OVERVIEW OF SUPERCONDUCTING MAGNET POWER SUPPLY SYSTEM FOR THE KSTAR 1ST PLASMA EXPERIMENT

JAE HOON CHOI[a*], HYUNG LYEOL YANG[a], HYUN SIK AHN[b], GYEYONG JANG[b], DONG KEUN LEE[a], KUK HEE KIM[a], SANG HEE HAHN[a], CHANG HWAN KIM[a], JAE SIC HONG[a], YONG CHU[a], JONG DAE KONG[a], SEONG LOK HONG[a], IN SUNG HWANG[a], MIN SEONG YUN[b], DAE KYUNG SEONG[b], YOUNG WUN LEE[b], HYUN SEOK SHIN[b], MOO HYUN CHO[c] and JOO SHIK BAK[a]

[a] National Fusion Research Institute, GWAHANGNO 113, Yuseong-Gu, Daejeon 305-333, KOREA

[b] POSCON Corporation R&D Center, 101 Korea Techno Complex Building, Korea University, Seoul 136-713, KOREA

[c] POSTECH, 790-784 San 31, Hyoja-Dong, Nam-Gu, Pohang, Gyungbuk, KOREA

[*] Corresponding author. E-mail : jaehoon@nfri.re.kr

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The KSTAR Magnet Power Supply (MPS) was dedicated to the SC coil commissioning and 1st plasma experiment as a part of the system commissioning. Although many efforts to develop large-current power supplies that are useful for high power electronic devices have been made in various application fields, such as for large metal-plating devices, there were clear discrepancies between conventional power supply technologies and that for the SC coils due to the special SC coil load conditions. Therefore, most of the power supply technologies for the SC coils were a challenge in the domestic research area due to their limited application. However, the MPS commissioning result showed that all of the hardware and controlling software operated well, and this result finally led to the success of SC coil commissioning and the KSTAR 1st plasma experiment.

This paper will describe key features of KSTAR MPS for the 1st plasma experiment, and will also report the commissioning results of the magnet power supplies.

KEYWORDS : KSTAR, TOKAMAK, Plasma, MPS, TF, PF

1. INTRODUCTION

The Korea Superconducting Tokamak Advanced Research (KSTAR) device is an advanced superconducting tokamak intended to establish the scientific and technological bases for an attractive fusion reactor [1]. This device requires 3.5 Tesla of toroidal field (TF) for plasma confinement, and requires a strong poloidal flux swing to generate an inductive voltage to produce and sustain the tokamak plasma. KSTAR was originally designed to have 16 serially connected TF magnets for which the nominal current rating is 35.2 kA. KSTAR also has 7 pairs of poloidal field (PF) coils that are driven to 1 MA/sec for generation of the tokamak plasma according to the operation scenarios. In the integrated commissioning and 1st plasma experiment, the target current for the superconducting (SC) coils and flux swing were set to be much lower than the designed value to achieve 1.5 Tesla of TF field and 100 kA of plasma current due to coil safety concerns and the limits of the electric power utilities system shown in Fig. 1.

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2. TF POWER SUPPLY SYSTEM

This section describes the general configuration,

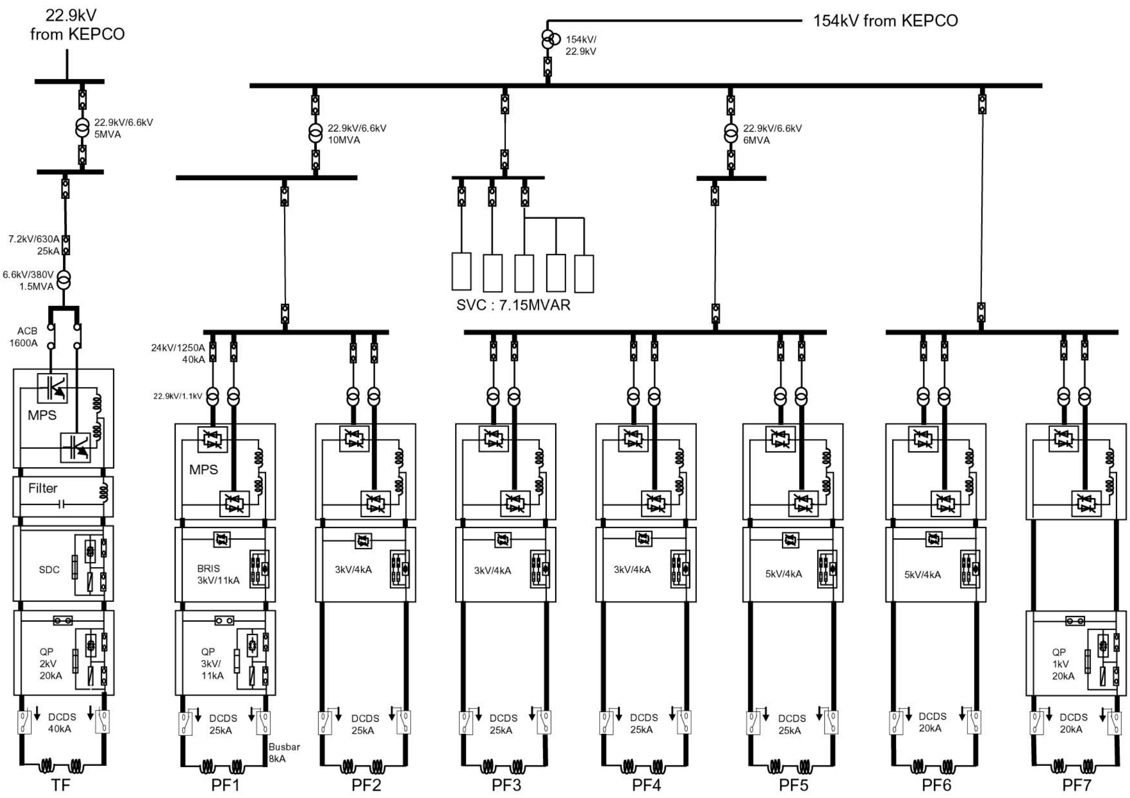

Fig. 1. Schematic of the Electric Power System

Table 1. Specifications of TF Power Supply

Inverter	QP*	SDC	QPR*	SDR	DCDS	DC Busbar
40 kA/25 V	20 kA/2 kV	40 kA/2 kV	114 mΩ(85 mΩ)/6 kV	2.2 mΩ/6 kV	40 kA/6 kV	32 kA/+25 °C

- QP*: 40 kA/6 kV Upgrade item
- QPR*: 85 mΩ (15 kA condition), 114 mΩ (40 kA condition)

specifications, experimental results, and control system for the TF power supply to produce a TF field of 1.5 Tesla in the 1st plasma experiment.

The TF power supply system was designed to operate in steady state for more than 8 hours during the plasma experiment. Therefore, this system required several tens of volts in output voltage and several tens of kA in output current due to the load conditions, which have high inductance and small resistance under a steady state DC current. The main components of the TF power supply are single-directional inverter units using Insulated Gate Bipolar Transistor (IGBT) devices, a quench protector (QP) for fast current discharge from the TF coils with a 7 s time constant in the event of a quench on the coil system, a quench protector resistor (QPR) for energy dump at the moment of QP triggering, a slow discharge circuit (SDC) for normal current discharge from the coils, a slow discharge resistor for energy dump at the moment of SDC operation, a direct current disconnection switch (DCDS) that is the connecting switch between the TF coils and power supply, and DC bus-bars. Table 1 shows the detailed specifications of the TF power supply. Figure 2 shows a schematic diagram of the TF power supply system.

The inverter unit for the TF power supply is comprised of 16 sets of IGBT devices, each with a current rating of 3 kA. The 16 IGBT devices are connected in parallel to form a unit inverter system. The current output terminals and DC bus-bars were actively cooled with de-ionized (DI) water for electrical insulation. The output current measurement requires a sensor with a current capacity of several tens of kA. A Hall sensor or DC shunt sensor is

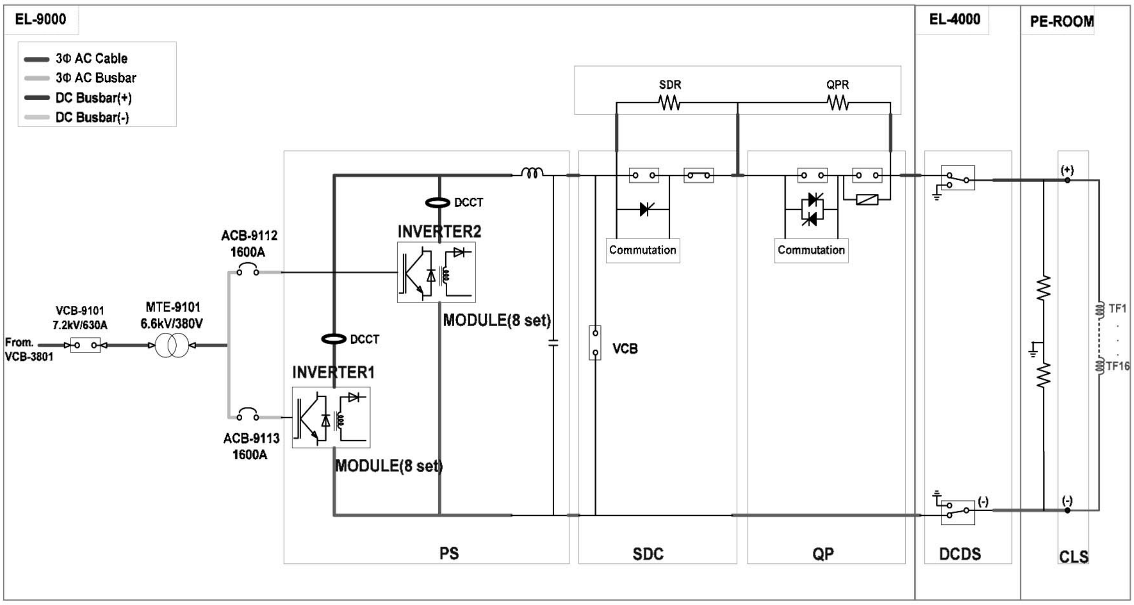

Fig. 2. Schematic of the TF Power Supply

generally used for the purpose. However, that kind of sensor has relatively low accuracy. Therefore, a DC current transducer (DCCT) is a good candidate for reliable high-current measurement. Two sets of DCCT with a current rating of 20 kA were used for output current measurements from each inverter. The summarized specifications of the inverter stack are as follows:

- Power: 1000 kW
- Input voltage: AC 380 V
- Output voltage: DC 0~50 V (variable)
- Output current: DC 0~40 kA (variable)
- Switching frequency: 16 kHz
- Max. isolation voltage: DC 6kV

Although the inverter unit has a current rating capacity of 40 kA as described above, the TF power supply has an intrinsic limit in the QP system for which the maximum current rating is 15 kA. Because the QP is the most important protection device for the safety of the SC coils, all components of the TF power supply were limited to 15 kA for the 1st plasma experiment.

For an independent system commissioning of the TF power supply before machine cool-down, the TF power supply was tested at room temperature by shorting the two current output terminals due to the unavailability of the SC TF coils in this period. The TF power supply system test at room temperature was successfully completed for the preparation of a real system test with the SC coil load after cool-down. The test included measurement of the insulation resistances and leakage currents for which the results are illustrated in Table 2 and Table 3, respectively. The room-temperature tests also covered several critical tests such as a current charge test to 20 kA and tests of QP, SDC, interlock, and local & remote control systems. The test results were satisfactory, although there were several trivial problems that were solved in a day.

The final system commissioning of the TF power supply with a superconducting load was performed

Table 2. Insulation Resistance Data of TF Power Supply

Inspection Item		Reference Value	Measurement Value	Remark
Insulation Resistance	Power supply	>2.5 MΩ	6.2 MΩ	DCDS open
	QPR & SDR	>10 MΩ	2000 MΩ	
	DC Busbar	>10 MΩ	26 MΩ	DCDS open

Table 3. Leakage Current Data of TF Power Supply

Inspection Item		Reference Value	Measurement Value	Remark
Leakage Current	Power supply	<2.4 mA	1.52 mA	Cooling water : 7.06 MΩ
	QPR & SDR	<1.0 mA	0.15 mA	
	DC Busbar	<1.2 mA	0.4 mA	Cooling water : 7.08 MΩ

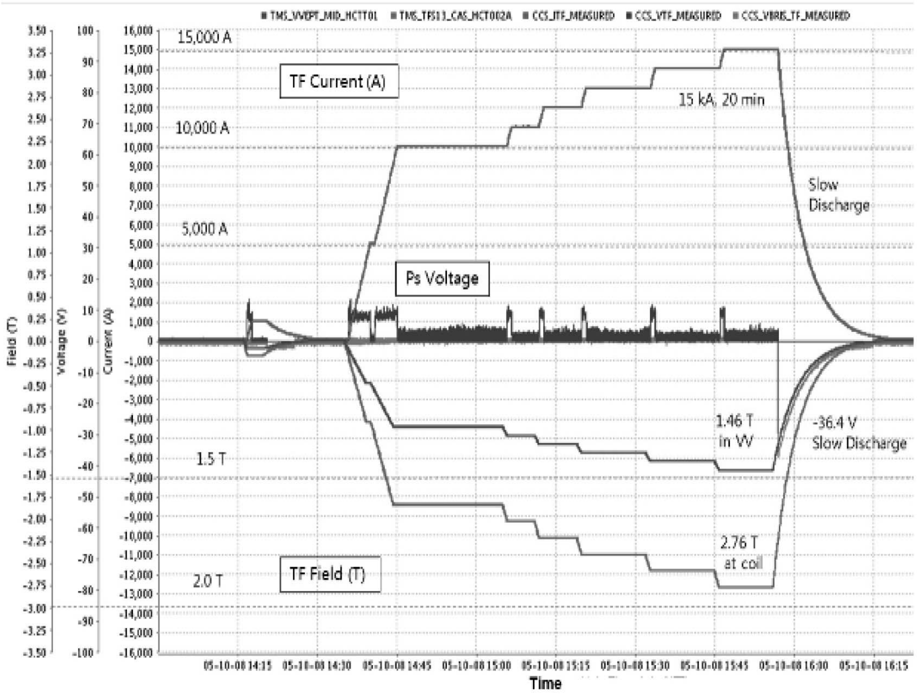

Fig. 3. Output Current Data of the TF Power Supply (Ramping Rate 20 A/s, Output Current 15 kA, Current Ripple ± 10 A)

simultaneously with that of the TF SC coils in early June 2008. The test started with step-by-step current charging of the TF coils, which was followed by fine gain adjustment to find the optimum conditions for minimum current ripple. The operational reliability was also checked for the QP, SDC, interlock, and remote control systems for a several kA range of the applied current. As a final step in the system commissioning for both the TF power supply and the TF coil, a current charging experiment to 15 kA for 8 hours was successfully implemented during the SC coil commissioning stage. Figure 3 shows the output current waveform during the final power supply test. The maximum output current was 15 kA, the current ramping rate was maintained at 20 A/sec, and the current ripple was controlled within ± 10 A (0.1%), which meets the TF power supply requirement.

3. PF POWER SUPPLY SYSTEM

The PF power supply system consists of 7 independent supplies to apply current to the 7 pairs of PF SC coils up to 20 or 25 kA [2]. Accordingly, the output voltage of each PF power supply shows various values from several hundred V to 1 kV according to the load characteristics and operation regime. Each PF power supply is composed of a converter unit that uses bi-directional and 12-phase thyristors, a QP for fast current discharge from the PF coils with a 4 s time constant in the event of a PF coil quench, a QPR for energy dump at the moment of QP triggering, a blip resistor insertion system (BRIS) for producing a flux swing from a rapid change in the current, a DCDS that acts as a main connecting switch between the PF coil and power supply, and a DC bus-bar.

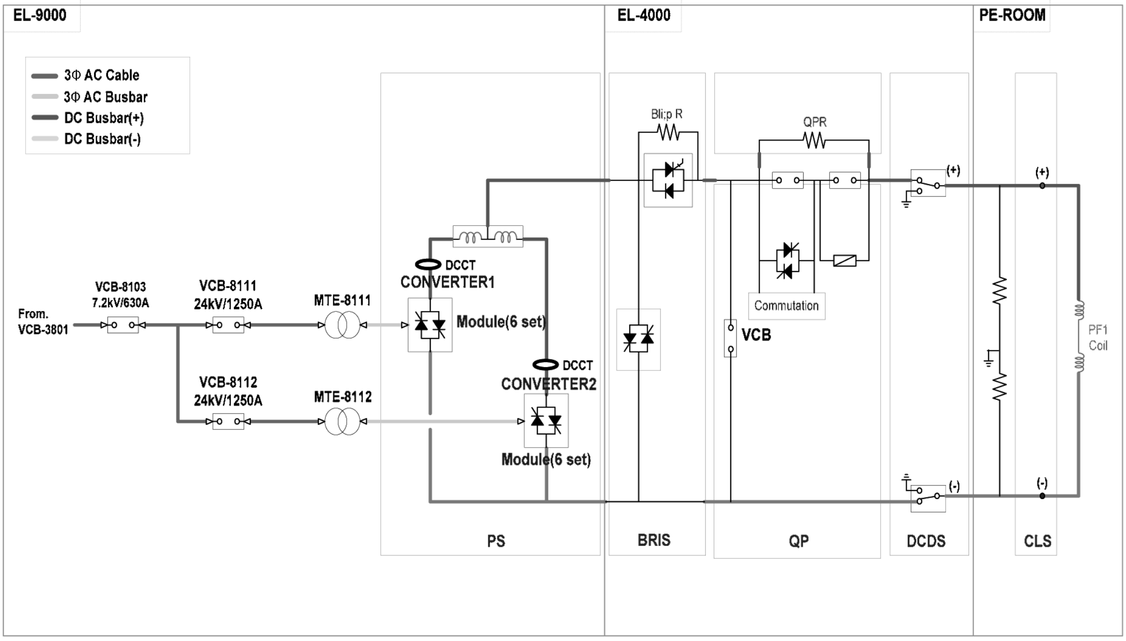

Fig. 4. Schematic of the PF1 Power Supply

Figure 4 shows a schematic diagram of the PF1 power supply that has all the components mentioned above. The major difference between the TF power supply and the PF power supplies is the converter type. As described earlier, the PF power supply uses thyristor units with which bi-directional operation is possible with the help

Table 4. Specifications of PF Power Supplies

	Converter	BRIS	QP	DCDS	DC Busbar
PF1 PS	25 kA /1 kV	2.7 kA /3 kV	25 kA /2 kV	25 kA	8 kA /300 sec
PF2 PS	25 kA /1 kV	2.1 kA /3 kV	-	25 kA	8 kA /300 sec
PF3 PS	25 kA /500 V	2.8 kA /3 kV	-	25 kA	8 kA /300 sec
PF4 PS	25 kA /500 V	2.6 kA /3 kV	-	25 kA	8 kA /300 sec
PF5 PS	25 kA /1 kV	2.1 kA /5 kV	-	25 kA	8 kA /300 sec
PF6 PS	20 kA /1 kV	2.3 kA /5 kV	-	20 kA	8 kA /300 sec
PF7 PS	20 kA /1 kV	-	20 kA /1 kV	20 kA	8 kA /300 sec

Table 5. Insulation Resistance Data of PF Power Supplies

Item		PF1	PF2	PF3	PF4	PF5	PF6	PF7
Cooling water [MΩ]		2.5	8.45	2.5	2.5	8.45	8.1	8.1
Power Supply	Reference Value	>2.5 MΩ						
	Measurement Value [MΩ]	9.07	11.35	6.71	8.80	8.55	10.96	10.25
DC Busbar	Reference Value	> 10 MΩ						
	Measurement Value [MΩ]	2000	2000	2000	2000	2000	2000	2000

Table 6. Leakage Current Data of PF Power Supplies

Item		PF1	PF2	PF3	PF4	PF5	PF6	PF7
Cooling water [MΩ]		2.5	8.45	2.5	2.5	8.45	8.1	8.1
Power Supply	Reference Value	<2.4 mA						
	Measurement Value [mA]	1.19	0.7	0.71	0.76	1.1	0.6	0.6
DC Busbar	Reference Value	< 1.0 mA						
	Measurement Value [mA]	0.12	0.12	0.17	0.02	0.05	0.1	0.05

of a 12 pulse-phase control method, while the TF power supply uses a one-directional inverter unit.

Although the converter unit for each PF power supply has current rating of 20 kA (or 25 kA) and bi-directional operation is possible, the PF power supplies could not be equipped with QP except for the PF1 and PF 7 power supplies for the 1st plasma experiment. This restriction required that the BRIS, in which one-directional current flows in the converter, should protect the PF coil in the event of quench on the PF coil. The limit also made it impossible for the PF coils to be operated in a bi-directional operation scenario for the 1st plasma experiment. Moreover, the maximum current rating of the BRIS for each PF power supply was less than 3 kA, which is a much lower value than that of the converter and DCDS. The two major limits mentioned above imply that the maximum available current was 3 kA, and maximum total flux was less than 1 Webber (volt-second) in the 1st plasma experiment. The limited available total flux was a major constriction for the pulse length of the 1st plasma experiment, which was set at about 100 msec. Table 4 shows the summarized configuration and specifications of the PF power supply system.

A system test of the 7 sets of PF power supplies with a dummy coil was carried out by measurements of insulation resistance and leakage current. Tables 5 and 6 show the measured insulation resistances and leakage currents, respectively. Measurements of the resistances and the leakage currents were followed by current charging tests with two dummy loads that had self inductances of 2 mH and 30 mH, respectively. The tests included forward-direction current charging, reversed-

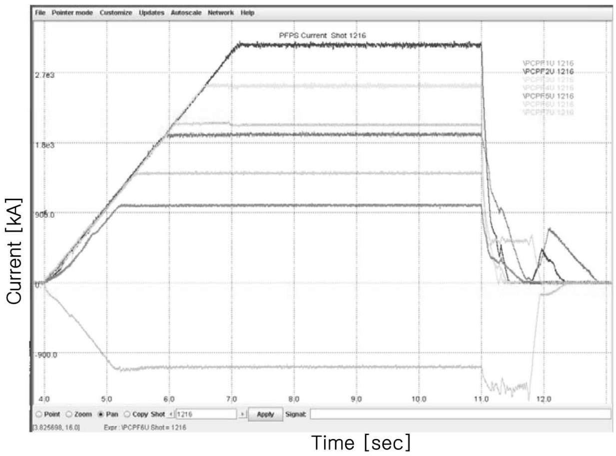

Fig. 5. Output Current Data of the PF Power Supply (Output Current 3 kA Max., Current Ripple ± 50 A)

direction current charging, and zero-crossing tests. The PF QP, BRIS, interlock system, and remote control system were also finally tested after the current charging tests. In this period, every major and minor problem was successfully solved and all of the PF power supplies were ready for final commissioning with real SC coil loads.

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The final system commissioning of the PF power supplies with superconducting loads was performed with PF SC coils in the middle of June 2008. Gains of all the PF power supplies were carefully tuned for optimum conditions for the current ripple with low output current. The operational reliability was also checked for the PF QP, PF BRIS, interlock, and remote control systems. In this commissioning, the maximum current applied to the PF coils was 3 kA in the forward direction. The QP operated well when an artificial quench signal was generated and sent to the QP system [3]. The current waveforms with the BRIS operation also satisfied the requirement for the 1st plasma generation. Figure 5 shows the current waveforms applied to the 7 sets of PF coils.

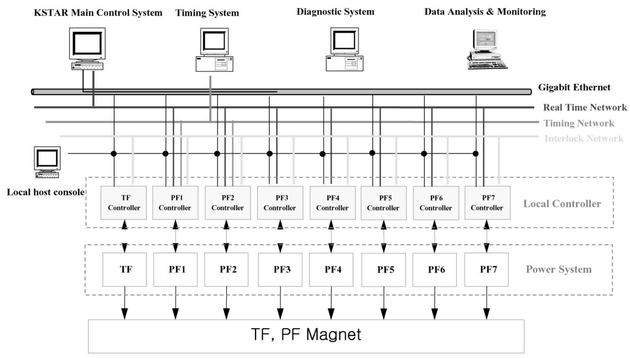

Fig. 6. Power Supply Control System Configuration

4. LOCAL CONTROL SYSTEM

The general configuration of the local control system for the magnet power supply is shown in Fig. 6. The specifications of the local control system for both the TF and the PF power supplies are as follows:

- Local host console: Sun Ultra 25 workstation
- VME system: 19" Rack mountable dual type subrack
- CPU: IBM Power PC 750 GX @1 GHz
- RFM: High-speed fiber optic network with 128MB
- Digital I/O: 32 bits of high-voltage inputs and outputs

The local control system (LCS) that was established in a local control room for the power supplies is composed of VME-based hardware and EPICS-based software. The LCS for the TF power supply is connected to a central control system (CCS) that was developed for integrated system control of KSTAR. As a result, the TF power supply is remotely operated with the help of the CCS and the TF LCS. The PF power supplies are remotely controlled by the plasma control system (PCS) that regulates all the current waveforms that generate and sustain the 1st plasma experiment. Because the blip time of the PF coils should be synchronized with other pulsed systems such as the gas puffing and data acquisition systems, the BRIS is controlled by the central timing system. Most of the remote control systems of the TF and PF power supplies were successfully operated in the integrated system commissioning and 1st plasma experiment period. However, several minor disconnections between the CCS, PCS and LCS of the power supplies need to be further investigated to achieve operation reliability in future operation stages.

5. CONCLUSIONS

The TF and PF power supply systems satisfactorily operated in the integrated commissioning phase and in the 1st plasma experiment period with no severe problem preventing machine operation. A successful result in the magnet power supply commissioning and operation was one of the most important factors for the success of the KSTAR 1st plasma experiment. However, every power supply system in the 1st plasma experiment had a configuration restricted from its full specification. This fact was a major limit for the 1st plasma experiment, which achieved 133 kA of plasma current and a duration of 249 ms for a current of over 100 kA. It is most urgent for the power supply to be upgraded for future KSTAR operations. Therefore, the current capacity of the TF QP will be upgraded from 20 kA to 40 kA from late 2008. The BRIS of the PF power supplies will be upgraded from 3 kA to 25 kA, and QPs for PF2 ~ PF6 will be newly fabricated and installed in the near future.

ACKNOWLEDGEMENTS

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