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ScienceDirect
Fusion Engineering and Design 81 (2006) 2555–2559
Fusion Engineering and Design
www.elsevier.com/locate/fusengdes

Open-loop excitation and electrical parameter estimation of LHD superconducting coils

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Available online 22 August 2006

Abstract

The LHD contains six sets of large-scale superconducting coils and six dc power supplies to charge them. In its usual operation, the current regulator installed in the power supplies controls the coil currents. This paper focuses on an open-loop control of the current controller, which has no current feedback. The electrical parameters that are estimated and the open-loop controller was designed and tested. The results show that the open-loop control can be adapted to the LHD power supplies for short-term plasma experiments and can provide a new tool for plasma experiment, in which the coil current controller exerts no effect on plasma.

Keywords: Current control; Open-loop control; Inductance matrix; Parameter estimation; Superconducting coil

1. Introduction

The power supplies of the LHD superconducting coils require higher accurate coil current response and control. In previous reports, the authors have described and tested current controllers for this power system [1,2].

In the above experiments regarding plasma current, the change of plasma current induced voltages to the coils and the coil current controller produced counter voltage to regulate the coil currents. These counter voltages induced a plasma one-turn voltage and affected the plasma current [2]. This induced one-turn voltage depends on the current-control scheme, and smaller one-turn voltage is expected in some plasma experiments. The use of an open-loop system, which involves no feedback of coil currents, is possible way to remove this effect.

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doi:10.1016/j.fusengdes.2006.07.015

The design of such an open-loop system must take into account accurate electrical parameters of the inductance matrix and resistances of the coil system. We measured the inductance matrix before the first operation of the LHD at a coil temperature at around 100 K because the machine time is limited before the operation and we do not have time to measure after the superconducting transition [3]. Therefore, the measured matrix may include some measurement errors. Also, the circuit resistances are important to suppress the current drift in the open-loop system. However, they were approximately estimated only, because the coil terminal voltages have a large ripple, thus making accurate measurement difficult.

In the following section, the current-control system of the LHD is introduced. Next, the circuit resistances and the inductance matrix are estimated. An open-loop controller using the estimated parameters is then built and tested.

2. Current control of the LHD superconducting coils

Fig. 1 show a diagram of the power supplies of the LHD and a block diagram of the coil current controller. In the figure, $\mathbf{i}^*$, $\mathbf{i}$, $\mathbf{v}^*$, and $\mathbf{v}$ are vectors of the coil current reference, coil current, coil voltage reference, and coil voltage, respectively. The voltage equations of the coils and the current controller are generally follows:

$$\mathbf{v} = \mathbf{ri} + \mathbf{L}\frac{\mathrm{d}\mathbf{i}}{\mathrm{d}t} \quad (1)$$

$$\mathbf{v}^* = \mathbf{f}(\mathbf{i}^*, \mathbf{i}) \quad (2)$$

$$\mathbf{v} = \mathbf{v}^* + \mathbf{e}, \quad (3)$$

where $\mathbf{f}(\mathbf{i}^*, \mathbf{i})$, $\mathbf{L}$, $\mathbf{e}$, and $\mathbf{r}$ are the control scheme, inductance matrix, error voltage vector in the power supply, and circuit resistance matrix in the coil system.

Usually, the LHD uses the following Proportional (*P*) control scheme:

$$\mathbf{v}^* = k\mathbf{L}^*(\mathbf{i}^* - \mathbf{i}), \quad (4)$$

where k is control gain and $\mathbf{L}^*$ is the estimated inductance matrix of the LHD.

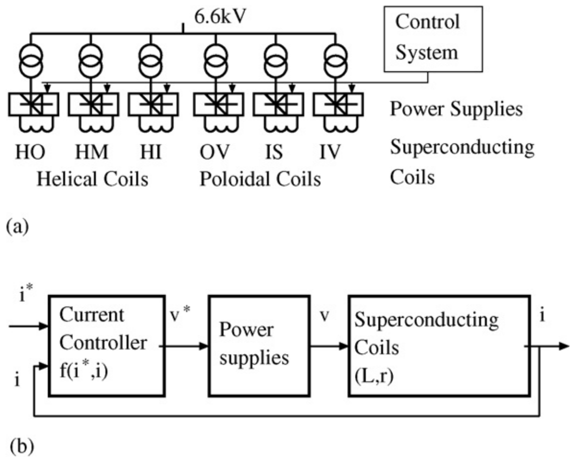

Fig. 1. (a) Circuit diagram of the LHD power supplies and (b) block diagram of the current-control system.

The open-loop control scheme considered in this paper is described as follows:

$$\mathbf{v}^* = \mathbf{L}^*\frac{\mathrm{d}\mathbf{i}^*}{\mathrm{d}t} + \mathbf{r}^*\mathbf{i}^*, \quad (5)$$

where $\mathbf{r}^*$ is the estimated resistance matrix in the circuit. In our previous experiments, we approximately estimated $\mathbf{r}^*$ as 0.1 mΩ based on the coil terminal voltage and coil currents in the steady state.

Fig. 2 shows an example of the test operation of the open-loop controller using the parameters used in the previous controller. As shown in the figure, the coil currents drift about 30 A in the 60 s test period. The output voltage error, caused by the difference between $\mathbf{r}$ and $\mathbf{r}^*$ and $\mathbf{e}$ (as explained in Eq. (3)), causes this drift.

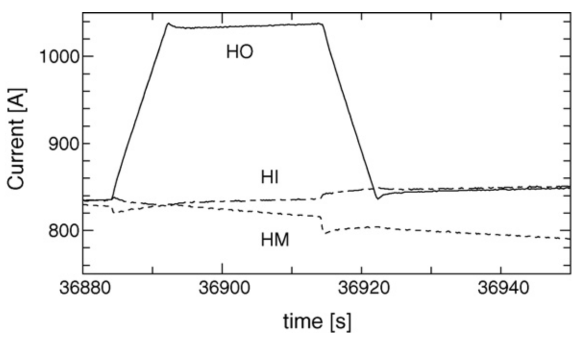

Fig. 2. Current waveforms using the open-loop controller with old parameters.