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RESEARCH ARTICLE

Magnetic coupling coefficient determination of IPT systems under operating conditions

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This study presents a method of determining the magnetic coupling coefficient of inductive power transfer (IPT) systems under real-time operating conditions by measuring the open-circuit voltage and short-circuit current of coupled coils. Besides the theoretical analysis, the proposed method is verified by finite elements simulation and practical evaluation. Both simulation and experimental results have demonstrated that the proposed method can determine the coupling coefficient of both closely and loosely coupled coils with high-quality factors. The method can be used for online monitoring of the coupling condition and real-time power flow controller design of IPT systems.

Keywords: Inductive power transfer, Magnetic coupling coefficient

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I. INTRODUCTION

The magnetic coupling coefficient is a very important parameter determining the performance of inductive power transfer (IPT) systems [1–3]. The output power of an IPT system can be quantified as a function of the magnetic coupling coefficient k by [4],

$$P_{out} = V_1 I_1 k^2 Q_s, \tag{1}$$

where $(V_1 I_1)$ is the volt–ampere of the primary side, and Q_s is the quality factor of the secondary circuit.

Currently, the magnetic coupling coefficient is measured manually using LCR meters [5–9]. However, the method can only be used offline, so it does not work for live IPT systems. The actual magnetic coupling coefficient often varies in practical operation, particularly for loosely coupled IPT systems having large air gap variations [10–12]. It is important to monitor the real-time magnetic coupling condition of an IPT system for its power flow control [13].

This paper proposes a method for determining the magnetic coupling coefficient of IPT systems during operation. The proposed method uses the voltage and current ratios, which can be easily obtained from open-circuit and short-circuit tests.

II. EXISTING METHODS

There are mainly two methods widely accepted for determining the magnetic coupling coefficient of the coupled coils of IPT systems [5]. The first one is based on the measurements of self and leakage inductances, which can be expressed by

$$k = \sqrt{1 - \left(\frac{L_{lk1}}{L_1}\right)} \qquad \text{or} \qquad k = \sqrt{1 - \left(\frac{L_{lk2}}{L_2}\right)}, \tag{2}$$

where L_1 and L_2 are the self-inductances of the primary and the secondary coils measured at each coil when the other coil is open; and L_{lk1} and L_{lk2} are the leakage inductances measured at each coil when the other coil is shorted.

The second method is a series-aiding/series-opposing approach, which can be expressed by

$$k = \frac{L_{sr+} - L_{sr-}}{4\sqrt{L_1 L_2}} = \frac{M}{\sqrt{L_1 L_2}}, \tag{3}$$

where $L_{sr+} = L_1 + L_2 = 2M$ is measured when the total inductance of the primary and secondary coils are connected in series with aiding polarities; and $L_{sr-} = L_1 + L_2 - 2M$ is measured when the two coils are connected in series with opposing polarities.

III. THE PROPOSED METHOD

Unlike the existing methods that are based on off-line measurements, the new method determines the magnetic coupling coefficient of the coupled coils by online measurements of the voltage and current ratios, which can be expressed by

$$k = \sqrt{\frac{|V_{oc}|}{|V_1|} \cdot \frac{|I_{sc}|}{|I_1|}}, \tag{4}$$

where V_{oc} is the open-circuit voltage of the secondary coil when the voltage of the primary coil is V_1, and I_{sc} is the

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short-circuit current flowing through the secondary coil when the current of the primary coil is I_1.

It should be noted that in IPT systems, the open-circuit voltage (V_{oc}) and the short-circuit current (I_{sc}) are the two fundamental parameters used to determine the performance of the secondary power pickup and power transfer capability analysis [11, 14–16]. The results of these tests can then be advantageously used to determine the magnetic coupling coefficient of the system from (4).

A) Theoretical proof

The two coupled coils of an IPT system can be modeled with a T-equivalent circuit as shown in Fig. 1.

From this model, the open-circuit voltage (when $R_L = \infty$) and short-circuit current (when $R_L = 0$) can be expressed as

$$V_{oc} = V_1 \cdot \frac{j\omega M}{R_1 + j\omega[M + (L_1 - M)]}, \tag{5}$$

$$I_{sc} = I_1 \cdot \frac{j\omega M}{R_2 + j\omega[M + (L_2 - M)]}. \tag{6}$$

From (5) and (6) a voltage gain G_v as a ratio of V_{oc} and V_1, and a current gain G_i as a ratio of I_{sc} and I_1, can be expressed as following:

$$|G_v| = \frac{|V_{oc}|}{|V_1|} = \frac{\omega M}{\sqrt{{R_1}^2 + (\omega L_1)^2}}, \tag{7}$$

$$|G_i| = \frac{|I_{sc}|}{|I_1|} = \frac{\omega M}{\sqrt{{R_2}^2 + (\omega L_2)^2}}. \tag{8}$$

These two gains can be further expressed using the quality factors of the primary coil ($Q_1 = \omega L_1/R_1$) and the secondary coil ($Q_2 = \omega L_2/R_2$),

$$|G_v| = \frac{M/L_1}{\sqrt{1/{Q_1}^2 + 1}}, \tag{9}$$

$$|G_i| = \frac{M/L_2}{\sqrt{1/{Q_2}^2 + 1}}. \tag{10}$$

In a practical IPT system, coil quality factors are normally designed to very high (Q_1 and $Q_2 \gg 1$). Thus, (9) and (10) can be simplified as

$$|G_v| = \frac{M}{L_1} \quad \text{and} \quad |G_i| = \frac{M}{L_2}. \tag{11}$$

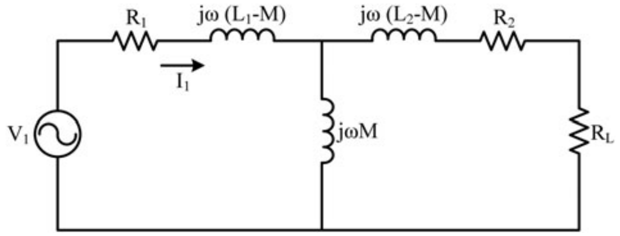

Fig. 1. *T*-equivalent circuit of two magnetically coupled coils.

From (11) it can be proven that the magnetic coupling coefficient k can be determined by (4), which can also be expressed by the voltage and current gains,

$$k = \frac{M}{\sqrt{L_1 L_2}} = \sqrt{|G_v| \times |G_i|} = \sqrt{\frac{|V_{oc}|}{|V_1|} \cdot \frac{|I_{sc}|}{|I_1|}}. \tag{12}$$

B) Simulation and practical verifications

To verify the proposed method, a closely coupled setup similar to a traditional transformer, and a loosely coupled setup with an air gap of 5 mm are built. Fig. 2 shows their three-

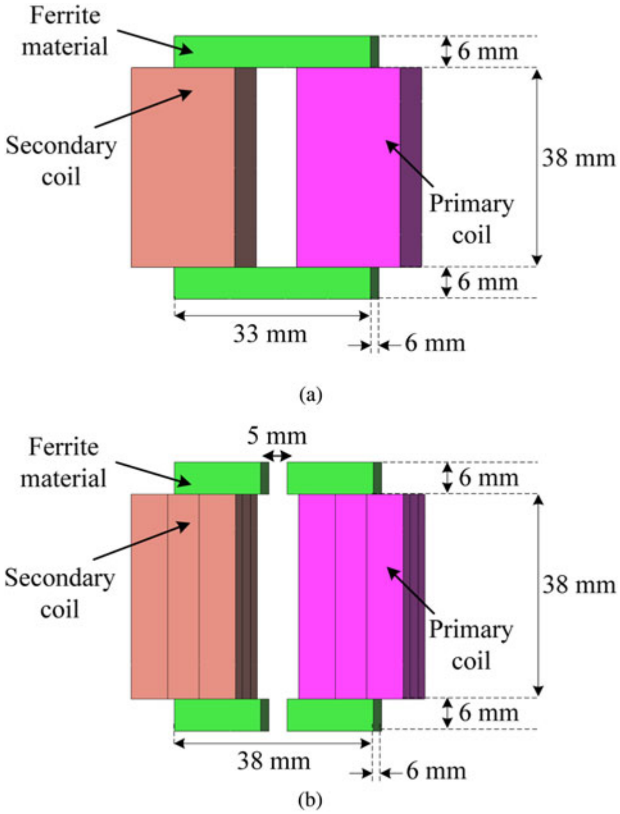

Fig. 2. 3D finite-element models: (a) un-gapped setup and (b) gapped setup.

Table 1. Systems specifications.

Parameter	Value
f (kHz)	50
$N_1 = N_2$	18
$L_1 = L_2$ (μH) (closely coupled setup)	260
$L_1 = L_2$ (μH) (loosely coupled setup)	16.1
$Q_1 = Q_2$ (closely coupled setup)	1614
$Q_1 = Q_2$ (loosely coupled setup)	101
Air gap (mm)	5
Bs of the Mn–Zn ferrite material (T)	0.5

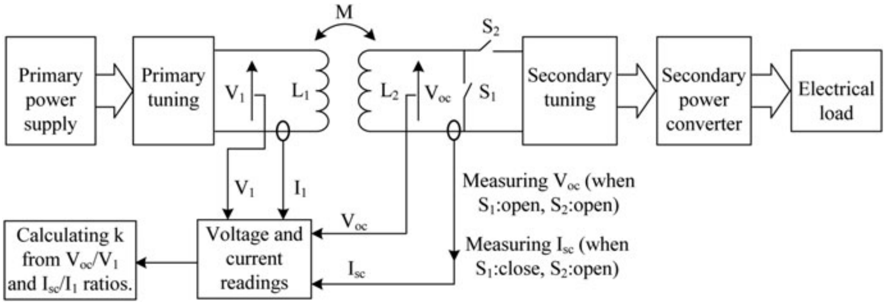

Fig. 3. The proposed method for measuring the coupling coefficient *k*.

dimensional (3D) finite-element models developed by JMAG package. The practical setups are built with the same geometries wound around the U-shape ferrite cores as the simulated model (see Fig. 2). In this research, the simulation and experiments were accomplished at 5 W output power from the power pickup as an example for verification. It should be noted that the actual layout of the magnetic structure and the power level of IPT systems can vary depending on specific application and load requirements.

Table 1 shows the system parameters for simulation study and practical experiments. The magnetic coupling coefficient is obtained from the finite elements simulation for both setups. Then practical testing is performed using the traditional self and leakage inductances offline measurements method. The offline measurement is conducted by disconnecting the coils from the circuit and measuring the inductances of both side coils individually using an LCR meter and then calculating the magnetic coupling coefficient between them from (2). Finally each setup is driven by a high-frequency power converter, and the magnetic coupling coefficients are determined using the proposed method. The primary side voltage and current are measured directly across the primary coil using voltage/current probes and an oscilloscope (Model: DSO5054A Agilent). As the operating frequency of circuit is only at kHz levels and the impedance of the measurement probe is very high, the effect of the probe connection to the circuit on the system tuning is negligible. On the secondary side, when the pickup circuit and the load are in operation, they are disconnected for a short time for getting the reading using the two added switches S_1 and S_2 as shown in Fig. 3. As practical power pickups have filters at the output with high time constants [1, 17, 18], the effect of short time disconnection from the pickup coil on the output voltage would be very small.

There is another measurement method that has been proposed in [19], which requires the values of the inductances as well as the capacitances of the system for the initial measurements, and then the contribution of the capacitance is subtracted from the calculated results to separate the contribution of the inductive components. The proposed method determines the magnetic coupling using the voltage and current ratios (V_{oc}/V_1 and I_{sc}/I_1) without the inductances values, and it does not need to involve the capacitances of the system, making online measurement of the coupling coefficient possible.

Table 2. Magnetic coupling coefficient (*k*) results.

Magnetic coupling structure	JMAG simulation	Offline method	The proposed online method
Un-gapped structure	0.9513	0.9510	0.9479
Gapped structure	0.2253	0.2191	0.2141

The results are listed in Table 2, which shows a very good agreement between the simulation, offline and the proposed online method. This signifies that accurate magnetic coupling coefficient can be obtained using the proposed method.

IV. CONCLUSION

This paper has presented an online method for determining the magnetic coupling coefficient between two coupled coils for IPT applications. It has been found that the real-time magnetic coupling coefficient can be obtained by online measurements of the open-circuit voltage and short-circuit current of IPT systems during practical operation. The results from the finite-element simulation and practical experiments have shown that the proposed method can be used to accurately determine the magnetic coupling coefficients of both closely and loosely coupled coils with high-quality factors.

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