CONSORZIO RFX CONTRIBUTION TO THE JT-60SA PROJECT IN THE FRAME OF THE BROADER APPROACH AGREEMENT

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Abstract

The contribution of Consorzio RFX to the JT-60SA project in the frame of the Broader Approach Agreement was related to the development, realization and test of two key components of the JT-60SA machine: the Quench Protection Circuits (QPC) for the superconducting coils and the Power Supply System for RWM control (RWM-PS). Since the very beginning of the project in 2007, the contribution was indeed voluntarily widen to preliminary joint studies aimed at a deep understanding of the requirements to better meet the target and performance expectations. The next R&D phase was addressed at identifying suitable design solutions for the both the systems, able to take benefit from the state-of-the-art technology to improve the final result. The paper gives a brief overview of the main steps of the development and realization of both the systems. The preliminary studies, the main phases of their procurement and relevant results are presented and the innovative aspects of the systems highlighted: JT-60SA QPC represents the first application of hybrid mechanical-static technology for protection of superconducting magnets in fusion experiments and RWM-PS is the first PS system in fusion experiments adopting Silicon-SiliconCarbide power switches. The future work and the expected outcomes from the operation of these systems, useful for ITER and DEMO, are also discussed.

1. INTRODUCTION

The JT-60SA satellite tokamak is now under advanced assembly phase in Naka (Japan); it is being developed in the framework of the Broader Approach (BA) agreement, using infrastructure and some components of the existing JT-60 Upgrade experiment [1]. The JT-60SA superconducting magnet system is equipped with 18 D-shaped Toroidal Field (TF) coils, Central Solenoid coil with four modules and 6 Equilibrium Field coils [2]. The magnet system is energized by Power Supplies (PS) [3] and cooled by a cryogenic system at 4K. The PS and control systems have been renewed in large part. The majority of the new PS are provided by Europe, and the Italian National Research Council (CNR), acting through Consorzio RFX, has provided two systems as in-kind contribution: the Quench Protection Circuits (QPC) for the superconducting coils and the Power Supply System for RWM control (RWM-PS).

2. THE QUENCH PROTECTION CIRCUITS FOR THE JT-60SA SUPERCONDUCTING MAGNETS

The first analyses for the requirement definition and identification of a suitable design solution for the JT-60SA QPC started in 2006; details on the studies and main steps of the development, system realization and testing have been already described in [4] which reports a list of specific papers, too. Here, a brief overview of the main features and results is summarized and future plan outlined.

The QPC duty is to conduct the coil current in normal operation with negligible power losses and commutate it into a dump resistor in case of quench or other circuital faults by means of a dc Circuit Breaker (CB), so as to quickly discharge the coils stored energy. TABLE 1 summarizes the total energy stored in the TF, CS and EF coils.

TABLE 1. MAXIMUM ENERGY STORED IN THE TF, CS AND EF CIRCUITS

Total energy to be dissipated	[MJ]
Toroidal Field (TF) coils	1050
Central Solenoid (CS) coils	350
Equilibrium Field (EF) coils	1000

The total number of QPC units for JT-60SA is thirteen; their sharing among the circuits and their ratings in terms of nominal currents to be interrupted and maximum voltages applied to the coils at the discharge, are reported in TABLE 2.

TABLE 2. QPC main rating data

Superconducting Coils	QPC units	Current [kA]	Voltage [kV]
Toroidal Field (TF)	3	25.7	2.8
Central Solenoid (CS)	4	±20 kA	±5 kV
Equilibrium Field (EF)	6	±20 kA	±5 kV

Each QPC is composed of a Hybrid mechanical-static CB (HCB) consisting in a mechanical ByPass Switch for conducting the continuous current, in parallel to a Static Circuit Breaker based on Integrated Gate Commutated Thyristor (IGCT) for current interruption, plus a backup protection consisting in an explosive actuated CB, called Pyrobreaker.

The HCB design was the result of a R&D program carried out since 2006 to identify innovative solutions for the interruption of high dc current, able to improve the maintainability and availability of the CB. The scheme of one QPC, with the picture of the main components is shown in FIG. 1.

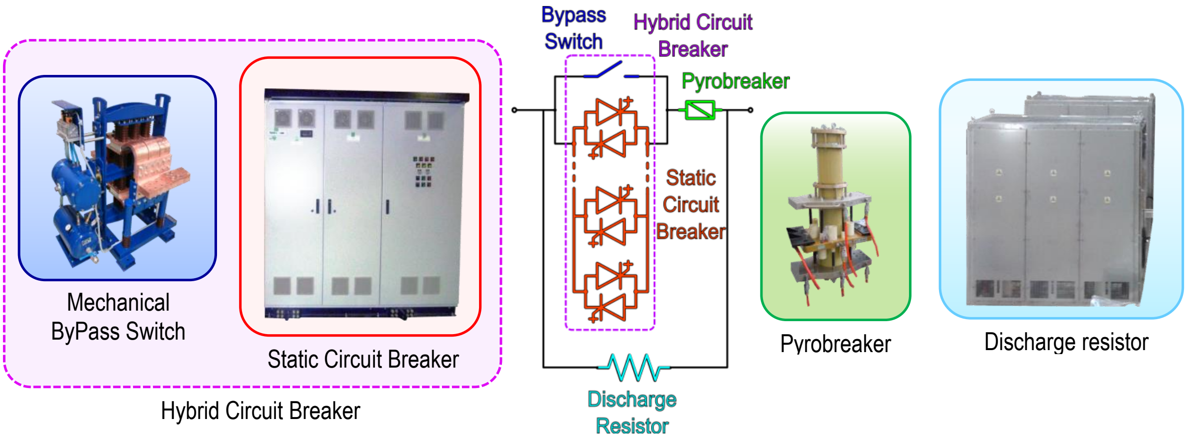

FIG. 1. Simplified scheme of one Quench Protection Circuit and pictures of its main components.

Besides the preliminary tests to explore the feasibility of the identified solution, due to the novelty of the design, a full characterization of the QPC operation up to the nominal current and beyond has been performed on a full–scale QPC prototypes: one for TF and one for PF coils. Special type tests have been designed and performed at the Consorzio RFX premises to verify the performance, the design margins, and the reliability; this was a key step of the procurement, documented in detail in [5].

The manufacturing of the 13 units was completed in 2014; then, they were delivered to Naka site in autumn 2014; the installation and commissioning activities, first experience of EU and JA joint work at Naka site, were successfully carried out within July 2015, as scheduled. A panoramic view of QPC units after the installation in one of the power supply hall is shown in FIG. 2.

FIG. 2. Panoramic view of some Quench Protection Circuits after installation in one Power Supply hall at Naka site.

The last key topic studied, using the QPC models validated against factory experimental tests, was the estimation of the peak transient voltage across the coils at the intervention of the Pyrobreaker, once known the power connection layout foreseen at Naka site [6]. An improved layout for the toroidal circuit was realized on the basis of those results. The future integrated tests planned in 2019 and 2020 will allow verifying the models predictions.

3. THE POWER SUPPLY SYSTEM FOR RESISTIVE WALL MODES CONTROL

The research work for the development of the whole Power Supply system for RWM control (RWM-PS) followed a long path, starting with the studies of the most important requirements, which called for a deep revision of the first conceptual design outlined in the 2007. It was originally based on Sector Coils (SC) planned to be installed behind a Stabilizing Plate (SP) inside the vessel. FEM analysis were performed in order to quantify the time derivatives of the magnetic flux on the SC during fast plasma transients and to obtain the over-currents induced in the SC and studies were made aimed at estimating the coil resistance and inductance as a function of frequency and the efficiency in producing the desired radial magnetic field. The analyses put in evidence the significant shielding effect of the stabilizing plate and also helped in supporting the selection of the conductor sheath; they also allowed enriching the set of requirements necessary for the PS design [7]. The final coil design was based on 18 coils, six located in toroidal direction and three in poloidal one, and placed on the plasma side of the SP.

Significant contribution to the requirement definition of the RWM control system was also given by Consorzio RFX via experimental campaigns in the RFX-mod device and joint activities on MHD stability and control modelling; that have continued and are still ongoing [8]. The experimental campaigns in particular gave some indications on the RWM control effectiveness as a function of coil number and covered torus surface, thanks to the powerful and flexible MHD active control system of RFX-mod [9].

As a result of all the studies, the main features of the RWM control system and consequently the requirements for the power supplies have been derived; the main ones are summarized in TABLE 3. Specific mention has to be given to the control system dynamics; in fact, the key concept resulting from the analyses was that, because of the exponential growing of the RWM, the magnetic field necessary to control them can be reduced if low time delays between field measurements and PS output voltage generation and fast response can be achieved. The relevant final requirements were an overall latency of the RWM control system lower than 150 μs (50 μs for PS) and a current bandwidth of 3 kHz.

TABLE 3. MAIN REQUIREMENTS

Main requirements of the Power Supply system for RWM control		
Nominal output voltage at the inverter output terminals	[V]	240
Maximum peak output current	[A]	300
Number of fast inverter units		18
Bandwidth of the current at -3 dB	[kHz]	3
Maximum operation duty (pulse duration / time between pulses)	[s]	100 / 1800
Maximum latency (between step reference and output voltage)	[μs]	50

The fast dynamics required implied technological issues for the RWM-PS, therefore the development of a fast inverter prototype was launched to gain confidence on technical feasibility, availability of suitable power switches and cost, with the aim to achieve significant risk mitigation for the procurement of the whole PS system. This task led to an innovative design solution adopting hybrid Silicon-Silicon Carbide (Si-SiC) power switches for the fast inverters and to the development of a new sophisticated on-board control [10].

Based on the positive outcomes of the R&D, the procurement strategy of the whole system was finalized in 2015; the final scheme, shown in FIG. 3, is composed of an input rectifier stage and 18 fast inverters, equipped with the new control board with a state-of-the-art Digital Signal Processor and Field Programmable Gate Array. Each inverter can be controlled in current control mode or voltage control mode; the real-time control algorithms are executed at 60 kHz by the DSP, thus allowing wide margin for the fulfillment of the dynamic requirements.

The final design of the on-board control takes advantage from all the key features already developed for the power supply system for MHD control of RFX-mod [11], like the feedforward compensation of the voltage drops on power switches, output filter and of the actual value of the dc-link voltage, fundamental to achieve the required accuracy of the voltage control loop. Another key feature is the compensation of the non-linearities due to the dead-time to be introduced in the power switches commands to prevent the simultaneous conduction of two switches in the same leg of the fast inverter H-bridge. Thanks to the deep experience in RFX-mod, an improved version of the dead-time compensation has been developed, with a sophisticated algorithm acting in real time and showing very good results during the tests, despite the further complication of the the random nature of the reference in these applications and the very low impedance of the load in JT-60SA.

Other fundamental aspects of the fast inverter design for the JT-60SA application were the differential output filter in order to reduce the resonances on the long output cable, the output current ripple and slope in case of short circuits and the common mode filter to smooth the Common Mode voltage oscillations at the load; this last one in particular was improved with respect to the first design developed for RFX-mod [12]. As for the possible overvoltage induced in case of plasma fast terminations, the analyses showed that their amplitude remain within the control capabilities of the fast inverter; nevertheless, a dynamic voltage clamp circuit has been provided in parallel to the dc-link so as to enhance the protection capability.

Special type tests allowed a full characterization of the prototype connected to a dummy load capable to reproduce the impedance at 3 kHz of the real load; the results confirmed the full compliance with the requirements. The system manufacturing, the factory routine and integrated tests were completed in July 2018; FIG. 4 shows the whole RWM-PS system in the final test arrangement.

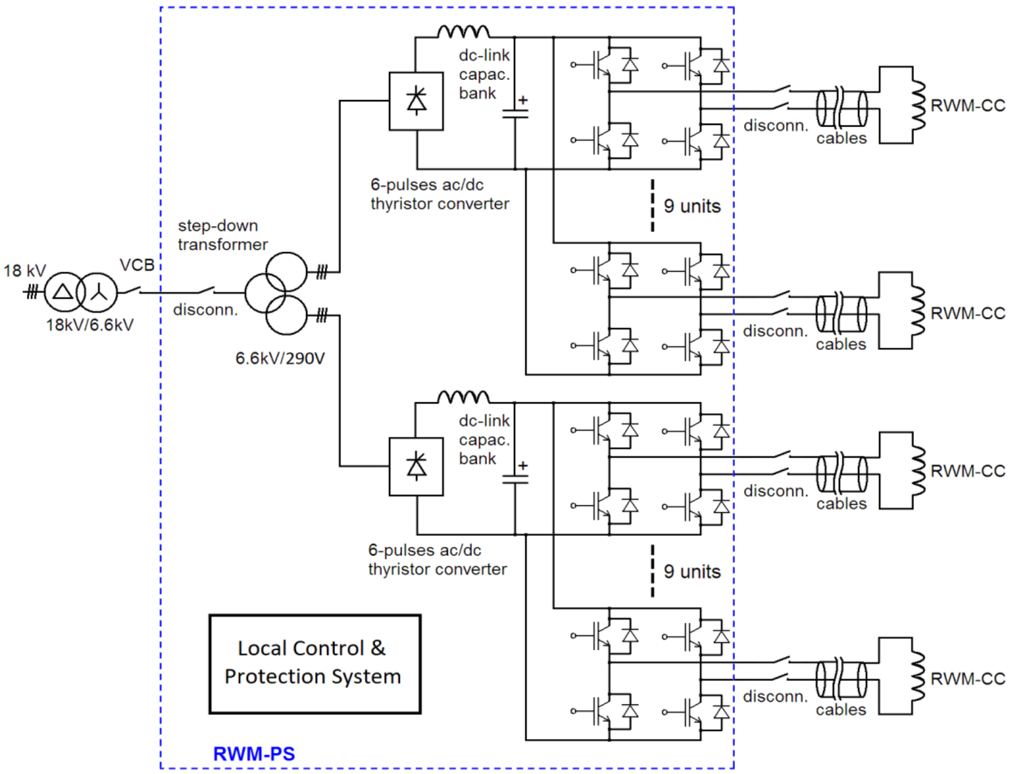

FIG. 3. Final simplified scheme of the Power Supply system for RWM control

4. CONCLUSIONS AND FUTURE WORK

Consorzio RFX has successfully completed the development, realization, testing and delivery of two important components of the JT-60SA machine: the Quench Protection Circuits (QPC) for the superconducting coils and the Power Supply System for RWM control (RWM-PS). The QPCs were delivered to Naka site in autumn 2014; the installation, commissioning and acceptance tests were completed in July 2015, fully in line with the schedule agreed in 2009. After the very successful conclusion of the final integrated tests, the RWM-PS system has just been delivered. For both the procured systems innovative design solutions have been developed, trying to exploit the state-of-the-art technology so as to improve their performance: RAMI in particular for QPC and dynamics for RWM-PS.

The future work will involve the QPCs initially in the integration of the PS sub-systems and then in the integrated commissioning; the RWM-PS will be used instead in the second experimental phase of JT-60SA. The validation of the models developed during the design phase will be another important task of future work, since they can be used for better understanding the systems behavior during the integration in JT-60SA and to study possible upgrades. From the operation of all these systems, useful outcomes for ITER and DEMO are also expected. Consorzio RFX contribution, widen with respect to the BA agreement to the physics and diagnostics areas, is expected to continue in an integrated way in the future BA phase II.

FIG. 4. Arrangement of the whole RWM-PS system for the final integrated tests

REFERENCES

[1] SHIRAI H. et al., Recent progress of the JT-60SA project, Nuclear Fusion 57 (2017)

[2] Koide Y. et al., JT-60SA superconducting magnet system, Nuclear Fusion 55 (2015)

[3] Novello L. et al., Overview of the new Magnet Power Supply Systems of JT-60SA procured by EU, Fusion Engineering and Design 98–99 (2015) 1122–1126

[4] Gaio E. et al., The new technological solution for the JT-60SA quench protection circuits, Nuclear Fusion, Volume 58, Number 7, (2018), 075001 (18pp)

[5] Maistrello A. et al., Experimental Qualification of the Hybrid Circuit Breaker Developed for JT-60SA Quench Protection Circuit, IEEE Transactions On Applied Superconductivity, Vol. 24, No. 3, (2014)

[6] 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 Engineering and Design 98–99 (2015) 1109–1112

[7] Ferro A. et al., Studies on the requirements of the power supply system for the resistive-wall-mode control in JT-60SA, Fusion Engineering and Design 88 (2013) 1509– 1512

[8] Pigatto L. et al., Resistive Wall Mode physics and control challenges in JT-60SA high βN scenarios, this conference

[9] Baruzzo, M. et al., RWM control studies on RFX-mod with a limited set of active coils, Nucl. Fusion 52 103001 (2012)

[10] Ferro A. et al., A 72 kVA very fast four-quadrant converter based on hybrid Si-SiC IGBTs, Proc. 17th European Conference on Power Electronics and Applications (EPE'15 ECCE-Europe), IEEE, (2015)

[11] V. Toigo et al., The power supply system for the active control of MHD modes in RFX, Fusion Engineering and Design 66_/68 (2003) 1143_/1147

[12] Ferro A. et al., Design and Manufacturing of the SiC-Based Power Supply System for Resistive-Wall-Mode Control in JT-60SA, IEEE Transactions on Plasma Science, Vol. 46, No. 5, (2018), 1670-1677