CONFERENCE PRE-PRINT

IMPROVEMENTS OF MAGNET POWER SUPPLY SYSTEM AND ACHIEVEMENTS IN COIL ENERGIZATION TESTS FOR FIRST PLASMA OF JT-60SA

K. YAMAUCHI
National Institutes for Quantum Science and Technology
Naka, Japan
Email: yamauchi.kunihito@qst.go.jp

S. HATAKEYAMA, Y. OHMORI, J. OKANO, K. SHIMADA
National Institutes for Quantum Science and Technology
Naka, Japan

G. FRELLO, L. NOVELLO
Fusion for Energy
Garching, Germany

Abstract

Three main improvements of superconducting magnet power supply (PS) system were implemented following the EF1 coil incident caused by insulation failure during JT-60SA integrated commissioning in 2021. The main goals of the improvements were to reduce the voltage to ground at the coil terminal and to suppress overvoltage across the coil from the viewpoint of coil insulation. The performance after each improvement was verified by power test with a dummy load. The results confirmed that these improvements are effective for the safe operation since the voltage to ground at the coil terminal was reduced by almost half during normal operating condition, and the maximum voltage across the coil was limited less than 2.7 kV in compliance with the validated coil insulation values. After the improvements of magnet PS system, the coil energization test with superconductive coils in JT-60SA integrated commissioning was restarted in August 2023. All the PS components, such as Base PS, Switching Network Unit, Booster PS and Quench Protection Circuit, were confirmed to operate as expected within the current operational range defined for Operation-1 phase (25.7 kA for toroidal field coils and ±5 kA for poloidal field coils). After the successful coil energization test, the first plasma of JT-60SA was successfully achieved.

1. INTRODUCTION

JT-60SA, collaboratively constructed by Europe and Japan, is the largest superconducting tokamak machine in the world currently in operation [1,2]. JT-60SA magnet system is made by superconducting coils, 18 Toroidal Field Coils (TFCs) forming a single series circuit, and 10 Poloidal Field Coils (PFCs) connected each one to an individual circuit. To energize these superconducting coils, the coil Power Supply (PS) system in JT-60SA consists of several components, such as DC PSs (low-voltage Base PSs [3,4] and high-voltage Booster PSs [5]), Switching Network Units (SNUs) [6] for selective high voltage generation, Quench Protection Circuits (QPCs) [7] for fast discharge of the stored coil energy, a motor-generator for supplying high pulsed electric power without affecting the external power grid, and a supervising control system including measurement data acquisition.

The integrated commissioning of JT-60SA was started initially in 2021. However, it was suspended due to short circuit incident (double ground fault) occurred at the joints of EF1 superconducting coil [1]. Although the root cause of this incident was the weak insulation of superconducting coil, magnet PS system was improved before the restart of integrated commissioning in 2023 in order to enhance reliability, reduce risk and prevent reoccurrence. In particular, three main improvements of superconducting magnet PS system were implemented. The main goals of these improvements were to reduce the voltage to ground at the coil terminal and to suppress overvoltage across the coil from the viewpoint of coil insulation. The performance after each improvement was verified by power test with a reused dummy load (inductance: 7.64 mH, resistance: 6.995 mΩ). The results confirmed that these improvements are effective for the safe operation: the voltage to ground at the coil terminal was reduced by almost half during normal operating condition, and the maximum voltage across the coil was limited to less than 2.7 kV, in compliance with the validated coil insulation values.

After the improvements of magnet PS system, the coil energization test with superconductive coils in JT-60SA integrated commissioning was restarted in August 2023. It was confirmed that all the PS components, such as Base PS, SNU, Booster PS and QPC, could be operated as expected with values up to the rated current of 25.7 kA for TFCs and ±5 kA for PFCs. This current range, defined in order not to exceed the maximum validated coil insulation performance even in case of QPC and SNU/Booster PS operation, was set as the operation range of Operation-1 phase (Tab. 1). With the successful coil energization test, the first plasma of JT-60SA could be achieved successfully. In this paper, three improvements of superconducting magnet PS system are described, showing the results of preliminary power tests performed using a dummy load, reporting the results of superconducting coil energization tests during JT-60SA integrated commissioning and highlighting the main achievements.

TABLE 1. REQUIRED AND ACHIEVED OPERATION RANGE OF OPERATION-1

	Coil	Design Rating	Operation-1 (required and achieved)
PFC	CS1–4, EF3/4	±20 kA, +1/–5 kV	±5 kA, +1/–2 kV
	EF1/2/5/6	+10/–20 kA, ±5 kV	±5 kA, ±2 kV
TFC	TF1–18	25.7 kA, +80 V/–1.93 kV	25.7 kA, +80 V/–1.93 kV

2. IMPROVEMENTS OF SUPERCONDUCTING MAGNET PS

The followings are the details of three improvements in superconducting magnet PS system after EF1 coil incident:

2.1. Movement of the Grounding Position in PFC Circuit

In the magnet PS system for PFC, the PS components, i.e. Base PS, SNU/Booster PS and QPC, are connected in series. In the original configuration, the grounding of the PFC circuit was made at the mid-point of the output terminals of Base PS, as shown in Fig. 1(a). The result was that almost the full output voltage generated by SNU/Booster PS or QPC was applied at only one side of coil terminal to ground during the activation of the component itself (Fig. 2(a)). As a consequence, a significant stress on the coil insulation is generated, that could be a contributing factor leading to insulation failure. It has been therefore decided to move the grounding from the original positions to the mid-point of the coils for all the PFC circuits (Fig. 1(b)). Following this modification, the voltage to ground is equalized across both terminals of the coil in all PS normal operating conditions, resulting in only half of the output voltage of PS system (Fig. 2(b)).

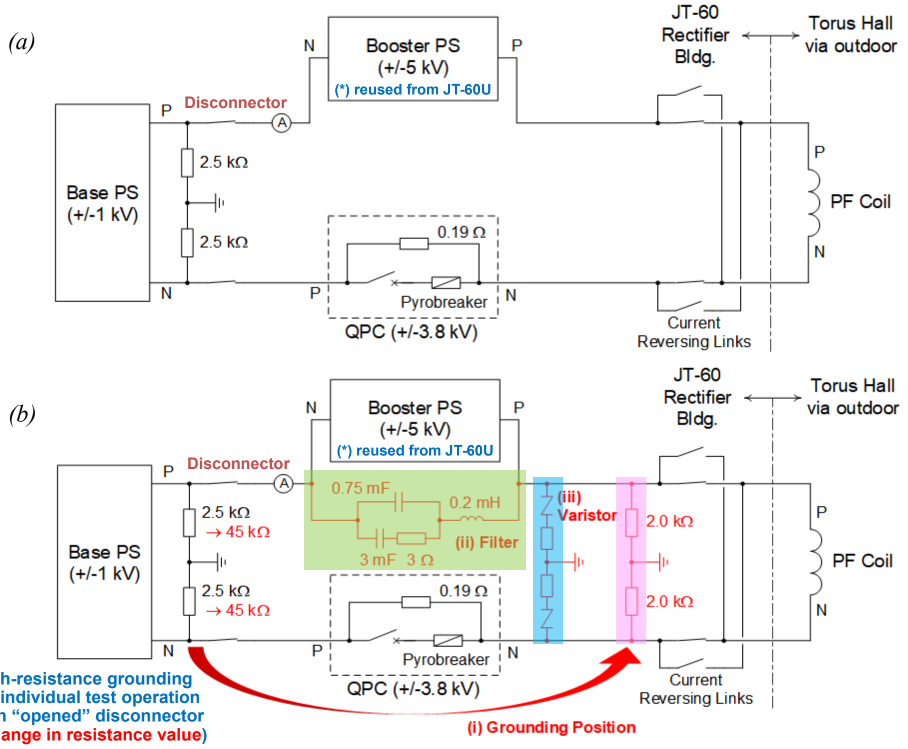


FIG. 1. Improvements of Magnet Power Supply System
(a) Before modifications, (b) After modifications.

2.2. Installation of Voltage Ripple Reduction Filter for Booster PS

Booster PS is used in EF1/2/5/6 coil (outer PFC) circuits for plasma initiation and shape control. The Booster PS is a reused equipment from the previous JT-60U and has a large voltage ripple of 4 kVp-p (±2 kV) superimposing on the maximum nominal operating voltage of ±5 kV (Fig. 2(a)). To reduce this voltage ripple, a 2nd order filter was installed in parallel to the Booster PS, as shown Fig. 1(b). The filter consists of two capacitors, a resistor and a current limiting reactor. The cut-off frequency of the filter was set at 90 Hz, a compromise between the desire to reduce the voltage ripple at the lowest ripple frequency of 325 Hz and the need to keep a sufficient dynamic to control the plasma shape. Thanks to the installed filter, the voltage ripple across the coil has been reduced to 400 Vp-p (±200 V), i.e. 1/10 of the original value (Fig. 2(b)). Here, it should be noted that, due to its connection position, this filter can not reduce the voltage ripple generated by the Base PS, that remains the highest contribution after the filter installation, as visible in Figure 2(b).

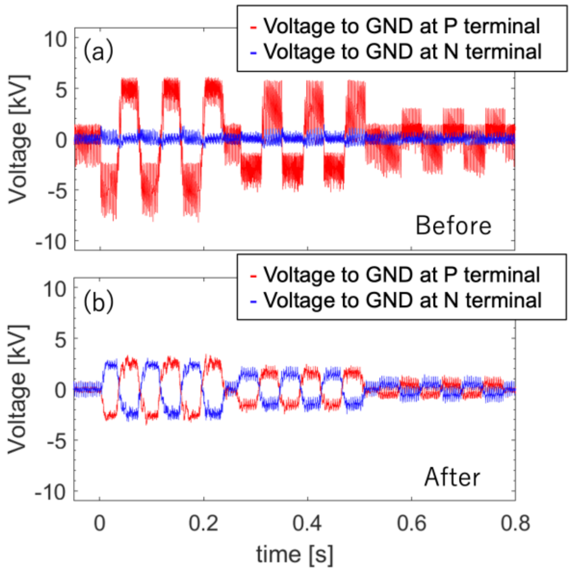


FIG. 2. Comparison between the waveforms of voltage to ground before and after improvements (in normal operation) (a) Before modifications, (b) After modifications (Booster PS output at ±5 kV, ±3 kV, ±1 kV and with dummy load coil).

2.3. Installation of Varistors at PFC Circuit

Following the EF1 coil incident, some power tests of intentional fault to ground have been performed with dummy load, connecting to ground one terminal of the circuit by means of a switch. During the tests it has been observed that a fast oscillation is generated at the other terminal of the load, with a peak voltage reaching a value of up to 1.7 times the total voltage applied by the PS system at the time of the fault. This fast oscillation is due to transitional resonance caused by stray capacitance and inductance of PFC circuit during ground fault conditions. To limit the overvoltage, varistors having voltage clamping function were installed at each side of coil terminal to ground, as shown in Fig. 1(b). The selection of varistor characteristics was made considering the worst result of the withstand voltage test under Paschen discharge conditions performed on the poloidal magnets before Operation-1 phase, proving that a discharge to ground could be generated at 2.8 kV. Following the installation of the selected varistors, it was confirmed that, with the nominal operating condition of 2 kV defined for Operation-1 phase, the overvoltage in the case of ground fault could be safely reduced from 3.4 kV to 2.7 kV.

3. IMPROVED JT-60SA MAGNET PS CIRCUITS FOR OPERATION-1

3.1. TFC Circuit Configuration

Figure 3 shows the configuration of TFC circuit. TFCs are energized at a constant current (usually at the rated value of 25.7 kA) every day before the start of plasma experiments, and then demagnetized after the end of the daily experiment period. Having no special dynamic requirements during operation, the series connection of the 18 TFCs is supplied by a single low-voltage DC PS [3], with a no-load output voltage of ±80 V, able to ramp-up/down the nominal current of 25.7 kA in less than 25 minutes. The fast discharge in case of coil quench occurrence is assured by the operation of dedicated PS components called QPC [7], that are installed in series to the PS. To reduce the voltage to ground of TFCs in the case of QPC operation to <1 kV (increasing to <2 kV in the worst case of QPC operation and ground fault), TFCs are divided into three blocks (6 TFCs in each), and three QPCs with the ground connection in the middle point of the discharge resistor are interleaved among them. Here it should be noted that no improvement was deemed necessary for TFC PS system after the EF1 coil incident.

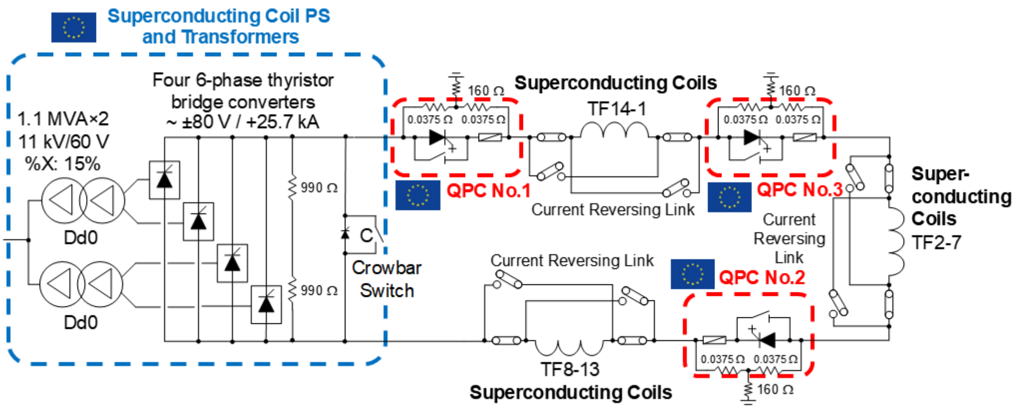


FIG. 3. Configuration of TFC circuit.

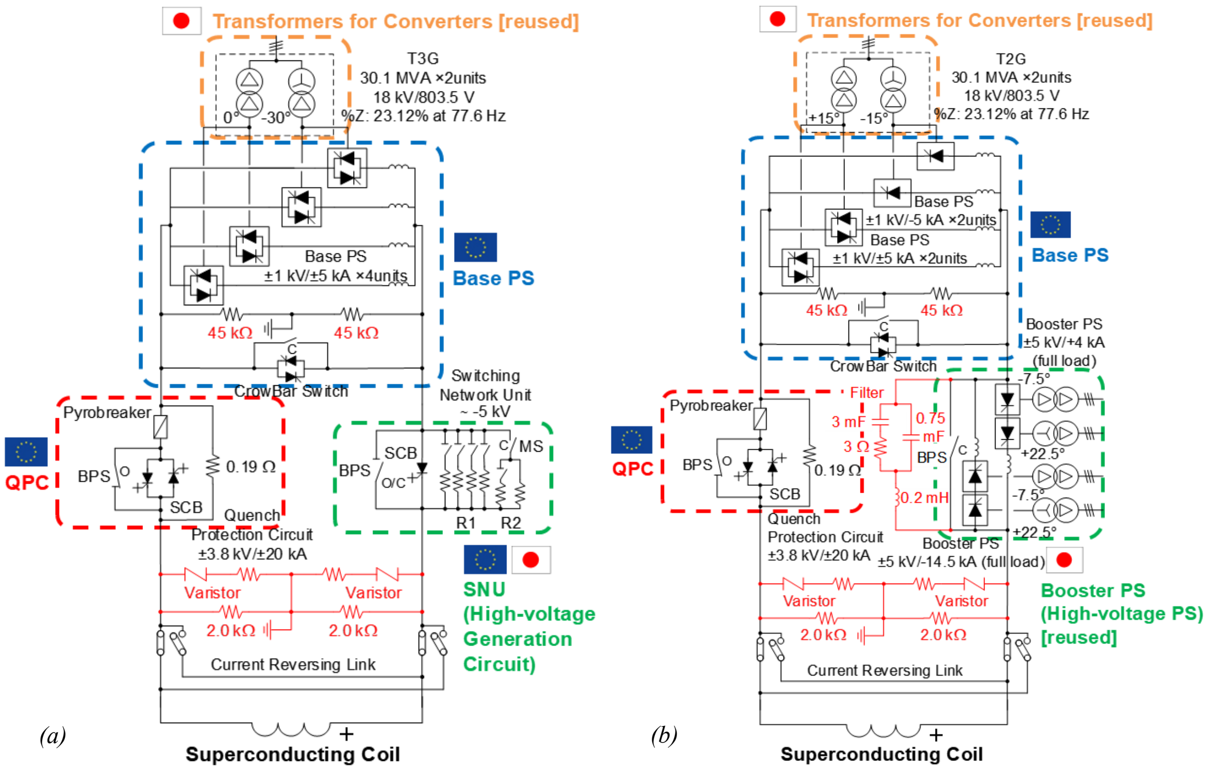


FIG. 4. Typical configuration of PFC circuits
(a) Inner PFC circuit with SNU (CS1), (b) Outer PFC circuit with Booster PS (EF1).

3.2. Inner PFC Circuit Configuration with SNU (CS1–4, EF3/4)

In JT-60SA, there are 10 superconducting PFCs, i.e. four Central Solenoids (CS1–4) and six Equilibrium Field (EF1–6) coils, having the common rating of 20 kA. The circuit configuration of them is classified into two groups. One is with Switching Network Unit (SNU) for the inner PFCs (CS1–4 and EF3/4), and another is with Booster PS for the outer PFCs (EF1/2/5/6). Figure 4(a) shows the circuit configuration of CS1 as a typical inner PFC circuit with SNU. For the whole period of normal operation, all PFCs are energized by low-voltage thyristor converters (±~1 kV, ±20 kA) with long-time rating, which is called Base PS. To protect the coil in case of quench, QPC is utilized like in TFCs. SNU is used to produce a negative high voltage (–5 kV at maximum) for stable breakdown and fast plasma current ramp-up. For flexible voltage generation by SNU, the value of SNU resistance can be changed with some pre-selectable discharge resistors in parallel.

3.3. Outer PFC Circuit Configuration with Booster PS (EF1/2/5/6)

Differently from inner PFCs equipped with SNU, for the outer PFC circuits it is necessary to use Booster PS for obtaining the high voltage required for stable plasma breakdown and fast plasma current ramp-up. In fact, a low pre-magnetization current is required in the outer PFC circuits, and thus the current polarity reverses immediately, preventing the use of SNUs. The circuit configuration of EF1 coil is shown in Fig. 4(b) as a typical outer PFC circuit with Booster PS. Booster PS consists of high-voltage thyristor converters (±5 kV, +4/–14.5 kA) with short-time rating, which are reused from JT-60U. A new filter to reduce the voltage ripple was added in parallel to the reused Booster PS, as described in previous section.

4. COIL ENERGIZATION TESTS

Thanks to the risk mitigation allowed by the described improvements of magnet PS system, the coil energization test with superconductive coils in JT-60SA integrated commissioning was safely restarted. Initially, the individual coil energization tests were performed on the superconductive magnets to confirm the performance of each coil PS component. After that, the integrated coil energization tests were performed step by step progressively increasing the number of superconductive coils in simultaneous operation.

4.1. Individual coil energization tests

The TFC energization tests were performed gradually increasing the current in stages up to the nominal rating at 25.7 kA. During long energization of superconducting TFCs, QPC activation test, temperature rise measurement in transformer windings and control parameter tuning were performed. Figure 5 indicates the results of TFC energization test with successful long operation (>6 h) at the full current of 25.7 kA. In this figure, the temperatures of each winding (U/V/W phase) in two transformers are also shown. Because the fault level of transformer winding was at 145 °C (Light Fault), no problem from the viewpoint of temperature was identified.

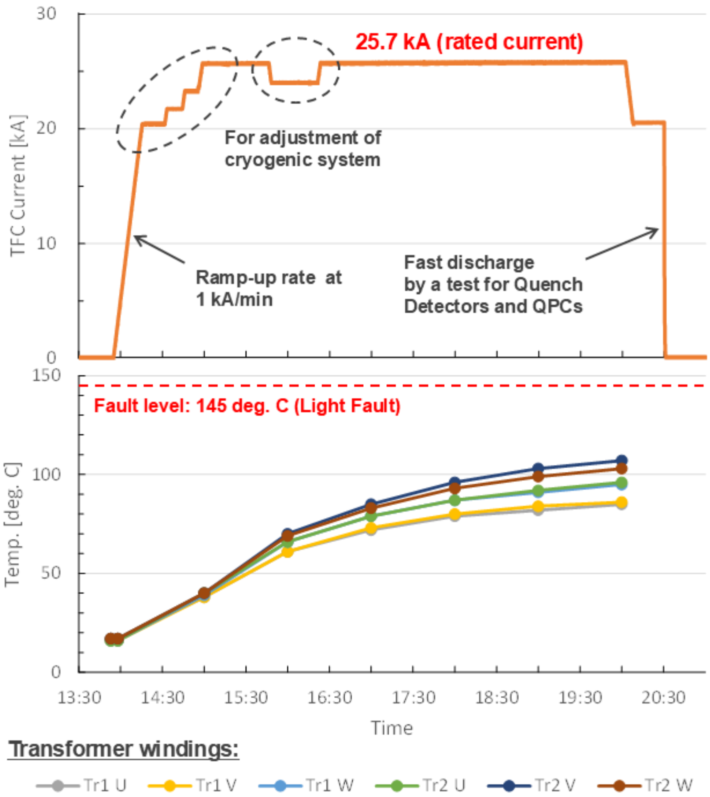


FIG. 5. Individual TFC energization test.

In addition, Pyrobreaker (explosive circuit breaker acting as backup device in QPC) operation test was successfully conducted with real TFCs, as shown in Fig. 6. In this test, the Pyrobreaker (PB) in one of three QPCs was operated under a simulated fault in mechanical Bypass Switch (BPS), which was disabled by removing compressed air to actuate BPS and thus forcing it in closed status. The test current was set limited to 15 kA to assure that the total TFC energy could be safely dissipated in the other two QPCs even in case of failure in the tested Pyrobreaker. In Fig. 6, (a) shows the current and voltage waveforms obtained in TFC QPC No.1 where the Pyrobreaker was operated. In this figure, t=0 ms represents the instant of QPC activation command. During normal QPC operation, the current could be commutated typically within 300 ms from the opened BPS to the turned-on Static Circuit Breaker (SCB) consisting of eight parallel semiconductor devices, called Integrated Gate-Commutated Thyristor (IGCT), and then SCB could interrupt the current at t=350 ms after the completion of BPS opening, resulting in the commutation of the current to Dump Resistor (DR) discharging TFCs. However, in the case of faulty BPS, the current could not be commutated to SCB nor to DR. In this case, at t=350 ms, the control system in QPC detected the failed operation of BPS (and/or SCB) and then immediately sent the activation command to the firing system for Pyrobreaker. Pyrobreaker can complete its operation within 3 ms in total, including fault detection, explosive charges detonators firing, and actual mechanical movements produced by the explosion. Thus, the current could be interrupted by Pyrobreaker and commutated to DR at around t=353 ms. Also from this figure, it was confirmed that no critical overvoltage was generated under this condition, proving the effectiveness of the layout optimization described in [8]. Figure 6(b) shows the current waveforms of TFC measured by a current transducer (LKAT2) and each rectifier in TFC PS. The TFC current was decreased by QPCs with the expected time constant of 13.8 s based on the total inductance (3.1 H) of 18 TFCs and the total resistance (3×0.075 Ω) of three series QPC DRs. In the case of QPC operation, the rectifiers in TFC PS stopped and the coil current was immediately bypassed by Crowbar circuit shown in Fig. 3.

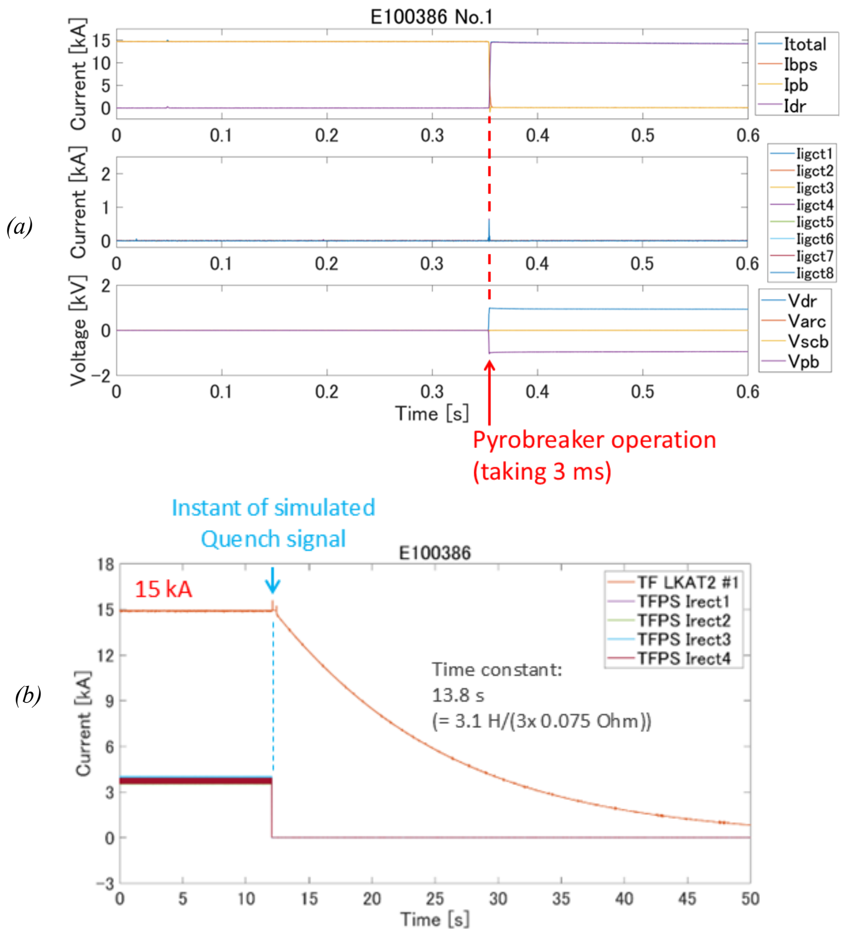


FIG. 6. Individual Pyrobreaker test with real TFCs
(a) Current and voltage waveforms of Pyrobreaker operation in TFC QPC No.1 with simulated BPS fault,
(b) Current waveforms of TFC and each rectifier in TFC PS.

4.2. Integrated coil energization tests

After the successful completion of the individual coil energization tests, the integrated coil energization test was performed step by step increasing the number of superconductive coil circuits in simultaneous operation. Furthermore, the integrated coil energization tests were performed in two phases changing the current and voltage limitations for PFCs, taking into consideration their validated electrical insulating performance. The first phase was up to ±3 kA and ±1 kV for first plasma, and the second one was up to ±5 kA and ±2 kV for higher current plasma.

Figure 7 shows the results of all PFC/TFC integrated energization test under ±3 kA and ±1 kV without SNU/Booster PS for PFCs. In this test, TFC current was at the constant full current of 25.7 kA. Based on the current scenario assumed to obtain the first plasma, all PFCs/TFCs could be successfully energized simultaneously. The magnet PS system was therefore declared ready for first plasma. In Fig. 8, the results of all PFC integrated energization test up to ±5 kA and ±2 kV with SNU/Booster PS are shown. It should be noted that during this test TFCs were not energized to avoid unexpected fast discharge triggered by a false quench detection due to noise induced by high-voltage operation. This test proved that all PFCs, supplied by several Base PSs and Booster PSs powered by the same motor-generator, could be successfully energized simultaneously without any significant mutual interference. This successful outcome led to the magnet PS readiness for higher current plasma.

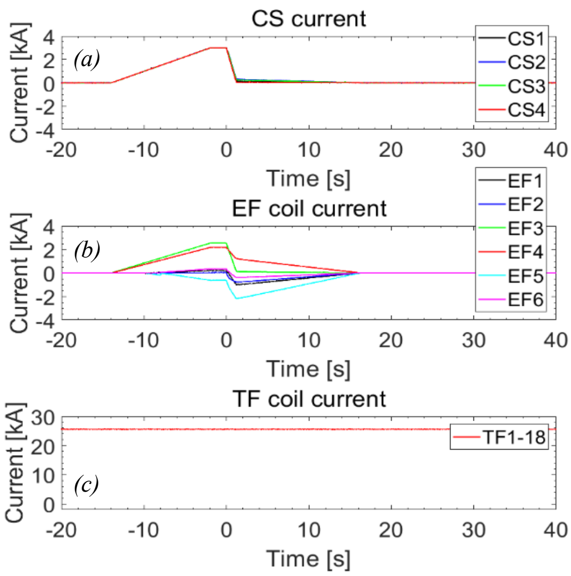


FIG. 7. All PFC/TFC integrated energization test without SNU/Booster PS
(a) Current waveforms of CS1–4, (b) Current waveforms of EF1–6, (c) Current waveform of TFC at the constant full current of 25.7 kA.

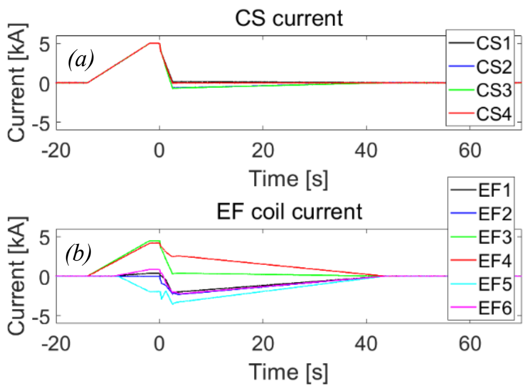
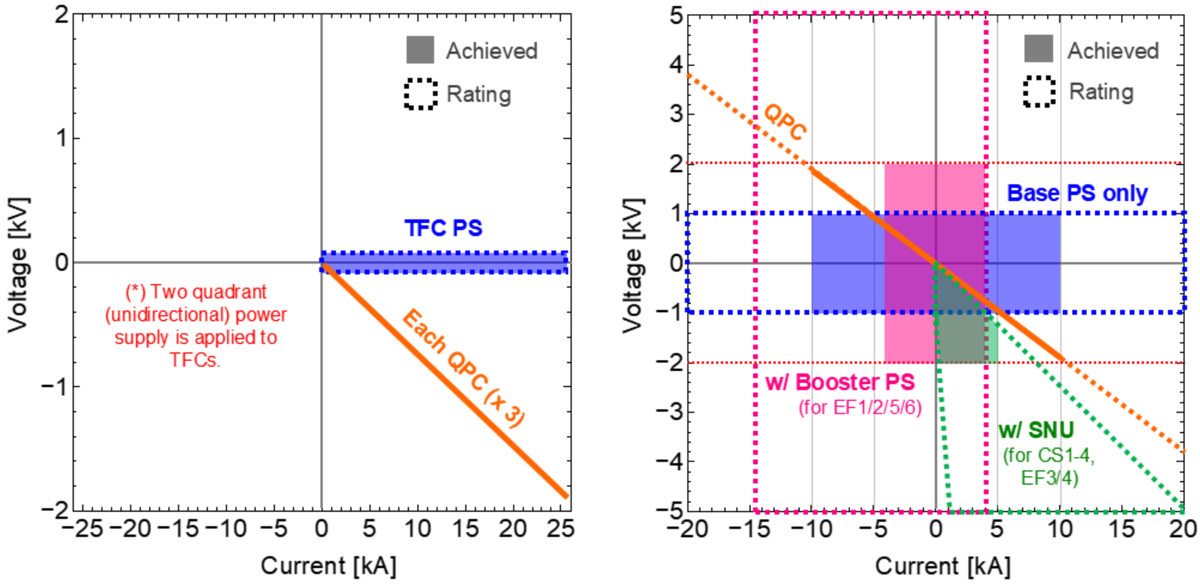


FIG. 8. All PFC integrated energization test with SNU/Booster PS
(a) Current waveforms of CS1–4, (b) Current waveforms of EF1–6.

5. SUMMARY

Figure 9(a) indicates the achieved operation range of TFC PS components. In Operation-1 phase, the TFC PS and TFC QPCs were fully operated to their rating without any problem. Successful Pyrobreaker operation was also confirmed with real TFCs. The achieved operation range of PFC PS components is shown in Fig. 9(b). In Operation-1, the operations of all PFC PSs were limited up to ±2 kV due to the insulation performance of the coils. Within the limitations all PFC energization tests were carefully performed step by step. All PFCs were energized up to ±5 kA simultaneously. Only in individual PFC energization test performed at the end of Operation-1 as preparatory tests towards Operation-2, Base PSs and QPCs (without SNUs/Booster PSs) were tested up to ±10 kA with superconducting PFCs (except CS3 and EF2 due to their limited electrical insulating performance). In Fig. 9(b), these results are also included.



(a) *(b)*

FIG. 9. Achieved operation range in JT-60SA integrated commissioning/Operation-1
(a) TFC PS components, (b) PFC PS components.

From the results of coil energization tests in JT-60SA integrated commissioning, the expected operation of all PS components including Pyrobreaker and the consequent expected coil energization were confirmed within the limited range in Operation-1, set at the rated current of 25.7 kA for TFCs and ±5 kA for PFCs considering the validated electrical insulating performance of the coils. Since the Pyrobreaker solution as back-up protection for fast discharge is applied not only to JT-60SA but also to the superconducting magnets of ITER, this achievement and the gained operation experience are important contributions to ITER by JT-60SA. Following the successful completion of the integrated commissioning, the plasma experiment phase started. In this phase, the magnet PS system successfully contributed to achieve the first tokamak plasma (plasma current I_P~130 kA) on October 23, 2023, and later higher current plasma (I_P~1.2 MA).

ACKNOWLEDGEMENTS

The authors are grateful to all the EU and JA magnet PS members including in the past and from the voluntary contributors. JT-60SA was jointly constructed and is jointly funded and exploited under the Broader Approach Agreement between Japan and EURATOM.

REFERENCES

[1] SHIRAI, H. et al., Recent progress of JT-60SA project toward plasma operation, Nucl. Fusion **64** (2024) 112008.
[2] KAMADA, U. et al., Completion of JT-60SA construction and contribution to ITER, Nucl. Fusion **62** (2022) 042002.
[3] NOVELLO, L. et al., Overview of the new magnet power supply systems of JT-60SA procured by EU, Fusion Eng. Des. **98–99** (2015) 1122–1126.
[4] ZITO, P. et al., Type tests of JT-60SA central solenoid/equilibrium field superconducting magnet power supplies, IEEE T. Plasma Sci., **46** (2018) 1489–1496.
[5] SHIMADA, K. et al., Minimization of reactive power fluctuation in JT-60SA magnet power supply, Plasma Sci. Technol. **15** (2013) 184–187.
[6] LAMPASI, A. et al., Installation, commissioning and tests of four fast switching units of up to 20 kA for the JT-60SA Nuclear Fusion Experiment, Energies **11** (2018) 996.
[7] GAIO, E. et al., The new technological solution for the JT-60SA quench protection circuits, Nucl. Fusion **58** (2018) 075001.
[8] MAISTRELLO, A. et al., Analyses of the impact of connections' layout on the coil transient voltage at the quench protection circuit intervention in JT-60SA, Fusion Eng. Des. **98–99** (2015) 1109–1112.