DC Power System for Superconducting Coils of Fusion Plasma Test Facility LHD

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Keywords: magnetic coupling, current control, dc power supply, LHD, H_∞ control

The Large Helical Device (LHD) operating at the National Institute for Fusion Science (NIFS) is a fusion experimental facility based on a set of superconducting coils. The size of the LHD is about 16 m in diameter and 8 m in height, and it is also the largest superconducting machine in the world under operation. This machine has twelve superconducting coils to form the magnetic field to confine plasma and six power supplies to magnetize the coils. The output voltages of power supplies are only 33 V or 45 V in spite of the large operating current of from 16 kA to 24 kA. So we use a 12-phase double star connected thyristor rectifier for each power supply. For the power supplies, following terms are required to this power system.

- Current measurement error is less than (0.03% of reading value + 4.5 A)
- Steady state current control error is less than (0.04% of set value + 6 A)
- Current overshoot at normal ramp up rate is not allowed
- Settling time for 0.1% is less than 1 s for normal ramp-up rate

In the design of a control system, the electrical parameters of the superconducting coil system are required to determine the control gains. The inductance matrix of superconducting coils and structures was measured from the coil terminals. Also the mutual inductance between plasma and coils are important and we estimate them using coil current deviations induced by plasma current.

For the LHD power supplies, we designed and tested five control schemes as following.

PI or P control They are simple but stable controller. The time constants of all current responses are same and the current balance is kept constant while currents are changing. But the control gain is limited by stability condition, the better response is difficult to built.

H_∞ control

advanced H_∞ control (1) This controller has a feed forward using plasma current signal and keep the coil currents constant even if the plasma current flows in the device.

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

advanced H_∞ control (2) This control keep interlinked magnetic flux constant and allows the coil current deviation when plasma current flows in the LHD.

advanced P controller This controller includes current error observer to cancel the steady state error and the feed forward of $L di_c/dt$ to make current response better.

The operator of LHD power system can select one of these control schemes even if the power supplies are exciting the coils. With this ability, the power system becomes more useful for plasma experiments.

Figure 1 shows an example of operation using the $H_\infty(1)$. This current controller keeps current constant while the plasma burning. The coil currents and terminal voltages are not disturbed so large when plasma discharge is finished.

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The Large Helical Device (LHD) is an experimental facility for fusion plasma using a large scale mutually coupled superconducting coil system and it is now operating at the National Institute for Fusion Science. This paper introduces the design and the operation results of the dc power systems to drive these coils. First, the outline of the LHD and the power supplies are described. Next, a control system and the current controller for the power supplies are introduced. Finally, some experimental results are introduced.

Keywords: magnetic coupling, current control, dc power supply, LHD

1. Introduction

The Large Helical Device (LHD) that is operating at the National Institute for Fusion Science (NIFS) is a fusion experimental facility using superconducting coils. The size of the LHD is about 16 m in diameter and 8 m in height, and it is also the largest superconducting device in the world under operation. This device has twelve superconducting coils to form the magnetic field to confine plasma⁽¹⁾⁽²⁾. The strength of the magnetic field is 3 T at the plasma center and amount of stored energy reaches to 1 GJ.

In the following sections, first we describe the outline of LHD and its operation scenario. Next, we present the design of the power supplies, which consist of thyristor rectifiers, dc filters and a computer control system. After that, the current control schemes are described and some operation results for each control scheme are introduced.

2. Outline of the LHD and its Operation

Figure 1 shows a cross section of LHD that includes superconducting coils. The LHD has six poloidal coils designated as OV-L, OV-U, IS-L, IS-U, IV-L, and IV-U, and two helical coil sets designated as H1 and H2, as displayed in the figure⁽³⁾. Each of the helical coils is divided in three sections

Fig. 1. Cross section of the LHD

wound in the same coil case as shown in Fig. 2.

The LHD project was planned in the following two phases. In the phase I operation, LHD operates in steady state with a magnetic field of 3 T at the plasma center, and in the next phase, the project is planning the experiments with a higher magnetic field of 4 T at the plasma center and dynamic swing of the coil currents. The current power system is designed and constructed based on the phase I operation.

The twelve coils of LHD form three poloidal coil pairs and three helical coil pairs designated as OV, IS, IV, HO, HM and HI coils respectively.

Usually, the coil power supplies start magnetization of superconducting coils in the morning, and they stop in the evening. Therefore, the coil currents flow through the day,

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Fig. 2. Cross section of a helical coil

and the experimental group changes the experimental condition without stopping excitation⁽⁴⁾.

For this operation, the plasma experimental division presents the following requirements.

- (1) Magnetic field error meaning the deviation from the designed value should be less than 10^{-4} to control the plasma position in a few millimeters.
- (2) The ramp-up time from zero to the rated current and fall time from the rating to zero are less than 40 minutes.
- (3) Magnetic field configuration can be changed within 5 minutes.

These requirements are related to the accuracy of current control and the output voltage.

3. Outline of Power Supplies of LHD

3.1 Main Circuits of Power Supplies Figure 3 shows the main circuits of the dc power supplies for steady state excitation for HO and OV coil sets. Similar power supplies are constructed for other coil sets. Table 1 shows the specifications of the power supplies. In this table, the output currents for poloidal coils were set to those of phase I operation to reduce the initial cost of the power supplies.

The output voltages of power supplies are only 33 V or 45 V in spite of the large operating current of from 16 kA to 24 kA. In a low voltage system like this, the voltage drop in the circuit, especially forward drop in the thyristors, should be reduced as possible. So we use a 12-phase double star connected thyristor rectifier for each power supply as shown in Fig. 3.

In the LHD plasma experiments, the coil currents flow unidirectionally except the IS coil, so the power supplies are based on a single rectifier. For the IS coil, the current reverses in some magnetic confinement and mode changes related to these confinements occur infrequently. In some plasma operations, the reverse currents are required. Therefore, we decided to use a mechanical cross switches in the power supply to reverse the coil currents.

For the LHD superconducting coils, the coil diagnostic device requires sufficiently small ripple for terminal voltage to make a high quality quench detection signal. To satisfy this requirement, the power supply includes a passive dc filter at the DC output of the rectifier. Although this filter may obstruct a quick response of current control, it is not a severe

Fig. 3. Diagram of the power supplies for LHD

Table 1. Rating of power supplies for steady state operation

	HO, HM, HI	OV	IS	IV
Voltage	45 V	33 V	33 V	33 V
Current	17.3 kA	23.5 kA	16.3 kA	15.7 kA

problem. Because the LHD operates in the steady state now and the current change is sufficiently slower than the filter response. We select the cut-off frequency as 50 Hz, that is about one tenth of the ripple frequency of 720 Hz and it is sufficiently high compared with the current change rate.

The resonance frequency of the filter capacitor and the load coil is on the order of 1 Hz and is much lower than rectifier control response frequency. Therefore, a current regulator introduced in the following section can suppress this resonance.

4. Control System for Power Supplies

Figure 4 shows the structure of a computer subsystem for the steady state power supplies. Each power supply has a current sensor and a local feedback loop and it controls the output voltage to track the voltage reference generated by the current controller. This local controller compensates the error such as a voltage drop in the circuit or a change in line voltage then the power supply works as an ideal controlled voltage source. One real time computer controls 3 power supplies for helical coils and another one controls 3 power supplies for poloidal coils. A supervisor workstation serves user interface and development environment. A remote terminal set in the LHD main control room also can operate the control system and usually an operator commands via this terminal. This computer block is linked with LHD control system using Ethernet and a real time plasma control computer with a high-speed optical link. With these computers, the operating coil current can be set automatically.

5. Current Controller

In this section, we describe the current control. The performance required to the regulator is shown in Table 2. The required accuracy shown in this table means that the steady state control error must be less than 0.01% of set value +1.5 A.

A control program controlling all power supplies, is installed in a computer system that connected to the power supplies with communication lines. This program keeps 8

Fig. 4. Block diagram of the computer system of LHD power system

Fig. 5. Reaction caused by plasma current

Table 2. Requirements for current control system

Current measurement error	less than (0.03% of reading value +4.5 A)
Steady state current control error	less than (0.04% of set value +6 A)
Current overshoot at normal ramp up rate	not allowed
Settling time for 0.1%	less than 1 s for normal ramp-up rate

Table 3. Estimated parameters for superconducting coil system of LHD

	(a) Inductance matrix [H]										(b) Resistance of passive circuits [Ω]			
	HO	HM	HI	OV	IS	IV	C1	C2	C3	C4	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	1.68	1.64	16.9	16.9
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	1				

different current controllers and each controller is described with state vector as following;

$$sX_c = A_c \cdot X_c + B_c \cdot \begin{bmatrix} I_c^* \\ I_c \end{bmatrix} \dots\dots\dots (1)$$

$$V_c^* = C_c \cdot X_c + D_c \cdot \begin{bmatrix} I_c^* \\ I_c \\ sI_p \end{bmatrix} \dots\dots\dots (2)$$

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 , I_p and V_c^* denote the current reference, the actual coil current, plasma current and the output voltage reference, respectively.

6. Parameter Estimation of Coil System

In the design of a control system, the electrical parameters of the superconducting coils are necessary to determine the control gains mentioned above. The inductance matrix of superconducting coils and structures was measured from the coil terminals⁽⁶⁾, and they are obtained as Table 3.

In the table, from C1 to C4 are equivalent circuits, which show coupled structures. This inductance matrix is asymmetric and some terms are negative. If a current flowing C1, C2, C3 and C4 are real current the matrix should be symmetric, but they are imaginary coils and the asymmetric matrix makes no problem to design a current controller.

Essentially helical type fusion plasma does not require plasma current but some operations with plasma current are

useful to study plasma dynamics. With this reason, some plasma experiments in LHD make plasma current. For these experiments and some coil current controllers requires mutual inductance between coils and plasma. But the plasma has a large cross section and current density in the plasma is difficult to calculate. Therefore, we estimate the mutual inductance using experimental results.

Figure 5 shows the induction caused by the plasma current when the P controller with $k = 0.1$, which will be mentioned in the following section, is used. In this figure, the curve of plasma current does not return to zero after a plasma operation because the signal of di_p/dt becomes too large and it exceeds the input signal range of the control system.

In this shot, the plasma current rises to 55 kA in 10 seconds and shuts down suddenly. When the plasma current disrupts, its induction increases the HI coil current.

Figure 6 shows plots of the coil current deviation when plasma experiments with plasma current were done. The horizontal axis is for the HI coil and the vertical axis is for the IV coil. The point of $I_{HI} = 11.0$ kA and $I_{IV} = 11.2$ kA shows a steady state operation point. The plots exist surround a line with slope of 0.324 as shown in the figure. This means that the ratio of mutual coupling between plasma, HI and IV coils is constant, and the plasma can be described with a one turn coil for the control system design.

The mutual inductances between plasma and coils are estimated by the following way.

When plasma current disrupts, the interlinked fluxes to the

Fig. 6. Plots of the coil current deviation

Table 4. Mutual inductance between coils and plasma [unit mH]

HO	HM	HI	OV	IS	IV
1.60	1.69	1.80	1.05	0.88	0.67

coils are almost constant because the time constant of the coil current control is enough longer. Therefore circuit equation in this situation is described as follows;

$$\Delta\psi = L_c \Delta i_c + M_{cp} \Delta i_p = 0 \quad (3)$$

where L_c , M_{cp} , Δi_c , Δi_p and $\Delta\psi$ are self-inductance of coils, mutual inductance between coils and plasma, coil current deviation, plasma current deviation and change of interlinked flux respectively. From this equation, M_{pc} can be calculated as following;

$$M_{pc} = -L_c \Delta i_c / \Delta i_p \quad (4)$$

Table 4 shows the estimated mutual inductances and they are about two third of calculated value which are obtained using a model that assumes a line current at the plasma center.

7. Basic Current Control Schemes

In this section, the basic current control schemes for LHD power system are described.

7.1 PI Controller First, the *PI* control scheme, which does not use a signal of plasma current, is designed for this system. 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;

$$V_c^* = \frac{k}{s} R_c (I_c^* - I_c) + k L_c (I_c^* - I_c) \quad (5)$$

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;

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

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

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

$$I_c = I_{c0} + \frac{1}{1 + s\tau} (I_c^* - I_{c0}) \quad (6)$$

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 (5). In this *P* control, the steady state control error $I_e = I_c^* - I_c$ remains as following;

$$I_e = (k L_c)^{-1} \cdot R_c \cdot I_c^* \quad (7)$$

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 5 shows the system size and some characteristic parameters for each control system. The H_∞ control and advanced control schemes will be 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 7 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 2 A. With this result, the independent current control for each coils are confirmed. For the *PI* controller, a similar result is observed.

In the other viewpoint, the eddy current flowing in the structures changes when the coil current reaches to steady state value. This eddy current induces a noise signal to quench detector, and it becomes larger if the corner of the coil current waveform is too sharp. The low gain *P* controller makes soft landing of coil current to the steady state, and they causes only low induced voltage to the quench detector. Also the low gain *P* control scheme has following advantages; it is very stable, terminal voltage ripple is small and the induced noise to quench detector is also small. With these reason, the *P* controller with $k = 0.1$ is used in usual plasma experiments even though it does not satisfy the specification of accuracy and settling time.

7.2 H_∞ Controller In the *PI* controller mentioned above, the control gain has limitation because of the stability requirement. The H_∞ using μ -synthesis design scheme is one of the solutions to manage both the stability and fast response⁽⁵⁾. The H_∞ controller using μ -synthesis design method has robustness for control performance as well as stability and uncertainty of the controlled subject can be taken into consideration.

In Fig. 8, P shows the controlled object, i.e., LHD coils, K shows the controller obtained by the H_∞ theory, and G_m shows a transfer function to determine the output response of coil current to the current reference. The G_m should be specified properly to get the desired output characteristics. In this controller, the feed forward controller calculates the coil voltage required to follow the current reference. The response of coil current to various disturbances can be determined by the feedback controller K . This control scheme can determine

Table 5. Comparison of the current control system

Control scheme	Basic control scheme				Advanced control scheme		
	P $k=0.1$	P $k=1$	PI $k=1$	H_∞	$H_\infty(1)$	$H_\infty(2)$	Advanced P control $k=0.1$
Size of X_c	6	6	12	56	62	68	18
Numbers of parameters	84	84	108	4,200	5,028	5,984	186
Steady state control error	0.1%	0.01%	< 0.01%	< 0.01%	< 0.01%	- (*1)	< 0.01%
Response time constant (*2)	10 s	1 s	1 s	< 0.3 s	< 0.3 s	< 0.3 s	1 s

(*1) There is a current drift and steady state error cannot be defined.

(*2) For the major components. There are longer time constant components in some scheme but their amplitude is small enough.

Fig. 7. Ramp response of the coil current with P control ($k = 1$) Fig. 8. Block diagram of H_∞ control for LHD power supply

response characteristics to disturbances and current reference independently, so it is called as two-degree-of-freedom control scheme. The function of $G_m(s)$ was chosen $g_m(s)U$. Then $G_m(s)$ becomes a diagonal matrix and the interaction of each coil current can be avoided by the zero component of this matrix. The $g_m(s)$ was chosen as $g_m = \{8/(1 + 8s)\}^2$ from the simulation results of the closed loop controller to get the fastest response without overshoot for stepwise current reference.

The H_∞ controller was designed as follows. A block diagram of the design problem is shown in Fig. 9. P_n shows the nominal model of the plant, W_a shows the frequency weighting function for modeling error, W_M shows the frequency weighting function for disturbance, Δ shows the additive modeling error, Δ_F shows the fictitious uncertainty which introduces disturbance. W_a and W_M are diagonal matrix and in the relation of trade off each other. We made some simulations and set the weighting functions as shown in Fig. 10 for this power supply. The gain and phase characteristics of the H_∞ controller is shown in Fig. 11.

Figure 12 shows a ramp response of the H_∞ controller designed for LHD and it is clear that the H_∞ control realizes the better response than the PI controller.

Fig. 9. Block diagram for H_∞ control design Fig. 10. Gain characteristics of weighting function W_M and W_a Fig. 11. Gain and phase characteristics of the H_∞ controller

8. Advanced Current Control Schemes

In the previous section, basic PI and H_∞ control schemes are described. These control schemes are stable enough but could not suppress the coil current deviation caused by the plasma current even if the H_∞ control was applied. To resolve the problem, we designed advanced controllers based on the H_∞ control.

On the other hand, the P control with low control gain K is also useful mentioned above. A current error observer and feed forward control are useful to improve the current

Fig. 12. Ramp response of the coil current with H_{∞} control

Fig. 13. Block diagram of $H_{\infty}(1)$ controller

Fig. 14. Block diagram of $H_{\infty}(2)$ controller

response and steady state error. Then we also designed one advanced controller based on the P control.

8.1 Advanced H_{∞} Controllers The information of the plasma current is useful to reduce the interaction to the coil currents from the plasma current. Then we designed two types of advance H_{∞} controllers, which use the plasma current signal and have different characteristics, for the LHD power system.

One, named $H_{\infty}(1)$, is designed to keep the coil currents constant even if the plasma current is excited. The block diagram is shown in Fig. 13. This controller uses the plasma current detected by Logowski coil to generate feed forward term for the coil voltage. A non-linear LPF inserted to limit the level of Logowski coil output as shown in the figure. The other one, named $H_{\infty}(2)$, is designed to keep magnetic flux constant while a plasma experiment. This controller estimates the coil current deviation induced by change of plasma current and allows the deviation. Figure 14 shows a control diagram of $H_{\infty}(2)$ controller. With the $H_{\infty}(2)$ control, the coil currents may be changed when plasma current is excited but the terminal voltages will be kept as almost zero.

Figure 15 show the waveforms of coil currents (HO, HM,

Fig. 15. Voltage and current waveforms with $H_{\infty}(1)$ control scheme

Fig. 16. Voltage and current waveforms with $H_{\infty}(2)$ control scheme

HI), plasma current I_p , coil terminal voltages (HO, HM, HI) and calculated plasma induced voltage V_p using the $H_{\infty}(1)$ control. Also Fig. 16 shows the waveforms using the $H_{\infty}(2)$ control. In these experiments, we wanted to show the effect to the plasma current caused by coil current controllers and the non-linear LPF was not used to make simple the response. Figure 15 shows that the controller kept coil currents constant while plasma current ramp up and it reached flattop. When the plasma breaks, the dI_p/dt signal becomes too large and the calculated output voltage exceeded the maximum

Fig. 17. Current waveforms with $H_\infty(1)$ control scheme Fig. 18. Current waveforms with $H_\infty(2)$ control scheme

output voltage of the power supplies. With this reason the controller was disturbed and the coil currents show some transient waveforms but it did not cause any instability. In Fig. 16, the controller keeps the interlinked magnetic flux and the coil current show some deviations. As shown in the figure, the coil terminal voltages were almost zero because the interlink flux were not changed. When this scheme was applied to the LHD, it is clear that the rebound of coil current when the plasma shut down was smaller than the case of Fig. 15, and coil currents returned to their references immediately. With comparing these two operation, the induced voltage to a plasma when the i_p ramps up and ramp up rate of i_p are different. When $H_\infty(2)$ was used, the induced voltage becomes larger and plasma current ramp up faster. In the figures, $t = 10$ s, a plasma heating device was changed. At this point, the plasma current and induced voltage changed larger when $H_\infty(2)$ control was used.

Figures 17 and 18 show the current waveforms when the $H_\infty(1)$ and $H_\infty(2)$ control schemes with non-linear LPF were used. The non-linear LPF clipped the peak of sI_p signal and the calculated output voltage did not exceed the rated output voltage. Therefore the coil currents and terminal voltages were not disturbed when plasma discharge is finished. In Fig. 18, the coil current drifted while plasma discharged in the operation. A dc offset voltage of the non-linear LPF causes this drift. Even though the long-term operation using this control scheme is difficult with this drift, usual plasma experiments are shorter than 30 s and this scheme can be applied.

8.2 Advanced P Control The last control scheme is advanced P control using additional a current error observer and feed forward shown as in Fig. 19.

Comparing this control scheme with PI control or H_∞

Fig. 19. Block diagram of an advanced P control scheme Fig. 20. Ramp response of the coil current with advanced P control ($k = 0.1$)

control scheme, the limiter to the observed error can be inserted at the observer output. With this limiter, the large turbulence caused by a spike noise in the current data can be avoided.

Figure 20 shows a result of current ramp test of this controller. As the result shows, this controller has satisfies the requirements for the response and the steady state error even if the control scheme is more simple than the H_∞ control schemes.

8.3 Dynamic Swapping of Current Controller In usual plasma operations, the P control scheme with $K = 0.1$ is used. For some LHD plasma experiments such as a plasma current feedback operation, this controller cannot satisfy requirements of dynamic characteristics and it is necessary to change the control scheme. Therefore we install ability of dynamic swapping of current controller in the control program.

To swap a control scheme, the program must initialize the internal variables in the controller to a suitable value to avoid the large transients

When the control system is in steady state and a current control error is small enough, $sX_c = 0$ and $I_c^* = I_c$ are kept in the equation (1). Then the state variable X_c becomes as following;

$$X_c = [U - A]^{-1}[B_1 + B_2]I_c^* \dots \dots \dots (8)$$

This X_c is used as an initial value.

For PI control scheme, matrix A is singular and X_{c0} cannot be calculated with above equation. In this case, the state equations are transformed into following form and initial vector X_{c0} is calculated;

$$\begin{bmatrix} \dot{X}_c \\ \dot{X}_i \end{bmatrix} = \begin{bmatrix} A_1 & A_2 \\ A_3 & U \end{bmatrix} \begin{bmatrix} X_c \\ X_i \end{bmatrix} + [B_1, B_2] \begin{bmatrix} I_c^* \\ I_c \end{bmatrix} \dots \dots \dots (9)$$

Fig. 21. Swap of control scheme from usual P controller to a high gain P controller

$$V = [C_1 C_2] \begin{bmatrix} X_c \\ X_i \end{bmatrix} + [D_1, D_2] \begin{bmatrix} I_c^* \\ I_c \end{bmatrix} \dots\dots\dots (10)$$

$$\begin{bmatrix} X_{c0} \\ X_{i0} \end{bmatrix} = \begin{bmatrix} [U - A_1]^{-1} [B_1 + B_2] I_c^* \\ 0 \end{bmatrix} \dots\dots\dots (11)$$

Figure 21 shows the current waveforms when control scheme was swapped from a P controller with $K = 0.1$ to the P controller with $K = 1.0$. Even though the P control with $K = 0.1$ causes a steady state error, the control scheme can be changed without any turbulence. and it becomes an initial offset for high gain controller, each control scheme is stable enough and it did not make any problem.

With this ability of swapping the current control scheme even if the coils are magnetized, the power system becomes more useful for plasma experiments.

9. Conclusions

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 several types of the controllers are designed and tested. The test results show that these controllers are stable and perform required characteristics. The control scheme can be selected with regard to the requirements from plasma experiment. The developed current control systems will contribute to the study on the plasma response characteristics under different coil current controls.

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