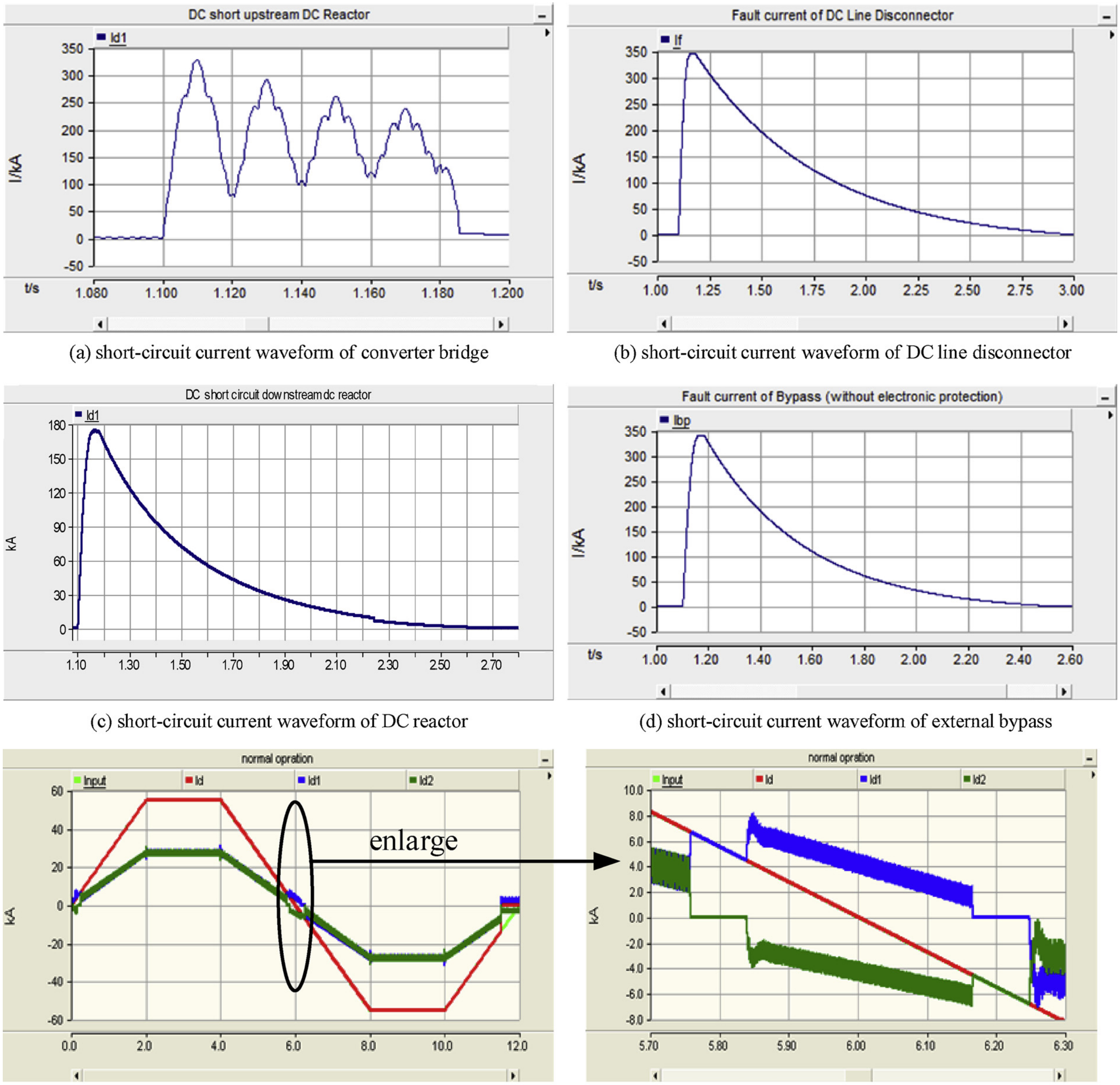
4.2. R&D of local controller

According to the requirements of ITER, the controller has been composed of three parts: local interlock controller, local safety controller and local conventional controller [9]. The local interlock controller is composed of fast interlock controller and slow interlock controller to detect interlock event, perform protection and transmit signals to plant interlock controller. The local safety controller is to detect occupational safety event and transmit to plant safety controller. The local conventional controller is a real-time controller with the control cycle less than 1 ms to deal with the voltage control of converter bridge



(a) Deformation distribution of DC reactor at 190 kA
(b) Temperature distribution of the coil
(c) Stress distribution of the converter bridge

Fig. 4. Simulation model of dynamic and thermal stability analysis for component.



(a) short-circuit current waveform of converter bridge

(b) short-circuit current waveform of DC line disconnector

(c) short-circuit current waveform of DC reactor

(d) short-circuit current waveform of external bypass

(e) simulation waveform of four-quadrant operation

Fig. 5. Simulation of short-circuit fault and four-quadrant operation of PF converter system.

and protection. The local conventional controller is connected to CCR to receive the voltage reference and send the status of each converter bridge. The real time control and real-time communication is accomplished with PXI, DSP and FPGA technologies.

4.3. System integration design

After the final design of component, the electrical parameters of each component are clear. Thus, the models with PSCAD, ANSYS and MATLAB have been adopted to simulate the ITER PF converter system with different operation modes, as shown in Fig. 5. The simulation results verify the system integration design and the component design [10–12].

4.4. Test procedure design

As to ITER PF converter system, there are no standards on FAT. From technical point of view, there are two issues:

(1) The test site condition and dummy load are quite different with those of ITER.
(2) The test items and acceptance criterion should be defined according to the steady state, dynamic state and fault protection actions.

A simulation model including the grid, step-down transformer, reactive power compensation system, PF converter unit and the dummy load with PSCAD has been set up to simulate especially the difference between ITER site and the test site and also the corresponding fluence on the operation of the ITER PF converter unit.

The four operation modes have been analyzed, and the key characteristics of performance have been researched. The list of test items and the acceptance criterions are shown in Tables 4 and 5.

5. Design validation

The ITER PF converter unit has a large capacity and special structure. The design validation is accomplished by prototype development, type tests and integration tests.

Table 4
The list of type tests items and acceptance criterions.

Test Items	Acceptance Criterions
FSC test of Converter Bridge with DC short upstream DC reactor	After withstanding the 350 kA short circuit current for four electric cycles, there should be no damaged or deformed parts in the mechanical structure of the converter bridge.
FSC test of Converter Bridge with DC short downstream DC reactor	After withstanding the 175 kA short current for 80 ms, there should be no mechanical damage or electrical damage on the tested converter bridge.
Dynamic current balance test of Converter Bridge	The dynamic current balance coefficient of the converter bridge arm should not be less than 0.72.
FSC test of DC Reactor	Before and after the FSC test, the measured inductance values shall be consistent within measurement tolerance limits and the oscillograms from the lightning impulse test at 100% of specified voltage shall show no change, agreeing within the limits of the high voltage dielectric test systems.
Temperature rise test of DC Reactor	The average temperature rise of winding shall be not more than 70 K. The temperature rise of hot-spot winding shall be not more than 78 K.
FSC test of DC Line Disconnector	It shall be demonstrated immediately after FSC test that the equipment can close and open properly. The contacts shall be able to carry the rated current without overheated
Temperature rise test of DC Line Disconnector	The temperature rise of parts which need not be touched shall be less than 40 K. The temperature rise of terminals shall be less than 65 K. During test, the ambient air temperature shall be in the range of +10 °C to +40 °C and the fluctuation shall be less than 10 K.
Prospective fault current of External Bypass with intervention of electronic protection	During and after the test, there shall be no failure of the thyristor.
FSC test of External Bypass with intervention of electronic protection	During and after the test, there is no electrical and mechanical damage of the external bypass.
FSC test of External Bypass without intervention of electronic protection	During and after the test, there shall be no deformed parts and/or loosening of fasteners in the mechanical structure of the external bypass assembly.
EMC test of Local Controller	The local controller shall withstand the EMC test without detriment.
EMC test in DC magnetic field for Local Controller	The local controller shall withstand the EMC test in DC magnetic field without detriment.
Environmental conditions test of Local Controller	The local controller shall withstand the environmental conditions test without detriment. After test, the local controller shall still be fully functional.

5.1. Prototype development

To verify the design of converter topology and local controller, a converter module with capacity at 33 MVA is manufactured. It can provide the rated DC current at ± 15 kA and the rated voltage at 1.1 kV. The prototypes of converter module and local controller as shown in Fig. 6 are installed and implemented in EAST, another tokamak device in China. The performance of the prototype is verified by simulation results and test results as shown in Fig. 7.

5.2. Full-size prototype development

A full-size prototype of each component (shown in Fig. 8) has been manufactured and tested under short-circuited, full rated current and dynamic conditions. Then the whole system has been integrated, installed, and tested. In total, 81 type tests and 66 routine tests have been performed to verify the design.

5.3. Type and factory tests on each component

The type tests and factory acceptance tests have been accomplished on each component as specified in the test procedure.

The converter transformer, converter module, DC reactor, AC busbar and external bypass have experienced the short-circuited tests and temperature rise tests with rated input voltage and output current. The test results are shown in Fig. 9. It can be concluded that the converter module, DC disconnector and external bypass can withstand short-circuit current at 350 kA and the DC reactor can withstand short-circuit current at 175 kA without mechanical damage. Fig. 9 (e) and (f) shows that the DC reactor and converter module operate continuously for nearly four hours under the rated 27.5 kA current, and the temperature rise of each measure points are within the required limit. Fig. 9

Table 5
The list of Integration tests items and acceptance criterions.

Test Items	Acceptance Criterions
Visual inspection	The main circuit is connected correctly and there are no cracks or deformation on the surface of all components.
I&C test	Mini CODAC HMI function, communication performance, control logic and control signal and fault simulating test must meets the design requirement.
Checking the Properties of the Control Equipment under No-load	All lights of trigger and trigger pulse operate normally. The relationship between the trigger signal and synchronous signal should meet requirement. The output signal of pulse distributor shall meet requirement.
No-load test	During the test, there is no evidence of seepage and leakage and the water pressures meet the requirements of ITER. The output voltage waveform of each Converter Bridge is 6-pulse.
6-Pulse Gratze Bridge Full Current Test	The converter bridges (CU1, CU2, CU3 and CU4) work at 27.5 kA ± 5% without commutation failure or any other fault alarm.
Voltage Response Test	The response time in the full scale of symmetrical voltage (± 1.05 kV) shall be not more than 40 ms.
Circulating Current Operation Mode Test	During the steady-state circulating current test, the circulating current should be equal to 8 kA ± 10%, and the ripple of circulating current should be less than the circulating current.In the process of abrupt change of voltage or load current reverse, the circulating current cannot be equal to 0.
Parallel Operation Mode Test	The output voltage waveform of Converter Unit is 12-pulse. The unbalanced current of parallel operation shall be not more than 10%. During the dynamic process of the output voltage step change, there is no commutation failure or tripping protection.
4-Quadrant Operation Capability Test	The converter unit shall operate in 4-Quadrant mode from 0 to full rated current (± 55 kA). The performance circulating current operation, single bridge operation and parallel operation all meet test requirements respectively.
Rated Current Test	During the test, there is no commutation failure, fault alarm or local over-heating of some components. During parallel operation stage, the current difference of two parallel bridges does not exceed 10%.
Protective Test with Bypass Triggering	The external bypass shall be triggered normally and withstand the load current (55 kA or −55 kA) for 100 ms.

Fig. 6. The prototypes of converter module and local controller.

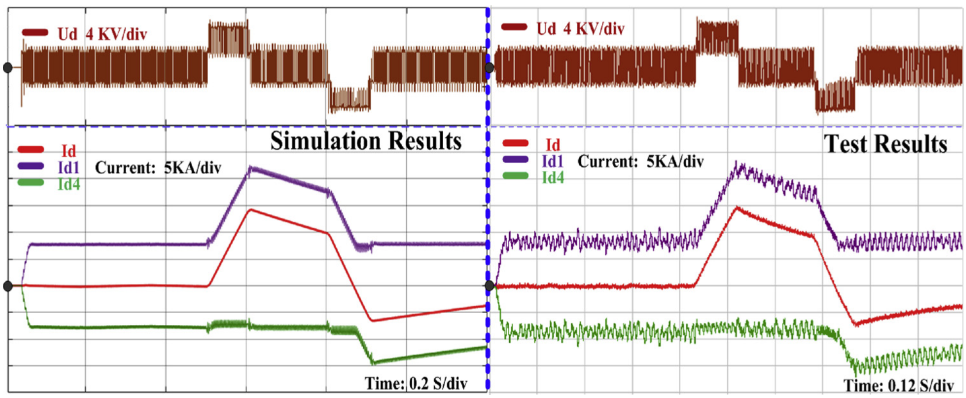


Fig. 7. The comparison of simulation results and test results.

Fig. 8. Manufacturing of each component and the system integration.

(g) shows the case for the DC disconnector operates continuously for nearly five hours under the rated current 55 kA to achieve the steady state, and the temperature rise of each points are within the required limit.

The EMI and EMC tests have been performed on the local controllers. The test site is shown in Fig. 10.

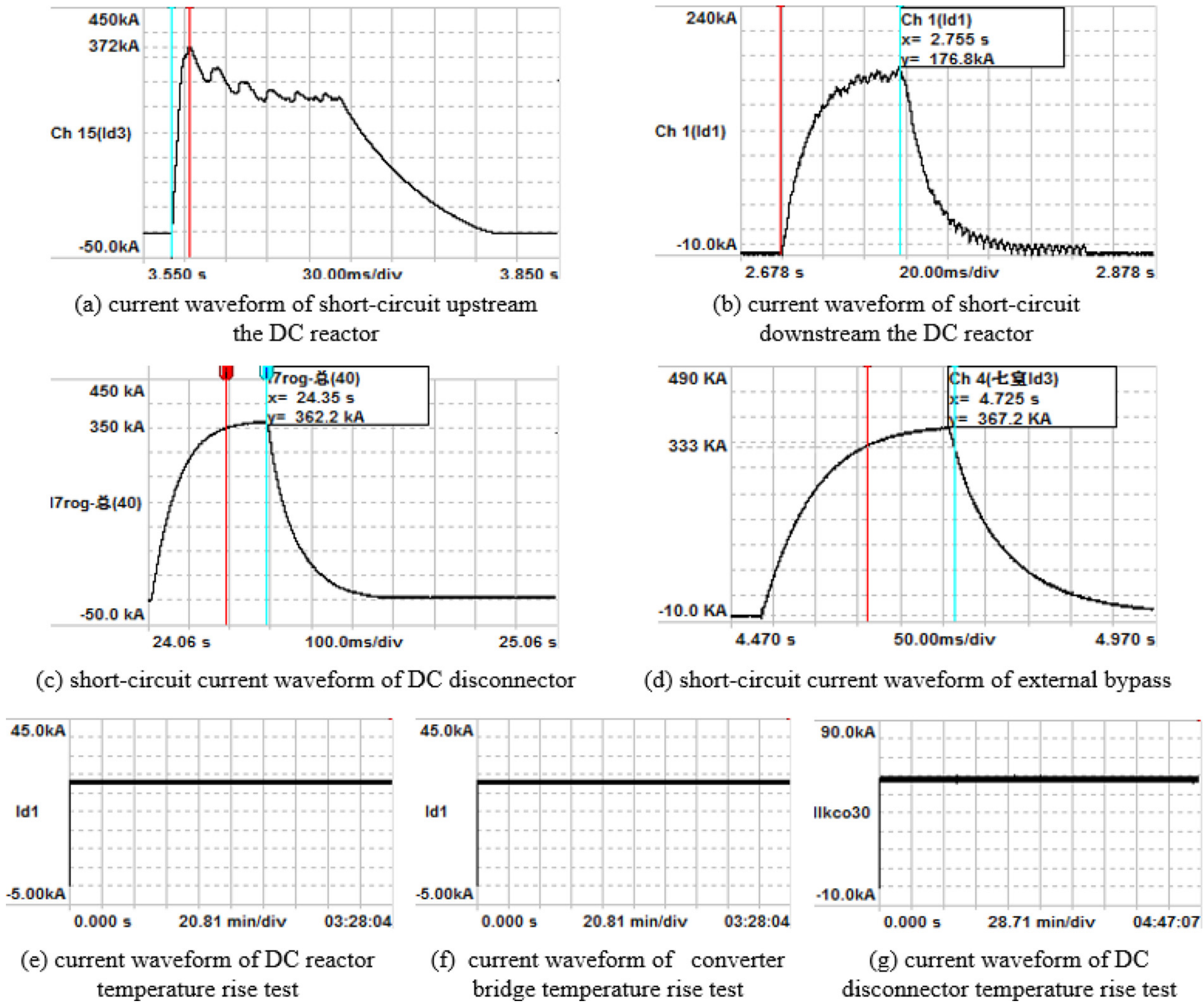
The factory acceptance tests are performed according to the relative IEC standards. As to the controllers, 61 tests have been performed, which include I&C cubicles factory tests, mechanical vibration and LCC function and logic tests.

The above test results confirm that the dynamic stability and thermal stability of each component meet the requirements of ITER system.

5.4. Integration tests on converter unit

The integration tests on ITER PF converter unit are performed to verify whether the steady state and dynamic performance of the prototype meets the system requirements or not.

The integration tests include no-load test, 6-pulse Converter Bridge



(a) current waveform of short-circuit upstream the DC reactor

(b) current waveform of short-circuit downstream the DC reactor

(c) short-circuit current waveform of DC disconnector

(d) short-circuit current waveform of external bypass

(e) current waveform of DC reactor temperature rise test

(f) current waveform of converter bridge temperature rise test

(g) current waveform of DC disconnector temperature rise test

Fig. 9. Short-circuit test and temperature rise test waveforms of each component.

Fig. 10. The EMI and EMC tests site of local controllers.

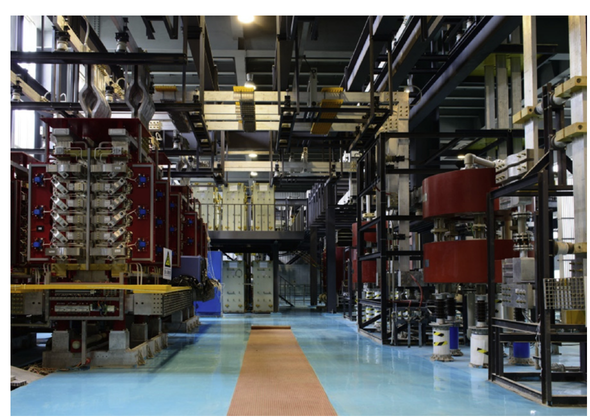


Fig. 11. The integration test site.

full current test, voltage response test, circulating current mode test, parallel operation mode test, four-quadrant operation test and protective test with bypass triggering. They are accomplished at the integrated test platform in ASIPP (as shown in Fig. 11) and the test results are shown in Fig. 12. All the test results are qualified and confirms the integration performances of the converter unit.

6. Manufacture, FAT and delivery

ITER AC/DC Converter is manufactured according to the quality plan (QP), and the manufacturing and inspection plan (MIP).The MIP clearly indicates the quality control requirement of each stakeholder.

There are seven types of control points in the MIP: Notification Point, Authorization to Proceed Point, Hold Point, Witness, Surveillance, Surveillance and Review Point. First, the manufacturer lists the technology process, and identifies the quality control points. Each stakeholder should also list its control points on the MIP. When it comes to that point such as the incoming inspect of electronic components, the corresponding stakeholder will be informed and perform the

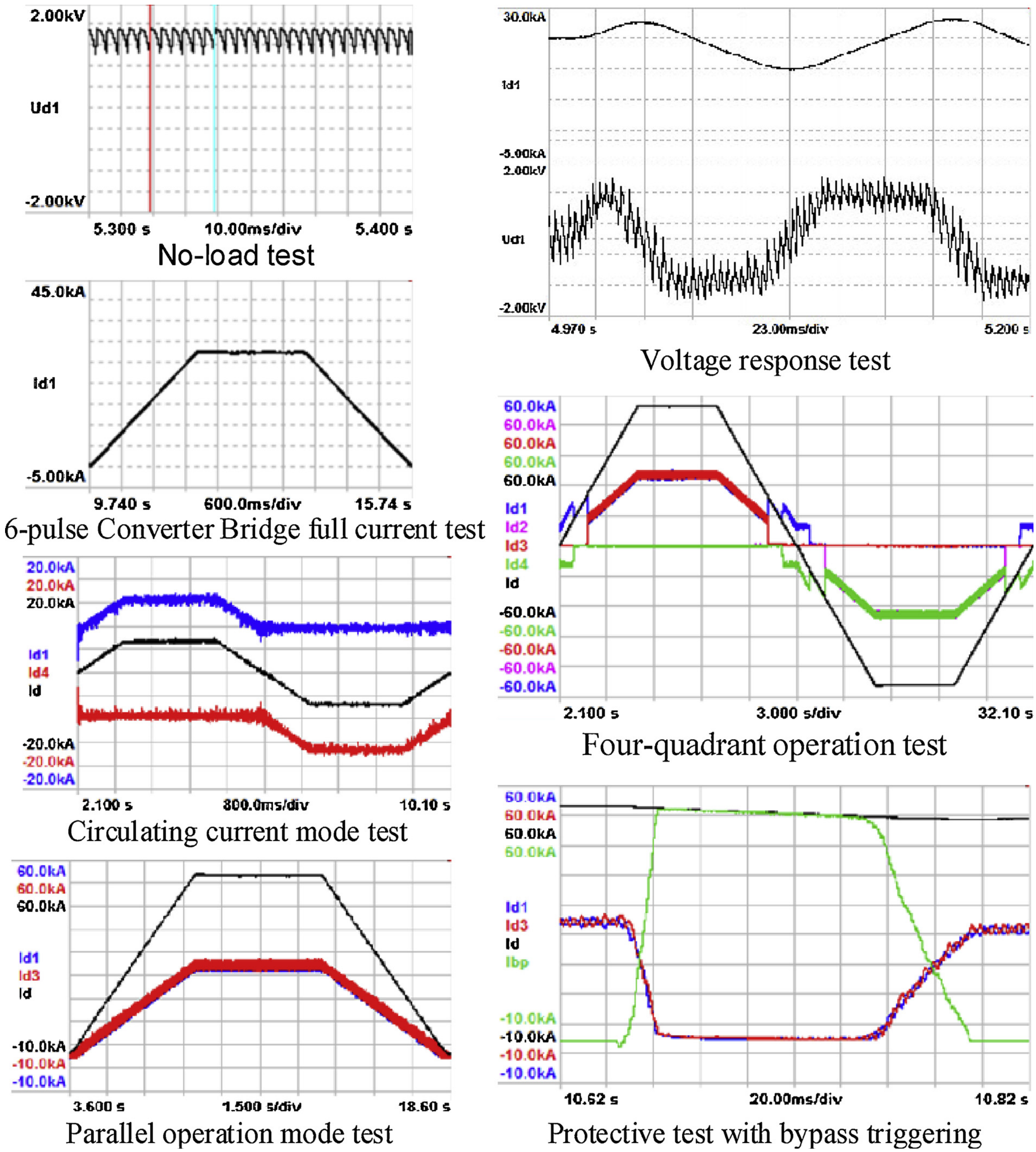


Fig. 12. The integration test results.

activity as listed.

FAT and integration test are the final processes before delivery. In order to ensure the testing process, a test control flow is developed to clarify the responsibility, inspection items and cautions. Moreover, a quality supervisor is set to supervise the whole test process, and complete the quality supervision table.

So far, 11 converter units have been manufactured and tested. Five have been delivered to ITER site.

7. Conclusion

This paper presents the design, manufacture, test and quality control of ITER PF converter system. To the special requirements and operation conditions of ITER, the analysis on the ITER PF converter system and each component are performed during design phase. Simulation, component development and test are adopted as design validation to guarantee the correctness of design. To control the quality of manufacture of 14 PF converter systems, MIP with different kinds of control points is developed and implemented by each involved part, and the FAT verifies the quality of manufacture. The quality of ITER PF converter system is well controlled and assured. Up to now, the manufacturing and factory acceptance test of 11sets PF converter units have been completed, and the test results have been approved by International Organization (IO), 5 sets PF converter units have been delivered to IO.

Acknowledgements

The authors gratefully acknowledge the colleagues working for power supply from Institute of Plasma Physics Chinese Academy of Science, China International Nuclear Fusion Energy Program Execution Center, and ITER Organization. The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.

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