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Real-Time Coil Current Control System for LHD Experiments

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Abstract

The real-time coil current control (RCC) system was designed and constructed for the real-time plasma current control experiments on the Large Helical Device (LHD). The main computer of the RCC system is a standard DOS/V machine, which operating system is Windows-NT. This computer is linked to the LHD power-supply (PS) control computer through the reflective memory. Calculations of coil currents for the plasma current control are carried out using the standard proportional-integral control algorithm in the RCC main computer. The control priority is back to the PS system when any abnormal state is detected. The operation of the RCC system was checked by simulation program. During the third experimental campaign, this RCC system was tested using the LHD PS system. The time behaviors of its coil current and voltage were compared with those of the simulation results. Experimental results agreed well with the simulation results.

Keywords:

super-conducting heliotron device, real-time coil current control, plasma current control, reflective memory

1. Introduction

The Large Helical Device (LHD) [1] is the largest super-conducting (SC) heliotron type device with a set of $l = 2/m = 10$ continuous helical windings. The major and averaged minor radii are 3.9 m and 0.65 m, respectively. Key issues of the LHD project are the demonstration of currentless steady-state plasma operation and the achievement of reactor-relevant plasma parameters (confinement of a high beta plasma). To achieve these issues, real-time control of plasma parameters is essential [2].

Although plasma current is essential for tokamaks to form the confining magnetic field, it is not essential for the heliotron type devices. Accordingly, the heliotron type device can confine the currentless plasma, and it is one of the big advantages against tokamaks. However, there exist some plasma currents like bootstrap current, beam driven current by neutral beam injection (NBI) and so on. These currents affect the plasma confinement. For this reason, real-time plasma current control is one of the essential issues for the plasma physics research and the real-time coil current control (RCC) system has been designed and installed in the present power supply (PS) system [3] of the LHD.

2. Out Line of RCC System

The LHD SC coils consist of one pair of helical field (HF) coils and three pairs of poloidal coils (OV, IS, IV) as shown in Fig. 1. It is possible to induce the plasma current by changing the inter-linkage flux for plasma. The RCC system has been designed to control the plasma current of LHD. Guiding concepts of the design are as follows; 1) small modification of the present system, 2) easy changing of the control

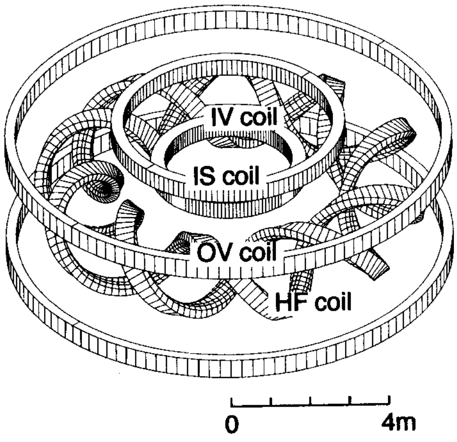

Fig. 1 Schematic of the LHD coil system.

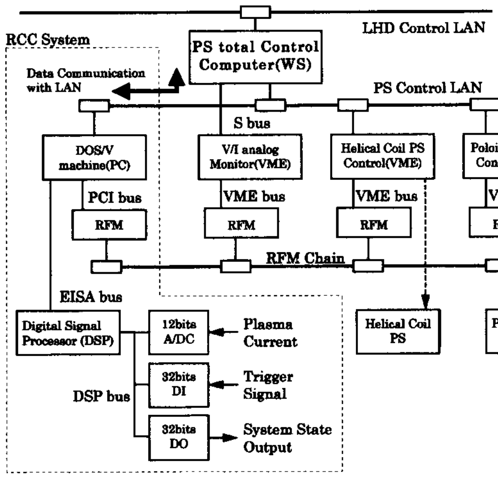

Fig. 2 Structure of the RCC system.

algorithm and programs, 3) applicable to other systems. The RCC system calculates the necessary coil currents using measured plasma current according to PI algorithm, which can be replaced easily by other algorithm, and sends them to the PS system. Then the PS system controls the coil currents using these values.

Figure 2 shows the structure of the RCC system installed in the PS system. The part surrounded by broken lines is the RCC system and the other part is the present PS system. The RCC system is connected to the PS system through the reflective memory (RFM). As shown in Fig. 2, the PS system consists of one PS total control computer (WS) and three real time control computers (VMEs) which control poloidal coil power supplies, helical coil power supplies and the analog output voltage and current monitor for all coils. The data communications among the total control computer and VMEs are done through the PS control LAN and the data communications among VMEs are done using RFMs.

The coil currents are controlled using the values written on the RFMs by the PS system or the RCC system. In the plasma current control experiments, the control priority of the power supply is switched to the RCC system by the PS total control computer. When the interlock signal and/or any abnormal signal are detected, the control priority of the power supply is switched to the PS total control computer immediately. The program of the PS system was modified for this switching operation of the control priority. The designed value of the control period for the RCC system is 20–100 msec because the time constant of the LHD structure is much larger than 20 msec.

The main computer of the RCC system is a standard DOS/V machine (MMX Pentium 200 MHz) which operating system is Windows-NT. The measured plasma current is inputted to the digital signal processor (DSP) through an analog digital converter (A/DC). The necessary coil currents are calculated according to some algorithm programmed in the DSP and sent to the RFM. The digital input and output (DI and DO) are used for the communication of the timing signal and the statements of the RCC system between the RCC system and the central control system computer.

3. Control Method of RCC System

The magnetic configuration is characterized by toroidal field B_0, magnetic axis position R_{ax}, ellipticity of cross-sectional shape κ and inter-linkage flux for the toroidal plasma Φ_p. To control the plasma current with keeping B_0, R_{ax} and κ constant, three poloidal coils should be controlled simultaneously. The necessary coil currents are calculated from B_0, R_{ax}, κ and $\Phi_P + \Delta\Phi_P$, where $\Delta\Phi_P$ is the necessary flux calculated from the actual and reference plasma currents. The helical coil currents calculated from B_0 is kept constant. To keep R_{ax} and κ constant, the dipole component (B_D) and the quadrupole component (B_Q) must be kept constant. The normalized components of the poloidal coils with respect to those of the helical coils are expressed as follows;

$$f_D = B_{D_{PC}} / B_{D_{HC}} , \tag{1}$$

$$f_Q = B_{Q_{PC}} / B_{Q_{HC}} , \tag{2}$$

$$f_D = aI_{OV} + bI_{IS} + cI_{IV} , \tag{3}$$

$$f_Q = dI_{OV} + eI_{IS} + fI_{IV}\ , \tag{4}$$

where the subscripts "PC" and "HC" mean poloidal coil and helical coil, respectively. I_{OV}, I_{IS} and I_{IV} are the coil currents of the OV, IS and IV poloidal coils, respectively. The inter-linkage flux Φ_P produced by the poloidal coils are expressed as follows;

$$\Phi_P = gI_{OV} + hI_{IS} + iI_{IV}\ , \tag{5}$$

where coefficients a-i are constant. The poloidal coil currents are derived from eqs. (3)-(5)

$$\begin{bmatrix} I_{OV} \\ I_{IS} \\ I_{IV} \end{bmatrix} = \begin{bmatrix} a & b & c \\ d & e & f \\ g & h & i \end{bmatrix}^{-1} \times \begin{bmatrix} f_D \\ f_Q \\ \Phi_P \end{bmatrix} . \tag{6}$$

Electromotive force e_P is expressed as follows by using plasma current I_P, plasma self-inductance L_P, plasma resistance R_P and inter-linkage flux Φ_P.

$$e_P = -\frac{d\Phi_P}{dt} = L_P \frac{dI_P}{dt} + R_P\, I_P\ . \tag{7}$$

The relation between I_P and Φ_P are expressed as follows,

$$-\Phi_P = L_P\, I_P + R_P \int I_P\, dt\ . \tag{8}$$

From Eq. (8) the flux change $\Delta\Phi_P$ that gives the additional current flow of ΔI_P is expressed as follows,

$$-\Delta\Phi_P = L_P\, \Delta I_P + R_P \int \Delta I_P\, dt\ . \tag{9}$$

The plasma current control system is designed using eqs. (6) and (9). The block diagram of this system is shown in Fig. 3. Current reference by PS-VME in this diagram is used to change the coil currents with constant changing rates in the usual experiment. Current reference by RCC system is used for feedback control of coil currents using plasma current. Changing the current reference means the switching operation of the control priority.

4. Simulation Results

Simulation program is coded according to the block diagram in Fig. 3. For the electrical matrix calculation of this RCC system, the LHD is assumed to consist of 10 electrical filament parts; six for coils, three for supporting structure and one for plasma. The dispersion model of 20 msec time span is used for this simulation because the PS system is controlled digitally with 20 msec cycle. Standard proportional (P) control with 20 msec cycle is used for the PS control system and proportional-integral (PI) control with 100 msec cycle is used for the plasma current control system.

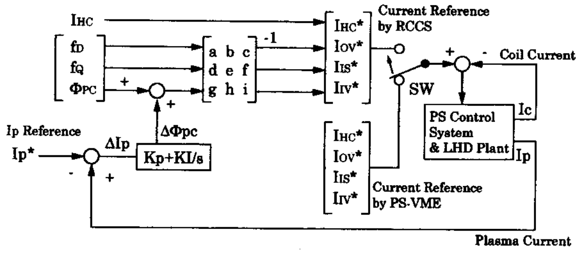

Fig. 3 Block diagram of the coil current feedback system.

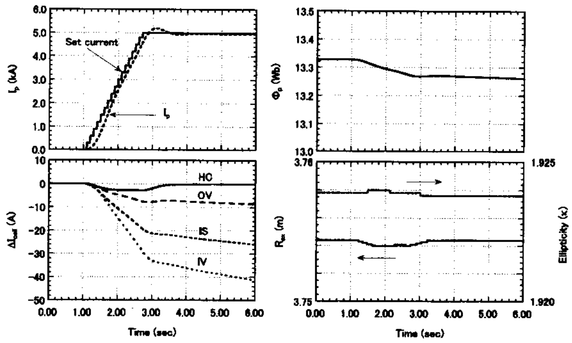

Fig. 4 Simulation results.

Figure 4 shows the simulation results of the plasma current control by the RCC system at 1.5 T. Plasma current reference is shown as 'set current' in Fig. 4. The L_P and R_P are assumed as 12.1 μH and 1.0 μΩ, respectively. Inductance matrix of the LHD coil system [3] is used to calculate the time responses of coil currents. The time behaviors of plasma current I_P, deviations of coil currents from 1.5 T operation ΔI_{coil}, inter-linkage magnetic flux Φ_P, magnetic axis position R_{ax} and ellipticity of cross-sectional shape κ are shown in this figure. The response time of plasma current is about 200 msec as same as the present PS system, and the change of R_{ax} and κ are small. For the limitation of the PS voltages, the changing rate of plasma current is limited to 5 kA/sec in this parameter region.

5. Experimental Results

The coil currents control with the RCC system was carried out twice campaign at 0.1 T and 1.5 T during the third cycle experimental. At the beginning of these experiments, all interlock and security systems were checked using the quasi-interlock signals and the normal operations of them were confirmed. Switching operation of control priority between the PS system and the RCC system was also confirmed at the coil exciting condition.

In the first stage of these experiments, all coils were excited with the same current ratio to keep the same magnetic field structure. In the next stage, the IV coil current was increased and decreased with the changing rate of 10 A/sec, 20 A/sec and 40 A/sec to change the inter-linkage flux for plasma. As the IV coil is located inside of torus as shown in Fig. 1, the influences of the IV coil current on the magnetic field configuration and the LHD cryogenic system are expected to be smaller than those of other coil currents. And single coil usage is useful to check the system reliability. Therefore, only IV coil is used in the first experiment of plasma current control.

Figure 5 shows experimental and simulation results of IV coil current changing at 0.1 T. The changing rate of the IV current is 40 A/sec. Although the saw-tooth like oscillations of about 2 V are observed on the output voltage, the IV current is controlled smoothly. These oscillations are caused by the difference of the control cycle between the RCC system (100 msec) and the PS system (20 msec). The IV current has time delay of about 500 msec to the set current as shown in Fig. 5.

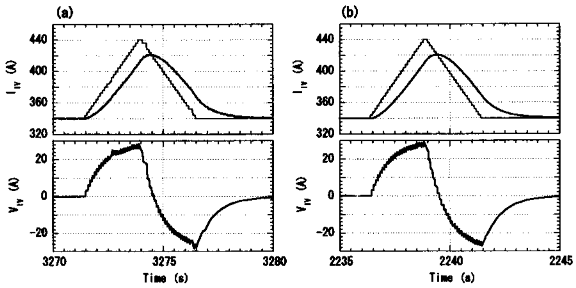

Fig. 5 Experimental and simulation results.

This time delay is caused by the thick stainless steel structure (vacuum vessel, coil supports and so on) without toroidal breaks and the limited abilities of the coil power supplies.

6. Summary

The RCC system has been designed and installed in the present PS. Possibility of plasma current control without other plasma parameter changes is shown by the simulation. In the experiment using the LHD coils, time behaviors of the coil currents and voltages agree well with the simulation results. All interlock and security systems of the PS system were checked to work well. Switching operation of control priority between the PS system and the RCC system was also confirmed at the coil exciting condition.

We are planning the plasma current control experiments with the RCC system in the next experimental campaign.

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