Estimation of Electrical Parameters of Large-Scale Superconducting Coil System for Fusion Plasma Experimental Facility

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Abstract—The Large Helical Device (LHD) in the National Institute for Fusion Science (NIFS) has six sets of large scale superconducting coils and six dc power supplies to charge them. For the current controllers of these power supplies, high accuracy of current control, good response and robustness of system are required. In the design of the controller, it was pointed out that the correct inductance matrix of the coil system and some electrical parameters that describe metal structures such as a supporting shell are necessary.

This paper introduces a method based on a frequency response of impedance to estimate these parameters. First, the measured inductances of the LHD superconducting coils, which are measured from coil terminals, are presented and discussed. Next, an estimation method for circuit parameters is described. Finally, an experimental result of coil excitation using these parameters is presented. The experimental result show that the coil current controller using the estimated model satisfies previous requirements and it is confirmed that this parameter estimation method is valid for the large scale coil system.

Index Terms—Inductance matrix, parameter estimation, superconducting coils.

I. INTRODUCTION

THE LARGE Helical Device (LHD) in the National Institute for Fusion Science (NIFS) has six sets of large-scale superconducting coils that form the magnetic field to confine plasma for fusion experimental research [1]. To magnetize these coils, six dc power supplies are constructed. For these power supplies, the following requirements were presented; the coil current control error is less than 0.01% of the set value, the current settling time for 0.1% of control error is less than 1 second and the control system must be robust against disturbances caused by the plasma experiments. To resolve these requirements, modern and post modern control systems are studied and designed. This study demonstrates that the modeling of the LHD coil system, which includes not only the coils but also metal structures such as a supporting shell, is important. Especially, the estimation of the self- and mutual-inductance of the coils with high accuracy is necessary to build a robust and accurate coil current regulator, but this is difficult with the usual inductance measurement techniques, because the current induced in the metal structure affect the

Fig. 1. Deposition of superconducting coils of LHD.

measurement. The mutual inductances between coils and structures are important to design the high speed current controller that will be required in future operation of LHD, but their estimations are also difficult because the voltage or current in the structural components cannot be measured directly.

This paper introduces a method that uses the frequency response of inductance to estimate the necessary parameters of coils. First, some examples of frequency response of inductances, which are measured from coil terminals, are presented and discussed. Next, the estimation of circuit parameters using these responses is described. Finally, an experimental result using the current controller designed with these parameters of coil excitation is presented.

II. OUTLINE OF THE COIL SYSTEM FOR LHD

The LHD has six poloidal field coils designated as OV-U, OV-L, IS-U, IS-L, IV-U and IV-L as shown in Fig. 1. In addition, it has two helical coils designated as H1 and H2 as shown in the figure. Each helical coil is divided in 3 blocks; for example, H1 coil is divided H1-O, H1-M and H1-I. These coils are connected as shown in Fig. 2 and the coil sets as designated as shown in this figure.

III. FREQUENCY RESPONSE OF INDUCTANCE OF COILS

To estimate the electrical parameters of the superconducting coil system, we measure the complex inductance $L = L_{re} + jL_{im}$ from the coil terminals for all coils in various frequency.

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Fig. 2. Connection of the superconducting coils of LHD.

Fig. 3. Frequency response of the real component of complex inductance related to HO coil. The solid lines are fitted using full parameters model and the dashed lines are using reduced model.

Fig. 3 shows some frequency response of L_{re} for self- and mutual-inductance related with HO coil. The plots in this figure show measured value. The solid lines are fitting curves with a full parameters model, described in the next section, and the dashed lines show the calculated value, which are carried out using a reduced model introduced later.

In this figure, all inductances are almost constant below 0.05 Hz. The dc inductance, which cannot be described in the figure, is the true inductance, determined by the configuration of the coil. At a higher frequency than 0.1 Hz, the measured inductances decrease because of induced current flowing in the structural material. The mutual inductances between HO and poloidal coils actually show negative values. The cause of these negative inductances will be described following section.

For a large-scale coil, a self-resonance, caused by the inductance itself and distributed capacitance of windings, may make some difficulties in the design of a power supply and its control system. The self-resonance of the LHD coils are observed around 2 kHz and these resonance are sufficiently higher than the output ripple frequency that they can be identified as a characteristic frequency of the dc power supply. Therefore, these resonance were ignored when the electrical parameters were estimated.

A. Explanations for the Negative Mutual Inductance

As show in Fig. 3, some mutual inductances have a negative value around 1 Hz of frequency. This phenomenon is explained by the transmission delay of the magnetic flux that passes through the metal structures such as the coil can surrounding

Fig. 4. Phase diagram of the mutual inductance between poloidal and HO coils.

helical coils. When a magnetic flux passes a conductor plate, the flux at the behind surface of the plate is described as

$$\phi_b e^{j\omega t} = e^{(-1-j)T/d} \phi_f e^{j\omega t} \quad (1)$$

where ϕ_f is the flux at the front surface of the plate, ω is frequency, T is the thickness of the plate and d is the skin depth $\sqrt{2/(\sigma\mu\omega)}$. From this equation, it is shown that the flux ϕ_b traces a spiral curve converged to the origin with increasing frequency.

When the source current is described as i , the interlinked flux with the destination coil is described as Li . Therefore, a phase diagram of L indicates the phase diagram of interlinked flux for the unit current. Fig. 4 shows a phase diagram of the complex mutual inductance between OV, IS and HO coils. The diagrams show spiral curves and agree qualitatively with the behavior that the interlinked flux between coils lags and decays when it passes through the metal structures. In the LHD coil system, many coils have linked flux. Moreover, there is also flux from the induced current flowing in the structural components. Therefore, the interlinked magnetic flux cannot be described with a simple equation such as (1).

IV. CIRCUIT MODEL FOR SUPERCONDUCTING COIL SYSTEM

An equivalent circuit model of the coil system is constructed to model the necessary parameters. To design a controller for steady state excitation of the LHD coil system, the parameters, which fit with the measured characteristics under the frequency of 0.05 Hz, are necessary. In addition, to design a controller for dynamic operation, the parameters, which fit less than 2 Hz, are required. The most important parameters are the true inductances of the coils, as determined decided by their configuration and they must be estimated with high accuracy.

A. Circuit Model for a Coil

To describe the inductance frequency response, we use an equivalent circuit shown in Fig. 5 for each coils. In the figure, L_c is a self-inductance which describes a true inductance of the superconducting coil. L_s and r_s are the self-inductance and resistance of a magnetically coupled circuit that describes a metal component such as a coil can, r_c is a resistance of the coil caused by the connection or terminals, and M is a mutual inductance

TABLE I
ESTIMATED PARAMETERS FOR REDUCED MODEL OF SUPERCONDUCTING COIL SYSTEM OF LHD

	a) Inductance matrix [H]									
	HO	HM	HI	OV	IS	IV	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
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

a) Resistance of passive circuits. [Ω]				
C1	C2	C3	C4	
1.68	1.64	16.9	16.9

Fig. 5. A model circuit that has a coupled passive circuit for a coil.

between the coil and the metal component. In these parameters, M , L_s and r_s cannot be measured directly because there are no electrical terminals to measure the current flowing in the structure.

With the assumption that every coupled circuits considered in the model are independent with each other, the effective coil inductance L_{eff} measured from its terminals is carried out as following;

$$L_{eq} = L_c \left(1 - \frac{\omega^2 M^2}{r_s^2 + \omega^2 L_s^2} \frac{L_s}{L_c} \right). \quad (2)$$

In the higher frequency, the skin effect of the structural component can not be neglected as described as previous section, therefore, we form r_s as $r_{s0}(\sqrt{1 + \omega/\omega_0})$, where r_{s0} is a dc resistance and ω_0 is a characteristic frequency of skin effect. In this region, L_{eff} is formed as follows;

$$L_{eq} = L_c \left(1 - \frac{\omega^2 \omega_0 M^2}{r_{s0}^2 (\omega + \omega_0) + \omega^2 \omega_0 L_s^2} \frac{L_s}{L_c} \right). \quad (3)$$

We can decide parameters appeared in L_{eff} with fitting to the measured value of L_{re} . In this model, the L_s has a freedom caused by a turn ratio between the superconducting coil and the passive circuit; therefore, it must be fixed at first by some way. We assume that the L_s is 1 H and continue the fitting procedure.

A similar model and procedure was adapted to the mutual inductance between coils. In Fig. 3, solid lines show some fit results using this model. To get better fitting, we use a model with two independent coupled circuits for each inductance between helical coils. In this model, one of the coupled circuits is assumed that it has a constant resistance to represent the response in the lower frequency, and the other is assumed that it

Fig. 6. Reduced model of the superconducting coil system of LHD. C1, C2, C3 and C4 are coupled circuits, which represent metal structural components.

has a frequency dependent resistance to represent the characteristic in the higher frequency region.

For the mutual inductance between helical and poloidal coils, the effect of transmission delay of the magnetic flux mentioned above cannot be modeled with a conventional LCR circuit; therefore, we approved a negative inductance as a parameter. Also to avoid the difficulty of fitting, we assumed that the frequency dependence of the resistance $r_s = r_{s0} \sqrt{(\omega/\omega_0)}$ for these inductances. The fit results are shown in Fig. 3 and it is pointed out that this model shows good fitting with the measured data in the whole region of frequency.

When the time constant of coupled circuits are considered, the circuits that have a constant resistance seem to represent the supporting shell and the circuits with the frequency dependent resistance seem to represent the coil cans or other components.

B. Reduction of Number of Coupled Circuits

In the previous procedure, we assumed independent circuits for every self- and mutual-inductance, then the number of passive circuits becomes 48. This assumption leads good fitting as described as before but the number of the circuits is too many for design of the control system. Therefore we combined the passive circuits with a similar time constant evaluated by L_s/r_s and built a reduced model shown in Fig. 6, where C1, C2, C3 and C4 show combined passive circuits. The mutual inductance estimated in the previous section is described by the following equation;

$$M_{OV-C1-HO} = M_{C1-HO} M_{OV-C1} / L_{C1} \quad (4)$$

where $M_{OV-C1-HO}$ describes a mutual inductance, which is imported to represent the frequency response of mutual

Fig. 7. Result of excitation test of LHD coils.

inductance between HO and OV coils in the previous section. M_{C1-HO} is the mutual inductance between C1 and HO, M_{OV-C1} is also the mutual inductance between OV and C1. L_{C1} is the self-inductance of the C1 coil, which is assumed to be 1 H in this paper. The mutual inductances between coils shown in the equivalent circuit are decided by the least squares fit with estimated parameters carried out in the previous section using above relation. With this simplification, the number of passive circuits decreases to 4 and the final parameters of the coil system that include all superconducting coils and metal structures are shown in Table I. In the table, the inductance matrix is not a diagonal matrix because this circuit model is not based on a physical model of the coil system. However, this does not cause any problem for the design of the controller, so we did not make any correction. In addition, the current design of the controller cannot consider the frequency dependence of the parameter, so the resistances are simplified to the constant shown in the table. The dashed curves in Fig. 3 are the calculated frequency responses of L_{re} using this simplified model. It is shown that the simplification causes some error in the high frequency region, $f > 2$ Hz. However, a postmodern control design can accept some inaccuracy of the model at higher frequency and we approved these modeling errors.

C. Current Control Using the Estimated Parameters

For the LHD power supplies, some current controllers were designed using the electrical parameters carried out in the pre-

vious section and tested. Fig. 7 shows a typical current waveforms of test operation with H_∞ controller which is one of the postmodern controller. In this test, the current reference for HO coil is swept and the other references are held constant. The actual current of the HO coil traced its reference and the perturbation of the HM and HI coil currents was less than 1 A, which is 0.02% of operating current. With these test operations, it is confirmed that the each coil current can be controlled to the desired value independently and the estimated parameters are appropriate. With the operation test of current control, it was confirmed that the parameter estimation method mentioned above is appropriate for a large-scale coil system.

V. SUMMARY

This paper describes the parameter estimation of the large-scale superconducting coil system, which has metal components such as supporting structure. The frequency responses of the inductance for all coils were measured. The results show that the effect of induced current in the structure and the transmission delay of the magnetic flux are significant. To estimate the true self- and mutual-inductance of the coil system, a circuit model considering the skin effect is imposed. The parameters in this model are determined by fitting with the measured inductance. Finally, the coil current controllers are designed using the parameters, then tested. The test results show that these controllers satisfied requirements and the parameter estimation mentioned in this paper is appropriate.

In the next stage of parameter estimation, the imaginary components of measured inductance and the flux transmission delay will be considered in the fitting and in the construction of coil model. Moreover, the correspondence between the parameters of circuit model and the physical components will be studied.

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