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Current Control System for Superconducting Coils of LHD

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Abstract

The LHD has six sets of large-scale superconducting coils and six dc power supplies to charge them. For the current controllers of these power supplies, high accuracy of current control, fast response and robustness of system are required. This paper, therefore, describes the current control system for the LHD dc power supplies. First, the outline of the power system is presented, and then, the current controllers for the LHD are described. Finally, experimental results are presented and discussed in case of coil excitation using these control systems. The results show the various characteristics for each control system and indicate it possible to control the system according to the requirements from a plasma experiment.

Keywords:

current control, H∞ control, inductance matrix, parameter estimation, superconducting coil, state variable

1. Introduction

The LHD has twelve superconducting coils and six dc power supplies to excite them.For these power supplies, the following conditions were required; the steady state control error is less than 0.01% of the set value, the current settling time for 0.1% of control error is less than 1 second and the control system must be robust against turbulence caused by the plasma experiments. To resolve these requirements, some control systems are studied, designed and tested.

In the following sections, the outline of the control system for power supplies is introduced at first. Next, the estimation of circuit parameters is described. Finally, the controller design and experimental results are presented.

2. Outline of the Power System

Each power supplies are controlled by the computer system shown as this figure. Each power supply for the LHD superconducting coil has a current sensor and a local feedback loop, which control the actual voltage to track the calculated voltage reference. With this local loop, the error such as a voltage drop in the circuit or a change in line voltage is compensated, in order for the power supply to work as an ideal controlled voltage source. In the computer system to control all power supplies, the current control scheme is described with state vector as following;

$$\frac{d}{dt}x_c = A_c \cdot x_c + B_c \cdot \begin{bmatrix} i_c^* \\ i_c \end{bmatrix} \tag{1}$$

$$v_c^* = C_c \cdot x_c + D_c \cdot \begin{bmatrix} i_c^* \\ i_c \end{bmatrix} \tag{2}$$

where x_c is a state vector, A_c, B_c, C_c and D_c are the matrix of the control gains. i_c^*, i_c and v_c^* demote the cur-

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rent reference, the actual coil current and the output voltage reference, respectively.

3. Parameter Estimation of Coil System

In the design of a control system, the electrical parameters of the superconducting coil system are required to determine the control gains mentioned above. To estimate them, the inductance L_{re} was measured from the coil terminals for all coils in various frequency. Figure 1 shows some frequency response of the self and mutual inductances. In this figure, HO, HM, HI, OV, IS and IV mean three helical coils and three poloidal coils, respectively. The measured value is plotted in the figure. The lines show the results calculated by a circuit model introduced later. To describe this frequency response, we assumed that the coil system has four coupled circuits to treat the induced current flowing in the structural material. We determined the circuit parameters by fitting to the measured inductance as shown in Table 1 [2]. In the table, C1, C2, C3 and C4 are coupled circuits.

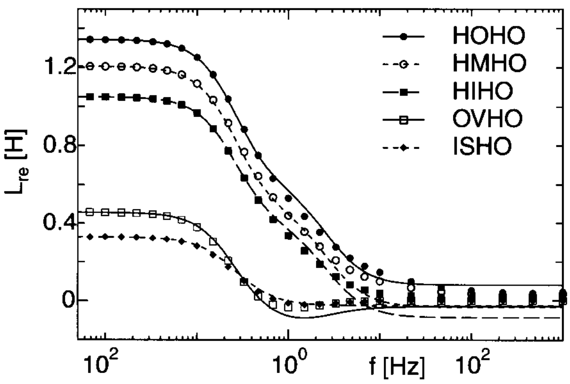

Fig. 1 Frequency response of inductance for LHD superconducting coils.

4. *PI* Controller

First, the *PI* control scheme is designed for this system based on the state variables. Although this control scheme is simple, it has adequate performance for the steady state current control. The current regulator used in this system is formed as follows;

$$v_c^* = kR_c \int (i_c^* - i_c)\mathrm{d}t + kL_c(i_c^* - i_c) \tag{3}$$

where L_c is inductance matrix of the superconducting coils, R_c is resistance, and k is the scalar control gain. From the equations, the control matrix in Equation (1) and (2) are evaluated as follows;

$$A_c = 0,\ B_c = \begin{bmatrix} U & 0 \\ 0 & -U \end{bmatrix},$$

$$C_c = kR_c,\ D_c = k\begin{bmatrix} L_c & 0 \\ 0 & -L_c \end{bmatrix}$$

where U is a unit matrix. The step response of the coil current is as following;

$$i_c = i_{c0} + (1 - e^{-t/\tau})\,(i_c^* - i_{c0}) \tag{4}$$

where $\tau = 1/k$ is a characteristic time constant, i_{c0} is an initial value of i_c. From this equation, it is clear that the every coil current has the same response and the balance of the coil currents are kept during the transient.

The control gain k deciding the system response has upper limit decided by the stability. This limit is determined due to the control theory as $k < 2\pi f_c/4$, where f_c is a cut-off frequency of a low pass filter inserted to reduce noise.In the LHD power system, the f_c is selected as 0.87 Hz, therefore the upper limit of k becomes 1.3.

The *P* control scheme is obtained by setting of R_c = 0 in the equation (3). In this *P* control, the steady state

Table 1 Estimated parameters of superconducting coil system of LHD

a) Coil inductance matrix L[H]

	HO	HM	HI	OV	IS	IV	C1	C2	C3	C4
HO	1.343	1.206	1.052	0.466	0.355	0.237	0.874	0.648	0.706	–0.24
HM	1.206	1.279	1.156	0.464	0.335	0.238	0.858	0.646	0.692	–0.24
HI	1.049	1.154	1.260	0.462	0.325	0.238	0.767	0.611	0.657	–0.21
OV	0.458	0.456	0.455	1.258	0.285	0.144	0.670	0.840	-0.140	0.485
IS	0.329	0.329	0.329	0.284	0.953	0.251	0.405	0.550	0	–0.15
IV	0.233	0.233	0.234	0.142	0.250	0.744	0.278	0.453	0	–0.15
C1	0.875	0.858	0.767	0	0	0	1	0	0	0
C2	0	0	0	0.840	0.550	0.430	0	1	0	0
C3	0.706	0.692	0.657	0	0	0	0	0	1	0
C4	0	0	0	0.485	0	0	0	0	0	

Table 2 Comparison of the current control system

Control scheme	P $k = 0.1$	P $k = 0.1$	PI $k = 0.1$	H∞(1)	H∞(2)
Size of x_c	6	6	12	33	86
Numbers of parameters	84	84	156	1755	9,016
Steady state control error	0.1%	0.01%	< 0.01%	< 0.01%	< 0.01%
Response time constant	10 s	1 s	1 s	< 0.3 s	< 0.3 s

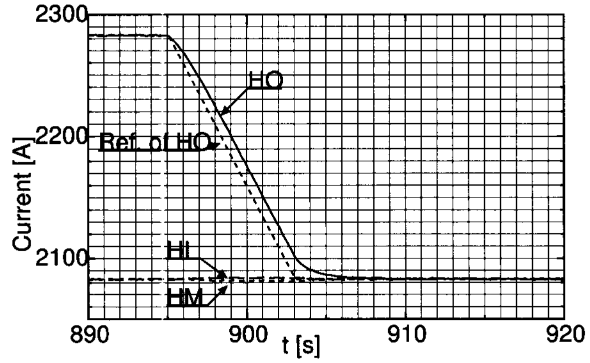

Fig. 2 Ramp response of the power supply when *P* controller with $k = 1$ is applied.

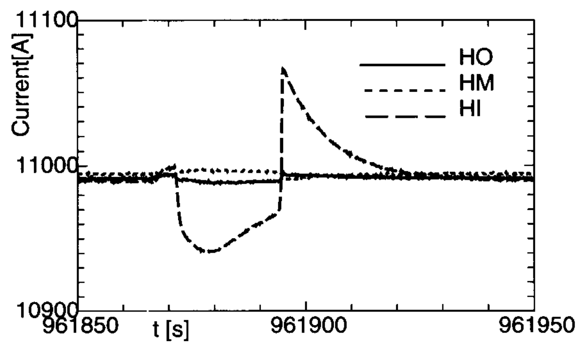

Fig. 3 Reaction caused by a plasma current. *P* controller with $k = 0.1$ is used.

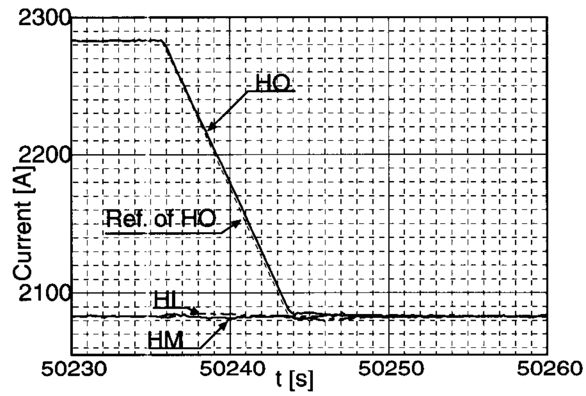

Fig. 4 Ramp response of the power supply when $H\infty(1)$ control is applied.

control error $i_e = i_c^* - i_c$ remains as following;

$$i_e = (kL_c)^{-1} \cdot R_c \cdot i_c^* \,. \tag{5}$$

In this system, i_e may become about 0.01% of i_c^* when $k = 1.0$ because the orders of R_c and L_c are 10^{-4} and 1, respectively.

Table 2 shows the system size and some characteristic parameters for each control system. The $H\infty(1)$ and $H\infty(2)$ controllers are described later. When we use the *P* control, $k = 1$ is necessary to satisfy the requirements for control error and response time as shown in the table. Figure 2 shows a ramp response of the *P* controller with $k = 1$. In this figure, the HO current reference is swept and the other current references are kept constant. The HO current traces its reference with 1 s delay and the disturbance of the other currents are less than 2A. With this result, the independent current control for each coils are confirmed. For the *PI* controller, a similar result is observed.

Figure 3 shows the reaction caused by the plasma current when the *P* controller with $k = 0.1$ is used. In this figure, the reaction is observed only on HI coil because the fast changing of the magnetic flux is shield by the HI coil current. For the *P* controller with $k = 1.0$ and *PI* controller, the experiments with a plasma are not executed yet.

5. *H*∞ Controller

In the *PI* controller mentioned above, the control gain is limited by the stability requirement, which means the response time constant cannot become so small. The $H\infty$ design scheme is one of the solutions to manage both the robustness and fast response. We designed two types of $H\infty$ controller for the LHD power system [3]. One, aiming $H\infty(2)$, realizes the robustness and fast response, but its size is large as shown in Table 2. The other, aiming $H\infty(1)$, is compact rather than the former one. These controllers realize the high accuracy and the fast response for the current control as shown in Table 2. Figure 4 shows a ramp response of the $H\infty(1)$ controller. For the $H\infty(2)$ controller, a similar response is observed. When this figure is compared with Fig. 3, it is clear that the $H\infty$ control realizes the better response than P or PI controller. Figure 5 shows the reaction caused by a plasma current with the $H\infty(1)$ control. This figure shows that the shielding effect by HI coil becomes weak, because the control response is much faster than the P control. For the $H\infty(2)$ controller, the plasma experiments is not executed yet.

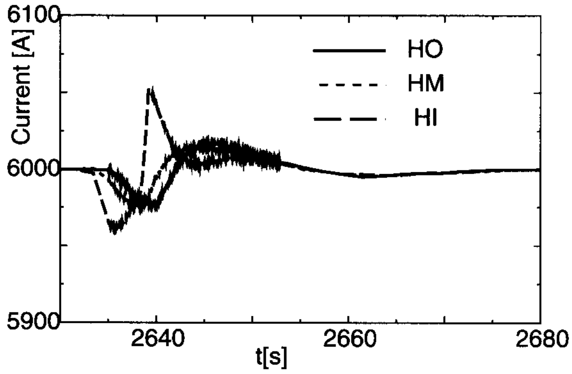

Fig. 5 Reaction caused by a plasma current. $H\infty(1)$ control is applied.

6. Summary

This paper describes the current control system in the LHD dc power system. To design the current controller, the electrical parameters of the coil system are estimated and some types of the controllers are designed. The test results show that these controllers are stable and satisfied requirements. The reaction caused by the plasma current is different for each control system, and the effect of different control response to the plasma characteristics will be studied.

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