

Examination on Equivalent Resistance and Coupling Coefficient of Zone-Control Induction Heating by Finite Element Method

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Abstract — The zone-control induction heating (ZCIH) system is a promising system used to ensure uniform and rapid heating of a workpiece, and it can also decrease the waste heat in a billet heating system. However, it is not easy to limit the current phase of each coil fed by different inverters to the same value because of the existence of the mutual inductance of the coil and resistance in the eddy current circuit. In this study, to improve the ZCIH control, we analyzed the mutual inductance of the coil and equivalent resistance in an eddy current circuit using the 3-D finite element method. We examined the behavior of the mutual inductance of the coil and resistance of the eddy current circuit. In addition, we examined the properties of the coupling coefficients of the inductance and equivalent resistance.

Index Terms — Coupling coefficient, equivalent resistance, finite element method, induction heating

I. INTRODUCTION

During induction heating, to ensure uniform heating of a workpiece, multiple heating coils [1], [2] are mounted on the workpiece, and the output of each coil fed by each inverter is controlled. However, the system is unstable because of the existence of mutual inductance between heating coils. To resolve these issues and to realize highly accurate temperature control, the zone-control induction heating (ZCIH) system [3-5], which consists of multiple heating coils and inverter-driving coils, is developed. The system can be operated under the same frequency and phase for all coil currents, although there is a mutual induction between the coils.

The ZCIH system is presented using an equivalent circuit with an inductance and a resistance of an eddy current circuit. To examine the control method of the ZCIH system, we need to understand the detailed behavior and physical meaning (a function of the exciting frequency and resistivity) of the mutual inductance between heating coils, a “self-equivalent resistance” of the eddy current circuit, and a “mutual-equivalent resistance” representing the relationship between eddy current circuits, which are induced by the heating coils. An understanding of the behavior of the parameter will enable us to miniaturize an inverter to control the ZCIH system.

In this study, the self- and mutual- inductances of heating coils and self- and mutual- equivalent resistances of the eddy

current circuit of the ZCIH system are analyzed by phasor analysis using the 3-D finite element method (FEM). The detailed behavior of the inductance, equivalent resistance, and coupling coefficient are examined. In addition, the effect of the opposing field due to the eddy current on these parameters is also discussed.

II. ANALYZED MODEL

Fig. 1 shows the billet heater model with three heating coils. A quarter of the region is analyzed. The number of turns of each coil is 6. The eddy current in the coil is ignored and the workpiece is assumed to be graphite, which has a relative permeability of unity. The resistivity ρ is $1200[\mu\Omega \cdot \text{cm}]$ (room temperature). The current of the coil I_0 is $100 \cos \omega t$ [A]. The so-called $j\omega$ method is used in the linear edge-based 3-D FEM. An in-house code is used, and the number of elements is 302,208.

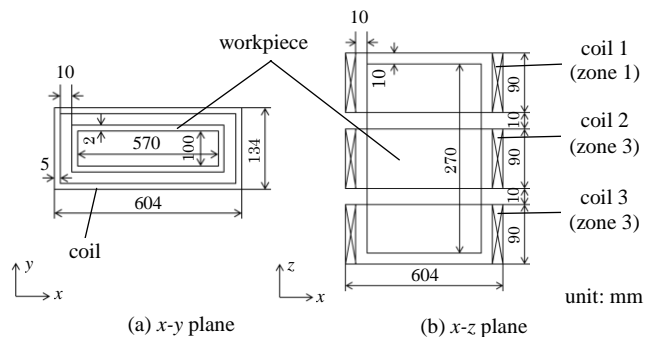


Fig. 1. Analyzed model of ZCIH.

III. ANALYSIS METHOD

A. Induced Voltage

The flux linkage Φ of the coil is given by

$$\Phi = \frac{n}{S} \iiint_{\Omega} \dot{\mathbf{A}} \cdot \mathbf{n}_s d\Omega \quad (1)$$

where S is the cross-sectional area of the coil, n is the number of turns of the coil, and Ω is the volume of the coil. $\dot{\mathbf{A}}$ is the magnetic vector potential, \mathbf{n}_s is the unit vector parallel to the current, and the dot ($\dot{\cdot}$) above the valuables represents the complex number followed by the phasor method.

The induced voltage \dot{V} of the coil is given by

$$\dot{V} = -j\omega\Phi \quad (2)$$

where ω is the angular frequency of the current.

B. Self-Inductance and Self-Equivalent Resistance

Using the induced voltage \dot{V}_1 in coil 1 and the current I_1 (angular frequency : ω) supplied to coil 1, the following equation is obtained:

$$\dot{Z} = \frac{\dot{V}_1}{I_1} = \frac{V_{1R}}{I_1} + j \frac{V_{1I}}{I_1} = R_1 + j\omega L_1 \quad (3)$$

where V_{1R} and V_{1I} are the real and imaginary parts of \dot{V}_1 , respectively, and L_1 is the self-inductance of coil 1. There is an apparent resistance R_1 as the real part of (3), in which the power is consumed by the eddy current induced in the workpiece. We define R_1 as the self-equivalent resistance.

C. Mutual-Inductance and Mutual-Equivalent Resistance

Using the induced voltage \dot{V}_2 in coil 2 and the current I_1 (angular frequency : ω) supplied to coil 1, we obtain:

$$\dot{Z} = \frac{\dot{V}_2}{I_1} = \frac{V_{2R}}{I_1} + j \frac{V_{2I}}{I_1} = R_{12} + j\omega M_{12} \quad (4)$$

where M_{12} is the mutual inductance of coil 1 and R_{12} is the resistance corresponding to the power consumed by the eddy current in workpiece 2 under coil 2 generated by coil 1. We define R_{12} as the mutual-equivalent resistance.

D. Coupling Coefficients

The inductance coupling coefficient k_{mn} between coils m and n is given by

$$k_{mn} = \frac{M_{mn}}{\sqrt{L_m L_n}} \quad (5)$$

In a similar way, we define the following equivalent resistance coupling coefficient k_{mn}^R between coils m and n as follows:

$$k_{mn}^R = \frac{R_{mn}}{\sqrt{R_m R_n}} \quad (6)$$

IV. RESULTS AND DISCUSSION

A. Inductances and Resistances

The inductances and resistances defined in (3) and (4) are analyzed using 3-D FEM. Fig. 2 shows the calculated inductances and equivalent resistances when the current I_1 (frequency:35 [kHz]) is supplied to coil 1. Fig. 3 shows the conceptual figure of fluxes that interlink two coils and two eddy current circuits. The ratio of the mutual-equivalent resistances R_{12}, R_{13} to the self-equivalent resistance R_1 is larger than that of the mutual inductances M_{12}, M_{13} to the self inductance L_1 , meaning that the flux Φ_{12}^R coupling the eddy current circuits is larger than the flux Φ_{12} coupling coils.

B. Effect of Frequency on the Coupling Coefficient

We analyze the coupling coefficients between zones 1 and 2 and zones 1 and 3 when the current I_1 is supplied to coil 1. The frequency of I_1 is 1[Hz]–100[kHz]. The resistivity of the workpiece is chosen as 1200[$\mu\Omega \cdot \text{cm}$], 100[$\mu\Omega \cdot \text{cm}$], and 2[$\mu\Omega \cdot \text{cm}$].

Fig. 4 shows the relationship between the frequency and equivalent coupling coefficient k^R . When the frequency is

low, there is little change in the coupling coefficient. When $\rho = 1200[\mu\Omega \cdot \text{cm}]$, the coupling coefficient k^R decreases at approximately 10[kHz]. When $\rho = 100[\mu\Omega \cdot \text{cm}]$, it decreases at approximately 100[Hz]. This can be explained as follows. The opposing flux due to the eddy current increases when the resistivity ρ is small. As a result, the eddy currents in workpieces 2 and 3 decreases, then the couplings workpieces 1 and 2 and workpieces 1 and 3 weakens at a lower frequency.

A similar figure is obtained for the inductance coupling coefficient k . However, the amplitude of k is smaller than that of k^R , as explained in Section IV. A.

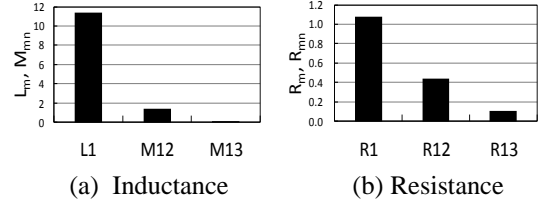


Fig. 2. Inductance and equivalent resistance when the current I_1 (frequency: 35 [kHz]) is supplied to coil 1 ($\rho = 1200[\mu\Omega \cdot \text{cm}]$).

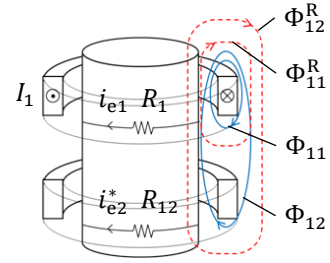


Fig. 3. Flux and eddy current distribution when the current I_1 is supplied to coil 1.

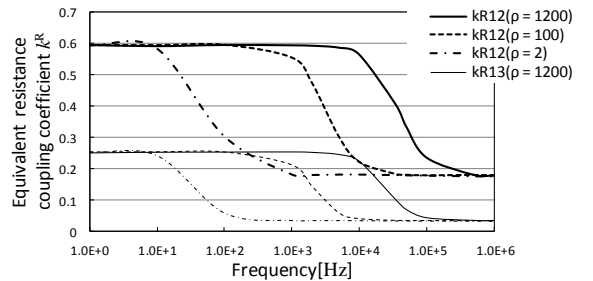


Fig. 4. Relationship between the frequency and equivalent resistance coupling coefficient.

REFERENCES

- [1] F. Forest, S. Faucher, J. Y. Gaspard, D. Montloup, J. J. Huselstein, and C. Joubert, *IEEE Trans. Ind. Electron.*, vol. 54, no. 1, pp. 441–452, Feb. 2007.
- [2] B. Saha, S. K. Kwon, N. A. Ahmed, H. Omori, and M. Nakaoka, *IEEE Trans. Ind. Electron.*, vol. 23, no. 1, pp. 412–419, Jan. 2008.
- [3] D. Miyagi, A. Saitou, N. Takahashi, N. Uchida, and K. Ozaki, *IEEE Trans. Magn.*, vol. 42, no. 2, pp. 292–294, 2006.
- [4] H. Kurose, D. Miyagi, N. Takahashi, N. Uchida, and K. Kawanaka, *IEEE Trans. Magn.*, vol. 45, no. 3, pp. 1847–1850, 2009.
- [5] H. Kagimoto, D. Miyagi, N. Takahashi, N. Uchida, and K. Kawanaka, *IEEE Trans. Magn.*, vol. 46, no. 8, pp. 3018–3021, 2010.