Current Control of Superconducting Coils for Fusion Experimental Facility

Toshifumi Ise 1), Daisuke Etou 1),
Hirotaka Chikaraishi 2), Shigeyuki Takami 2), Tomoyuki Inoue 2)

1) Dept. of Electrical Engineering, Graduate School of Engineering, Osaka University, Japan
2) National Institute for Fusion Science, Japan

E-mail address of main author: ise@pwr.eng.osaka-u.ac.jp

Abstract: The LHD (Large Helical Device) has twelve superconducting coils and six dc power supplies, and following specifications are required for its control system; each coil current must be controlled independently, the steady state control error is less than 0.01 % of the reference 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 appearance and disappearance of the plasma, parameter errors and external electro-magnetic noises. In this paper, the design and test results of the coil current control system for the LHD are described. The good response and robustness are in the relation of trade off each other. H-infinity controller is one of schemes to guarantee robustness for stability. However, the independent responses of six coils were impossible by the H-infinity ontroller only. To resolve this problem, we applied a feed-forward control with the H-infinity control. Moreover, the advanced design method of H-infinity controller using μ-synthesis was applied to guarantee the control performance in the whole operating condition. As a result, good control results were btained by experiments.

1. Introduction

In the large-scale fusion facility, the superconducting coil system is divided into several coils because of requirements of the apparatus. These coils, which have strong electromagnetic coupling with each other and structural material, will be excited by separated power supplies. For example, the Large Helical Device (LHD) is a nuclear fusion experimental system with two superconducting helical coils and three pairs of superconducting poloidal coils. All coils are coupled very closely to each other. Moreover, plasma, vacuum vessel, helical coil can and coil support can be seen as one-turn coils around superconducting coils which are magnetically coupled with the superconducting coils and give disturbances to the coil current control performance. Under these difficult situations, the coil current must be controlled accurately and independently, hence, a conventional controller such as PID is not enough to get required control performance.

From the above point of view, application of H-infinity controller using μ-synthesis design method with feed forward controller has been studied by authors. The H-infinity controller for LHD was designed and simulations were carried out. The designed controller was applied to the LHD system. Experimental results with the developed controller showed faster response and lower voltage ripple than previously developed current controllers. The configuration and characteristics of the developed controller are presented with some experimental results.

2. Configuration of the Power Supply and Requirements for the Current Controller

2.1 Configuration of the Power Supply

The coil system of LHD consists of two superconducting helical coils; H1 and H2, three pairs of superconducting poloidal coils; Outer Vertical coils (OV-U and OV-L), Inner Shaping coils (IS-U and IS-L) and Inner Vertical coils (IV-U and IV-L), a plasma vacuum vessel, cryogenic supporting structures and a torus-shaped cryostat. Each of the two superconducting helical coils; H1 and H2 are composed of three superconducting blocks, H1(H2)-O, H1(H2)-M, and H1(H2)-I. The H1 and H2 coils are connected in series as shown in Fig.1. The current of three sets of helical coils HO, HM and HI are controlled by using three independent power supplies in order to change the aspect ratio of the plasma. The two pair of poloidal coils, for example OV-U and OV-L, are connected in series as shown in Fig.1. These three sets of poloidal coils are also controlled by three sets of independent power supplies. The coils are controlled by six power supply units, and each unit has two sets of double-star thyristor rectifiers connected in parallel, a dc passive filter and a quench protection system, as shown in Fig.2[1].

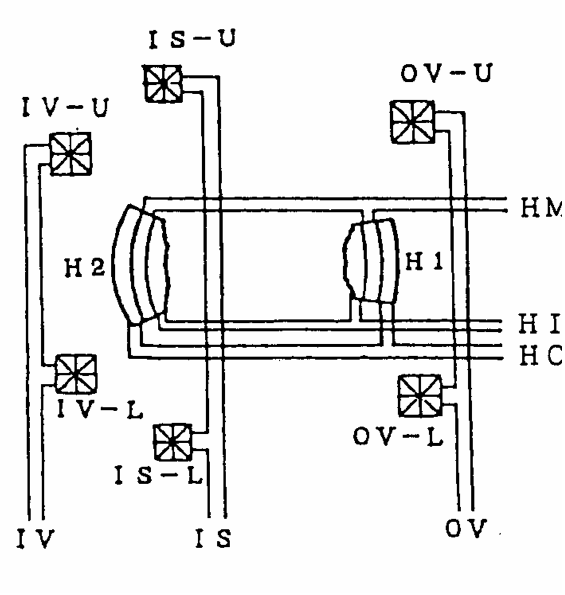


FIG.1. Electrical connection of coils.

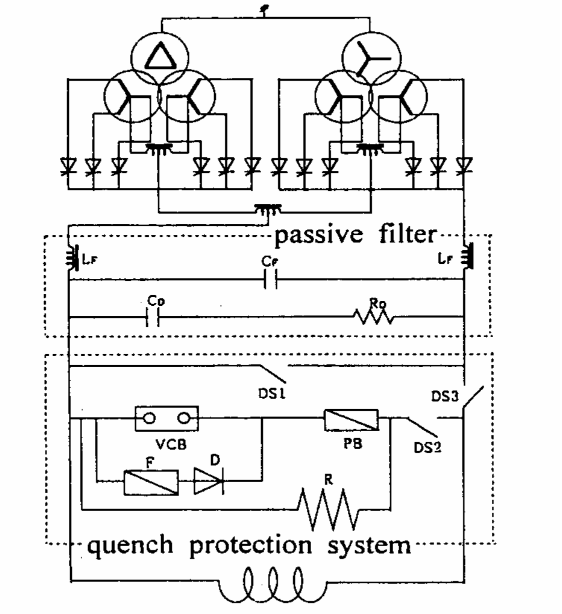


FIG.2. Circuit of each power supply.

2.2 Requirements for the Current Controller

One of requirements for the current controller of the system is precise control. The required accuracy of the superconducting coil current at steady state is within 0.01% and response time, in which each coil current reaches the specified value with 0.1% accuracy is within 1sec under the condition of strong mutual coupling between coils. Table I shows the measured inductance matrix of the coils[2]. Strong mutual couplings exist as shown in Table I.

The second requirement for the current controller is that it should be robust for disturbances.

TABLE I: MEASURED INDUCTANCE MATRIX (UNIT IN H).

	HO	HM	HI	OV	IS	IV	ST1	ST2	CC1	CC2
HO	1.3433	1.2061	1.0520	0.46636	0.35536	0.23722	0.8745	0.648	0.706	-0.24
HM	1.2058	1.2789	1.1559	0.46398	0.33502	0.23759	0.8579	0.646	0.692	-0.24
HI	1.0493	1.1536	1.2597	0.46191	0.32493	0.23811	0.7670	0.611	0.657	-0.21
OV	0.45768	0.45577	0.45458	1.2582	0.28507	0.14420	0.67	0.840	-0.14	0.485
IS	0.32895	0.32913	0.32906	0.28449	0.95346	0.25066	0.405	0.550	0	-0.15
IV	0.23295	0.23330	0.23424	0.14199	0.24926	0.74385	0.278	0.4530	0	-0.15
ST1	0.8745	0.8579	0.7670	0	0	0	1	0	0	0
ST2	0	0	0	0.840	0.550	0.430	0	1	0	0
CC1	0.706	0.692	0.657	0	0	0	0	0	1	0
CC2	0	0	0	0.485	0	0	0	0	0	1

Vacuum vessel, helical coil can and coil support. are considered as one-turn coils electrically, and cause disturbances for the controller due to mutual couplings between actual coils and these equivalent one-turn coils. The artificial coils of ST1, ST2, CC1, and CC2 in Table I were modeled as equivalent coils due to these equivalent one-turn coils. Appearance and disappearance of plasma was considered as disturbance for the controller. The third requirement is that overshoot of coil current is not allowed in the transient state in order to avoid quenching of superconducting coils.

3. Design of the Controller

As a current controller to satisfy above requirements, application of an H-infinity controller using μ-synthesis design was studied. The current controller was designed with the feedback plus feed forward system as shown in Fig.3. The H-infinity 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 [3]. The circuit parameters of LHD system shown in Table I was obtained by approximation, and actually has some non-linearity caused by the changing of current distribution for higher frequency in vacuum vessel, helical coil can and coil support which are magnetically coupled with superconducting coils. These non-linearity can be taken into consideration by using H-infinity controller as model uncertainty. Control performance for disturbances due to appearance and disappearance of plasma was also considered. On the other hand, mutual coupling between coils are decoupled by the feed forward controller shown in Fig.3. In Fig.3, "P" shows the controlled object, i.e., LHD coils, "K" shows the controller obtained by the H-infinity theory using μ-synthesis design method, 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 controller can determine response characteristics to disturbances and current reference independently, so it is called as two-degree-of-freedom controller. The function of $G_M(s)$ was chosen as follows:

$$G_M(s) = \begin{pmatrix} g_m & 0 & 0 & 0 & 0 & 0 \\ 0 & g_m & 0 & 0 & 0 & 0 \\ 0 & 0 & g_m & 0 & 0 & 0 \\ 0 & 0 & 0 & g_m & 0 & 0 \\ 0 & 0 & 0 & 0 & g_m & 0 \\ 0 & 0 & 0 & 0 & 0 & g_m \end{pmatrix} \qquad (1).$$

$$g_m(s) = \left\{ \frac{8}{s+8} \right\}^2$$

The interaction of each coil current can be avoided by the zero component of the matrix $G_M(s)$. The component $g_m(s)$ was chosen from the simulation results of the closed loop controller to get the fastest response without overshoot for stepwise current reference.

The gain and phase characteristics of the obtained controller are shown in Fig. 4. Fig.4(a) shows characteristics of the H-infinity controller "K" in Fig.3. The gain of the obtained H-infinity controller in high frequency region is low. The controller has less sensitive response to disturbances due to this characteristic. Fig.4(b) shows the gain characteristics of the whole controller shown in Fig.3, that is, the response from current reference to the input of "P" block in Fig.3. The feed forward block speeds the response to changes of current reference.

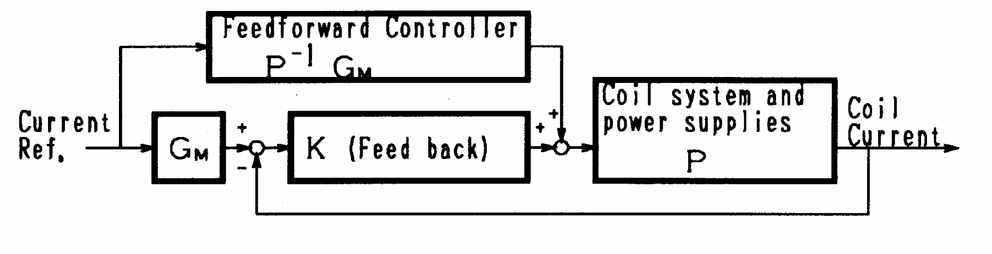
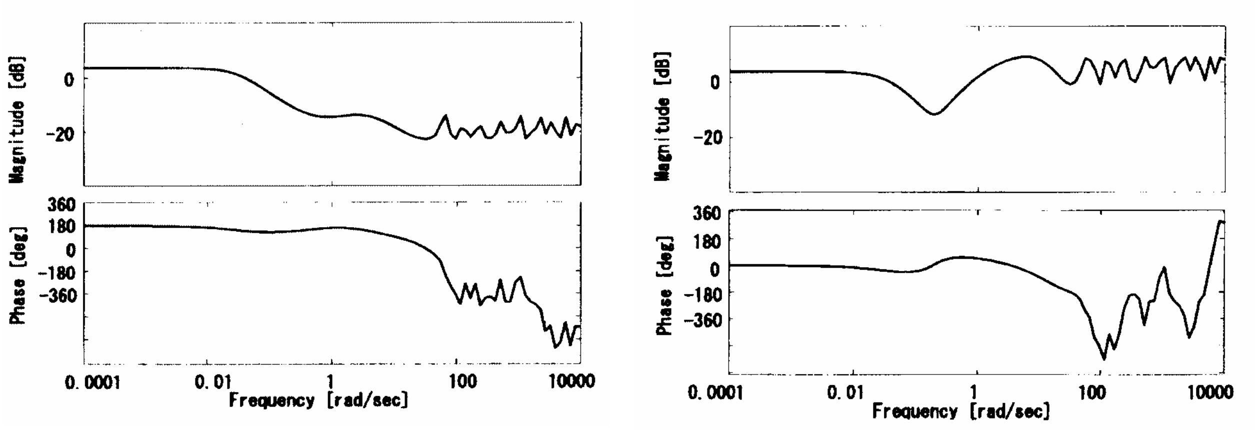


FIG.3. Configuration of the controller.



(a) From coil current to input of “P” (b) From current reference to input of “P”

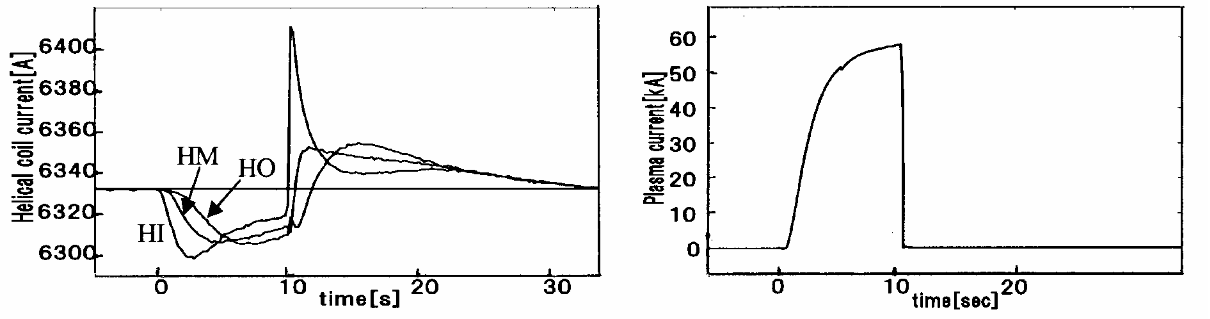
FIG.4. Gain and phase characteristics of the designed controller.

4. Experimental Result and Concluding Remarks

Fig.5(a) shows an experimental result using the H-infinity controller with feed forward. Plasma current, which was about 58 kA at its peak as shown in Fig.5(b), was driven by the plasma heating and it induced current change of 30A for HI coil, which is one set of the helical coils. Fig.6 (a) shows experimental result by using the proportional controller. From the comparison of these results, the H-infinity controller showed faster response.

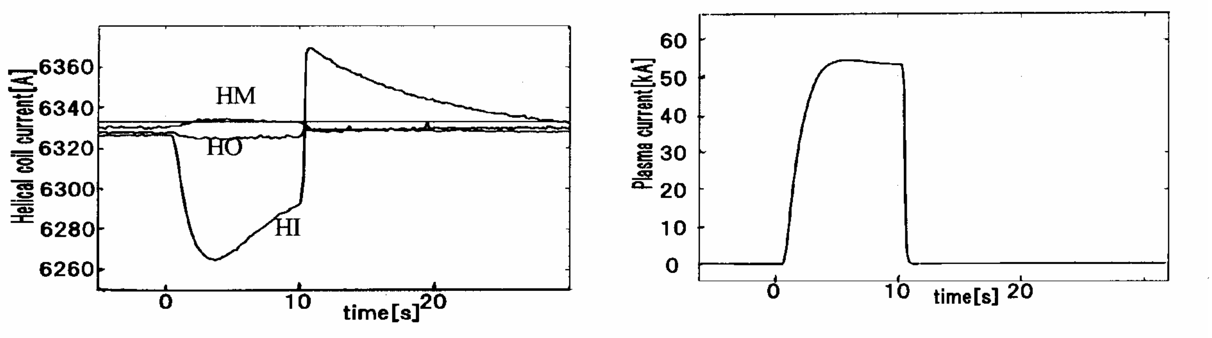
Table II shows comparison of operation results for three controllers. In this table, results from the proportional (P) control, which is usually used in the current LHD operation, and proportional plus integral (PI) control, which is one of the critical design of controller based on the state vector, are shown for comparison. As shown in this table, the H-infinity + FF (Feed Forward) controller realized faster current response than the optimized PI controller and the requirements for coil current control were satisfied. The ripple voltage shown in Table II was caused by the digitized step of coil current for digital control. The H-infinity + FF controller showed the least ripple voltage, though it is difficult to suppress this ripple in the faster and higher gain controller. This feature, which has not been discussed in the normal conducting coil system, leads the lower induced noise in the diagnostic system for superconducting coils and it offers great advantages for a noise sensitive device such as a quench detector. In case of the LHD, the noise for quench detector was reduced to less than 20% when the H-infinity + FF controller was applied compared with P controller.

Although satisfactory performance of the current control was obtained by the H-infinity + FF controller, current overshoot at the time of plasma disappearance can be seen in the experimental result. The way to solve this overshoot is under study with the help of feed back of plasma current.



(a) Helical coil current (b) Plasma coil current

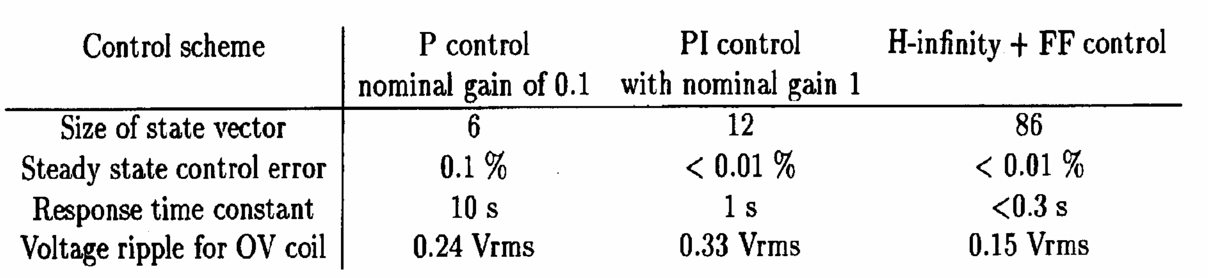
FIG.5. Experimental result using H-infinity controller with feed forward.



(a) Helical coil current (b)Plasma coil current

FIG.6. Experimental result using proportional controller.

TABLE II: COMPARISON OF THREE CONTROL SCHEMES.



Control scheme	P control nominal gain of 0.1	PI control with nominal gain 1	H-infinity + FF control
Size of state vector	6	12	86
Steady state control error	0.1 %	< 0.01 %	< 0.01 %
Response time constant	10 s	1 s	<0.3 s
Voltage ripple for OV coil	0.24 Vrms	0.33 Vrms	0.15 Vrms

References

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