§11. Current Control of Mutual Coupled Coils of LHD

Chikaraishi, H.

For the LHD superconducting coils, high accuracy of current control is required to make good plasma confinement. This report introduces the experimental results of coil current control for LHD.

The requirements to the current regulator are as follows:

1. Control error in current regulator in steady state is less than 0.01%.
2. Settling time to 0.1% of control error is less than 1 second for the normal ramp rate.
3. No overshoot of current is available.

To solve these requests, state variable based current regulator is designed and installed in the computer control system. For the first and second cycle operation, a simple P or PI controller is used.

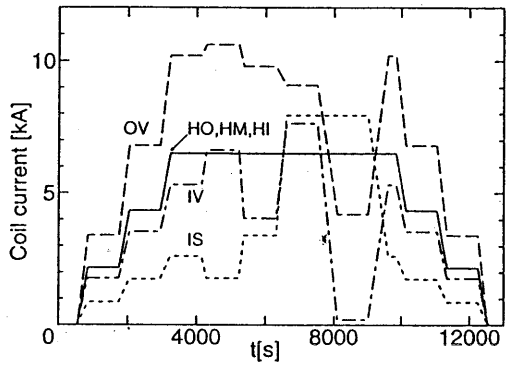

Fig. 1. An example of excitation for superconducting magnets test.

The control scheme is as following;

$$\begin{bmatrix} I_{f[n+1]} \\ X_{[n+1]} \end{bmatrix} = \begin{bmatrix} 0.9 & 0 \\ -dt & 1.0 \end{bmatrix} \begin{bmatrix} I_{f[n]} \\ X_{[n]} \end{bmatrix} + \begin{bmatrix} 0 & 0.1 \\ dt & 0 \end{bmatrix} \begin{bmatrix} I^*_{c[n]} \\ I_{c[n]} \end{bmatrix}$$

$$V_{[n]} = \begin{bmatrix} -K_p & K_i \end{bmatrix} \begin{bmatrix} I_{f[n]} \\ X_{[n]} \end{bmatrix} + \begin{bmatrix} K_p & 0 \end{bmatrix} \begin{bmatrix} I^*_{c[n]} \\ I_{c[n]} \end{bmatrix}$$

where I_c and I_c^* are coil current and its reference, I_f is filtered current, X is state variable, K_p and K_i are control gains, dt is the control period of 20 ms. In the regulator, a digital low pass filter, which cutoff frequency is 0.7 Hz, is inserted to smooth the current signal. The delay caused by this filter limits the maximum feedback gain to 1.25.

Figure 1 shows an example of waveforms of coil currents for 1.5 T operation. In this excitation, a special current set to generate maximum internal force is inserted. The ability of plasma γ control is also tested. Figure 2 shows one of experimental results. The currents of helical coil blocks are set in different value and different change rate as shown in the figure.

Table 1 shows current control errors in steady state for all tested control parameter. In this table, it is shown that the regulator using high control gain of $K_p = 1.0$ satisfies specified control accuracy and the accuracy becomes better when PI control is adapted.

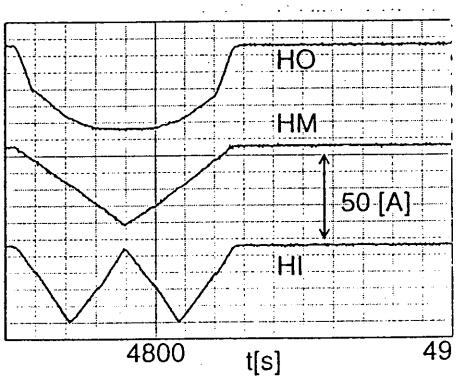

Fig. 2. Excitation with different helical coil block currents.

Table 1. Control error of coil currents for 1.5 T operation

	HO	HM	HI	Average	OV	IS	IV
Current reference [A]			6250		9801	2505	5105
Available error [A]			2.1		2.5	1.8	2.0
Error with P Control ($K_p = 0.1$) [A]	-10.1	4.4	-8.7	-4.8	-14.6	-7.9	-12.0
Error with P Control ($K_p = 1.0$) [A]	-0.9	0.2	-0.8	-0.5	-1.4	-0.9	-1.2
Error with PI Control ($K_p, K_i = 1.0$) [A]	0.2	-0.2	-0.1	<0.1	<0.1	<0.1	<0.1