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# Controls on KSTAR Superconducting Poloidal Field (PF) Magnets

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***Abstract***-- **As a part of the plasma control system (PCS) for the first plasma campaign of KSTAR, seven sets of fast feedback control loop for the superconducting poloidal field magnet power supply (PF MPS) have been implemented. A special real-time digital communication interface has been developed for the simultaneous exchanges of the current/voltage data from the 7 sets of 12-thyristor power supplies in a 200 microsecond control cycle. Preliminary power supply tests have been performed before actual cooldown of the device. A 29 mH / 50 mΩ solenoid dummy has been fabricated for a series of single power supply tests. Connectivity and response speed of the plasma control system have been verified. By changing hardware cabling, this load was also used to estimate mutual inductance coupling effects of two geometrically adjacent solenoid coils on each power supply. After the cooldown was complete, each pair of the up/down symmetric PF coils has been serially connected and tested as part of the device commissioning process. Bipolar operation and longer pulse attempts have been investigated. The responses of the coils and power supplies corresponding to the plasma magnetic controls in plasma discharges are also analyzed for the future upgrades.**

## 1. INTRODUCTION

The KSTAR tokamak [1] is a steady-state tokamak consisting of full superconducting magnets for both toroidal field (TF) coil and poloidal field (PF) coils. For the purpose of making plasma these PF coils should be simultaneously controlled.

For this purpose, controls of the currents of the 7 sets of up/down symmetric PF coils have been implemented as one of functions of the plasma control system (PCS) [2] for the first plasma campaign of KSTAR. Each PF magnet power supply (PF MPS) [3] can independently communicate with the PCS via a dedicated fast digital communication layer. These control loops change the PF coil currents to provide enough vertical magnetic flux swing for creating and maintaining tokamak plasma. Fig. 1 shows the locations of the PF coils of the KSTAR.

In this paper we will describe how the controls of the power supply system have been verified and how the controls have been applied to the real superconducting coils and the plasma control during the first commissioning period.

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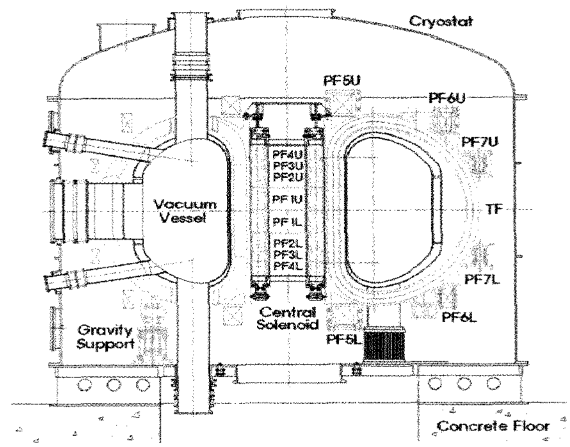



Fig. 1. Locations of the 7 pairs of the superconducting poloidal field (PF) coils operating in KSTAR.

## 2. PRELIMINARY TESTS

### 2.1. Control System Design

Real-time feedback control of PF MPS has been developed as one of the functions of the "Day-One" KSTAR plasma control system (PCS). Measurement of feedback parameters and exchange of the control commands are fully digitalized by reflective memory (RFM) [4] network. Figure 2 shows how the feedback loop communicates: the PCS sends the command, $V_{ref}$, and the PF MPS local controller system (LCS) sends set of [I,V]

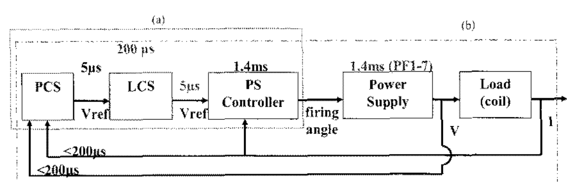



Fig. 2. A block diagram representing digital data flow between the plasma control system (PCS) and a single power supply. The LCS indicates a VME-based local controller with a reflective memory inside.

measured by writing the data in the predefined address at every 200 microseconds. The PCS operator chooses how the LCS should interpret the command from the PCS: If the PCS sends $V_{ref}$ as a voltage command, the PF MPS simply converts it as a thyristor firing angle by the following formula,

$$\alpha = \cos^{-1} \frac{V_{cmd}}{1.35V_{\max}},$$

where the $V_{\max}$ is the maximum allowable power supply voltage and $V_{cmd}$ is the command supplied from the PCS. If the command is the coil current, the PS controller in Fig. 1 gets the command and does the actual feedback.

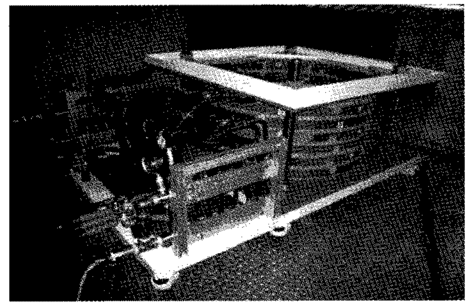
These 7 sets of digital feedback loop have been implemented in a single node of PCS hardware. The data written to the RFM can be also monitored in any device connected to the RFM layer. However, for minimizing the communication overhead reading other power supply's data written to the RFM from other ones has not been made in the first installation.

To validate this digital control loop (a) in Fig. 2, a kind of "echo" test has been performed. The test scheme is that the PCS sends a command signal and tries to receive the "echo" returned from the power supply controller, which simply copies the command to the RFM as soon as it receives the command. The PCS was run at the fastest operable cycle, 50 microseconds, to measure the average delay for this communication loop. The measured result was about 420 microseconds in average, which is within the maximum expected assuming the communication overhead for the RFM transfer is very small (< 5 microseconds). However the real power supply response, loop (b) in Fig. 2, is much longer, because the inherent activation cycle of the converted 12-phases thyristor firing angle adds up about 1.4~2.8 ms to the whole feedback loop.

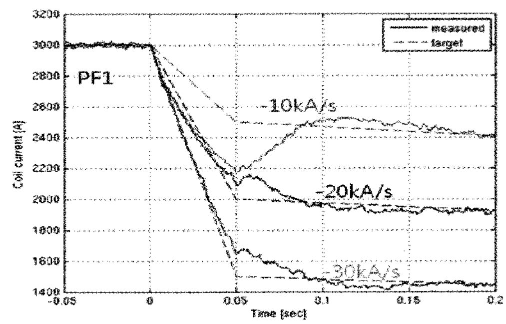
### 2.2. Dummy Load Test

For the first plasma campaign the PF coil power supplies were tested to qualify the following operation capabilities to provide enough loop voltage and adjust vertical magnetic field for robust startup of plasma:

1) initiating, rising and falling a PF coil current by current feedback of PCS
2) making a big flux swing by activation of IGCT-based blip resistor insertion system (BRIS) to provide ~3V of loop voltage along the toroidal direction for the plasma breakdown
3) adding additional PS voltage to the circuit to adjust the slew rate bigger or smaller during the blip resistor activation – provide bigger loop voltage
4) performing very long pulse operations (> 60 seconds) for the PF coil commissioning and superconductor AC loss phenomena
5) performing bipolar current operations for power supply capability



(a)




(b)

Fig. 3. (a) High-inductance dummy load used to the pre-commissioning of the PCS and the PF MPS controls. (b) Test result of coil current feedback control with PF1 + dummy load 29 mH/ 50 mΩ + 250 mΩ BRIS. In each shot the slew rate was adjusted by pre-programmed additional PS voltage during the 50 ms blip.

Before the cooldown, a high-inductance dummy load with 29 mH / 50 mΩ was prepared for single power supply qualifications, which consists of 7 circular solenoid coils stacked vertically and connected in series as shown in Fig. 3(a). Using 4kA-capable BRIS prepared for PF1 MPS, the ability to adjust the slew rate of the coil current was tested up to -30kA/s for 370V power supply (Fig. 3(b)). It has been found that the power supply is capable to adjust the coil current reduced up to -20kA/s during the blip phase by exerting additional positive PS voltage to the load when the inherent dI/dt is about -30kA/s at the 3kA level. Step response tests showed that there is a communication delay of 5 milliseconds in average. Approximately 5 ms of response time is observed for a voltage step waveform of the PCS running at 200 microseconds.

The BRIS resistance for each power supply system is shown in Table 1. The configuration for dummy load tests was designed to test each power supply and BRIS circuit at 4 kA. In the superconducting tests this configuration has been modified to be compatible with real plasma startup scenarios. Since the blip resistors of PF2~PF6 have been also used as quench protectors, this kind of modifications restricted the maximum operable coil current to the smaller level in the superconducting load tests after the cooldown.

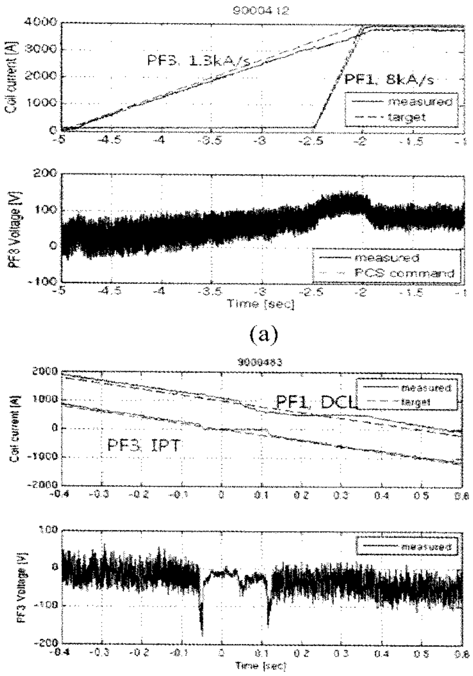



Fig. 4. (a) Mutual inductance effects are shown when the slew rates of two strongly-coupled solenoids are different. (b) For a zero-crossing situation, the mutual inductance effect is in the form of the induced voltage to the dead circuit.

TABLE I
INDIVIDUAL RESISTANCE OF BLIP RESISTOR INSERTION SYSTEM (BRIS) BEFORE /AFTER COOLDOWN.

| | For dummy load operations [Ω] (~March 2008) | For SC load operations [Ω] (May 2008~) |
|---|---|---|
| PF1 | 0.25 | 0.5 |
| PF2 | 0.25 | 0.5 |
| PF3 | 0.5 | 0.5 |
| PF4 | 0.5 | 0.7 |
| PF5 | 1.25 | 2.2 |
| PF6 | 1.25 | 2.1 |
| PF7 | - | - |

### 2.3. Influence of Mutual Inductances

Since the superconducting magnets have very large inductance with zero resistance, effects of the mutual inductances could be very large especially when the coils are stacked in the shape of a solenoid such as the central solenoid (CS) of the KSTAR. To verify the mutual interaction issues of the strongly coupled solenoid coils in the CS configuration, the electric connection of the 29 mH dummy load had been changed: the first upper 4 rings were serially connected to the PF1 power supply and the rest 3 below them were connected to the PF3 power supply. Such configuration enabled to test how the operations affect to each power supply circuit when the CS coils are charged simultaneously independently. Equation (1) shows the calculated mutual inductance matrix based on the Helmholtz coil model:

$$M = \begin{bmatrix} 12.4 & 5.0 \\ 5.0 & 7.65 \end{bmatrix} \text{(mH)} \qquad (1)$$

Under this configuration the interactions of adjacent coils and the effects of the off-diagonal mutual terms to the two power supplies can be analyzed.

Figure 4 shows how the coil current reacts due to the inductance coupling effect. In the Fig. 4(a) the PF1 coil current has faster slew rate to 8 kA/s, which introduces additional voltage drop to the PF3 coil circuit and causes higher voltage output made from the PF3 PS to maintain its current slope than a single coil case. The amount of voltage induced to the PF3 is about 8 kA/s * 5.0 mH = 40 Volts in this case. When the coils were running at the same slew rate, there was no effect on controls.

In a zero-crossing operation situation like Fig. 4(b), the PF3 is supposed to make a zero voltage when the PF3 coil current maintains zero during a "dead time". However in this case the mutual term induced from the current drop of PF1 causes an additional PF3 voltage of -10kA/s * 5 mH = -50 V in the PF3 circuit. In the resistive load situations it does not affect the safety of the operation, but in the real case of large superconducting loads, this induced voltage at the zero-current coil by the varying currents of other coils can be very large that could easily exceed the operable range of the terminal-to-terminal voltage of the converter, which could affect the operation of the power supply when the power supply tries to turn on the current again.

## 3. SUPERCONDUCTING COIL OPERATIONS

### 3.1. Single Coil Response

The 7 pairs of individual PF coils have been tested one by one with up-down symmetric serial connection after the coils have been cooled down to the superconducting (SC) level. To prevent principal mutual inductance effects, the other PF MPS were not connected to the corresponding road

TABLE II.
OPERATIONAL RANGES OF INDIVIDUAL PF POWER SUPPLY IN THE SUPERCONDUCTING STATE (YEAR 2008).

| | Max V [V] | Max I [A] | Lcalc [mH] | dI/dt [kA/s] | dB/dt [T/s] |
|---|---|---|---|---|---|
| PF1 | 320 | 4047 | 91.42 | -21.32 | -7.33 |
| PF2 | 320 | 3188 | 48.77 | -32.72 | -8.15 |
| PF3 | 160 | 3358 | 14.56 | -98.96 | -16.33 |
| PF4 | 160 | 3312 | 29.21 | -78.02 | -16.23 |
| PF5 | 320 | 2117 | 239.2 | -23.53 | -6.40 |
| PF6 | 1000 | 2329 | 450.9 | -17.17 | -2.85 |
| PF7 | 1000 | 4055 | 222.8 | 6.60 | 0.80 |

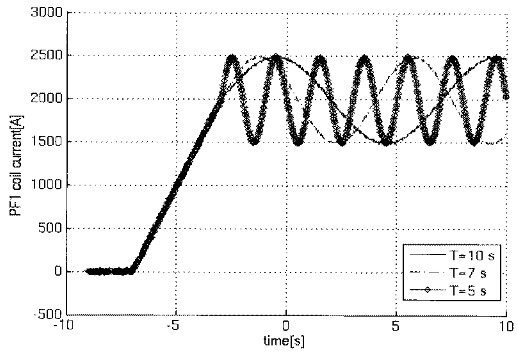
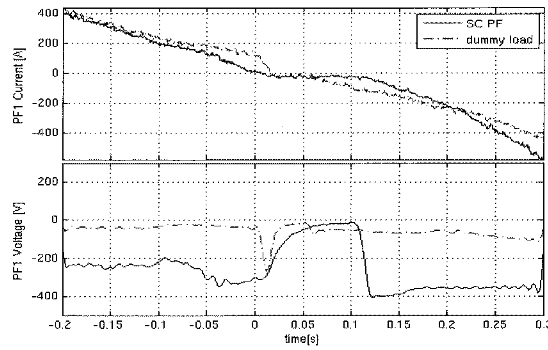
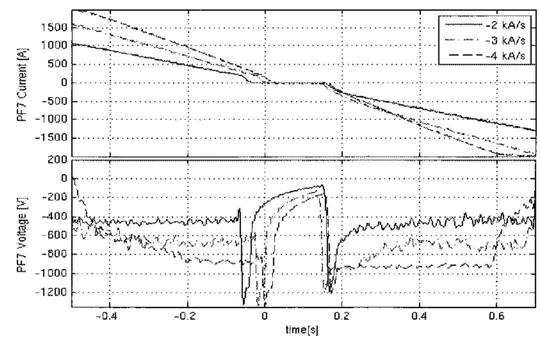



Fig. 5. Snapshots of the waveforms used on the PF1 AC loss measurements. Waveforms with period (T) = 5,7,10 seconds are shown.




(a)




(b)

Fig. 6. (a) Comparison of the dummy load (dash dot) and SC PF1 (solid) when the IPT-type zero-crossing is performed at -2 kA/s. (b) Behaviors of the PF7 voltage are compared for different ramp rates: -2 kA/s (solid), -3 kA/s (dash dot) and -4 kA/s (dash).

when the single coil control test was performed. Operated ranges for each power supply are shown in Table II. Due to the insulation voltage requirements of the each BRIS (< 4~5 kV) the operational limits were highly restrictive. However, it should be notified that the maximum dB/dt for a single coil, which was obtained by blip resistor operations, was quite comparable to the designed maximum dB/dt= -20 T/s.

### 3.2. Long Pulse Operations

The long-pulse operating capability for a single coil has been verified for a few selected sets of the PF power supplies. Using the reflective memory scheme, the KSTAR PCS is capable to operate for very long pulse. Under the PCS control, long pulses of a single PF coil operation continued without errors up to 20 minutes (~1200 seconds) as a slow sinusoidal wave of single frequency. These were performed as part of the SC AC loss measurements. The PF1, PF5 and PF6 were selected for the test. Figure 5 shows snapshots of the waveforms used on the PF1 AC loss measurements. In a single shot the current modulation frequency was fixed. To avoid unnecessary circuit property change due to the IGCT, the waveform maintained 1.0 kA oscillation centered at 1.5~2.0 kA, depending on the operational limit of the target coil.

Varying the frequency within 0.5~0.1 Hz shot by shot, the PF coil control has been stable enough to make good saturations on the PF temperature rise due to the AC loss of the SC coil. External fault triggering from the central control system has been used to detect and protect from unsafe events not only in the SC coil but also from the SC busline and the refrigeration system.

### 3.3. Bipolar Operations of Single SC Coil

Traditional tokamaks do the bipolar operations which swing the coil current both to the forward direction and reversed for two reasons: 1) to have doubled PF flux capability under the same electricity 2) to lengthen the ramp rate as long as possible for the longer sustainment of plasma flat-top to compensate the energy loss that the plasma suffers from contacting the first wall components. However, in principle, these kinds of operations could cause damages for back-to-back style in the SC coil cases. Hence special ways for treating these zero-crossing operations have been pursued. For KSTAR, two kinds of special hardware have been adopted for the zero-crossing: IPT-type and DCL-type. Generally the DCL-type operation, which does not have "dead time", is favored for the plasma. However the DCL-type needs a special inductive hardware for independent operation of the two 6-thyristor arms. The IPT-type operation was the default one installed for every power supply, whereas the DCL-type was possible for only the PF1 MPS in the first cooldown. Hence only the IPT-type cases are discussed in this paper.

SC load tests for bipolar operation were performed only for the selected set of a single SC coil, PF1 and PF7. In the IPT-type operation when the coil current reaches 150 Amps the power supply controller gets the controllability and tries to make the coil current to zero before the power supply is turned on again. The "dead time", when the PF MPS voltage remains zero, is depending on the power supply response and, hence, the target load.

Fig. 6(a) shows how the dead time depends on the target load. Two same current waveforms are provided by the same power supply (PF1) to the dummy load and the superconducting one. Since the superconducting one has an inductance three times bigger, it takes more than three times to make the coil current to zero and turn off both arms. There are also unknown nonlinear behaviors in the very low coil current which is not observed in the dummy load case. The IPT-type scheme also depends on the current slew rate before the coil current reaches at 150 Amps. As shown in Fig. 6(b), bigger ramp rate before the zero-crossing scheme starts makes the dead time shorter. It should be apparent because the sooner the current reaches to zero the earlier the power supply turns off its voltage for the reversed operation again. All these physical properties due to the SC load apparently make the dead time of IPT-type zero-crossing scheme much longer than the dummy load case.

### 3.4. Applications to Plasma Control

A coil-charging scenario for KSTAR plasma creation consists of 4 phases: 1) charging of the coil currents to the predetermined level 2) maintaining the current plateau until the 3) blip: the synchronized activation of the BRIS for large flux swing to induce a toroidal loop voltage 4) turning off the BRIS and activating the magnetic feedback of plasma column until the plasma disappears. Based on the dummy load test results, scenarios that charge the CS

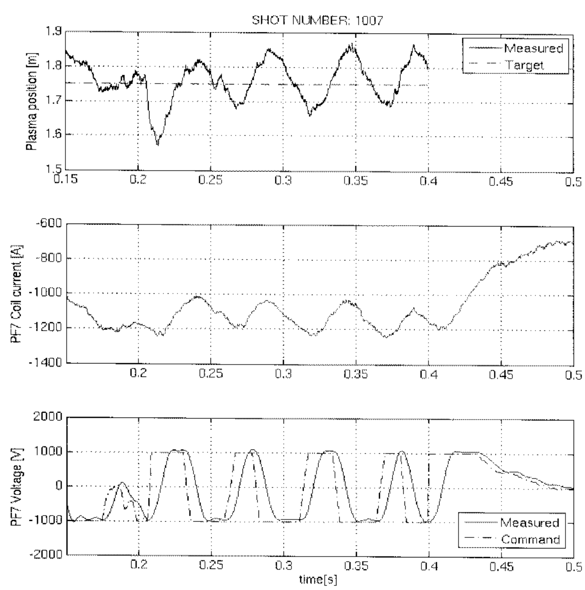



Fig. 7. Saturation of PF7 coil voltage (bottom) when the plasma center (top) is at 1.75 m in the outboard.

coil currents at the same rate has been adapted for the standard shot sequence. In the consequences, effects of mutual inductances have been minimized when the PCS charges the coil currents of seven coils at the same time.

Creating and maintaining a field null configuration for plasma creation for 30 ms after the flux swing has been tuned in an empirical manner. First we turned on the current feedback to the pre-programmed coil current waveform. After seeing the shot result, we turned off the feedback loop by adjusting all gains to zero and put the additional open-loop voltage instead if the vertical magnet field (Bz) seemed too large to push the plasma. Two types of the initial magnetization scenarios are investigated in the campaign. Without feedback controls, the feed-forward control of the blip resistor set enabled the plasma reach up to plasma current ~ 130 kA within 150ms, spending approximately 0.9 Webers of initial magnetic flux.

As for sustaining the created plasma after the blip ends, the feedback algorithm on the plasma centroid has been utilized to compensate the Bz to regulate the radial force balance of the plasma. The central coils, from PF1 to PF5, have been used for the plasma current feedback actuators and the two large PF coils outside (PF6, 7) have been used for the radial position feedback. One Rogowski coil and 2 inner/outer pairs of the midplane magnetic probes are used to estimate the radial position of the plasma centroid [2]. It is obvious that the resistive plasmas created during the first campaign require more volt-seconds from the PF coils when the ECH goes off after 0.3 seconds. As seen in Fig. 7, the PS voltages are all saturating very rapidly to make compensations required for the plasma radial position control, responding the oscillations the plasma column makes. However, due to the large inductances of the outer PFs the actual coil current response is slow. For minimizing the current excursions in the outer PFs the target value for the plasma center was deliberately set to be pushed gradually into the inboard side ($R_p < 1.7$m) to avoid unnecessary overshoots or saturations of the PS voltage. Using this technique with the maximum available flux (1.1 Wb), a record of 865 milliseconds of longest duration of the plasma pulse has been achieved.

Typically the solenoid coil currents descend at the same ramp rate to provide constant volt-seconds into the ohmic plasma column to maintain plasma current flattop. Hence it would not be a rare situation that the zero-crossing of a single coil occurs when others have still nonzero current ramp rates.

## 4. SUMMARY & FUTURE WORK

In the first campaign of KSTAR, 7 sets of full digital control loops for the PF coils have been constructed for simultaneous controls of the PF power supplies as magnetic actuator of the PCS. Responses of the control circuit and capability of utilizing blip resistors have been confirmed by preliminary tests with a reactive dummy. After the cooldown, each pair of the up/down symmetric

PF coils has been serially connected and tested as part of the device commissioning process. The responses of the coils and power supplies corresponding to the plasma magnetic controls in plasma discharges are also analyzed for the future upgrades. Further research of both the elimination of this dead time and controls for safe zero-crossing is required for longer and safer plasma operations.

## ACKNOWLEDGMENT

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