# Coupling Coefficient Extraction between Transmitter Coils and Receiver Coil in Wireless Power Transfer System for Automatic guided vehicles

**Sungryul Huh [1] Seongho Woo [1] Dongryul Park [1] Seungyoung Ahn [1]**
*1) KAIST, CCS Graduate School of Mobility, Daejeon, Korea*
*E-mail: tjdfuf2397@kaist.ac.kr, seongho@kaist.ac.kr, dongryulpark@kaist.ac.kr, sahn@kaist.ac.kr*

**ABSTRACT**: This paper proposes a method for extracting the coupling coefficients of a receiver coil and each transmitter coil in a wireless power transfer system composed of multiple transmitter coils for automatic guided vehicles (AGVs). The coupling coefficient is essential information because the operation state of several transmitter coils is determined depending on the coupling coefficient with the receiver coil. In addition, in case of movement of the receiver coil or a change in load, the information of the receiver coil should be monitored even in the deactivated transmitter coils. The proposed coupling coefficient extraction method is designed to extract the coupling coefficient even when the transmitter coil is deactivated. The proposed method was verified by targeting a 300 W class AGV, and the results of the proposed method had a small error of 2.5% compared to the results measured using dedicated equipment.

**KEY WORDS**: automatic guided vehicle, wireless power transfer, multiple coils, coupling coefficient, power electronics, LCC topology

## 1. INTRODUCTION

Recently, as the demand for electric vehicles (EVs) and automatic guided vehicles (AGVs) has rapidly increased, research on their charging system is being actively conducted. The wired charging method currently used has the advantage of stably transmitting high power using a charging cable. However, there are problems such as damage to the charging cable, inconvenience caused during charging, and risk due to damage to the charging terminal, so the paradigm of the charging system is changing to wireless charging, as in [1]-[3].

Although wireless charging has advantages such as automation and convenience of charging, there are still several problems, such as power transmission efficiency and misalignment between the transmitter (TX) and receiver (RX) coils. In particular, when lateral misalignment occurs, the coupling coefficient ($k$) between the coils is reduced, resulting in a sharp decrease in efficiency and amount of transmitted power. Therefore, many studies have been conducted on coil structures resistant to misalignment.

There are various types of AGVs in factories depending on their use, and the size and location of the RX coil may be different for each model. Therefore, even if the AGV is well parked on the charging pad, the TX coil and the RX coil may not be well aligned, so a different design of the charging pad or a new parking algorithm is required for each model.

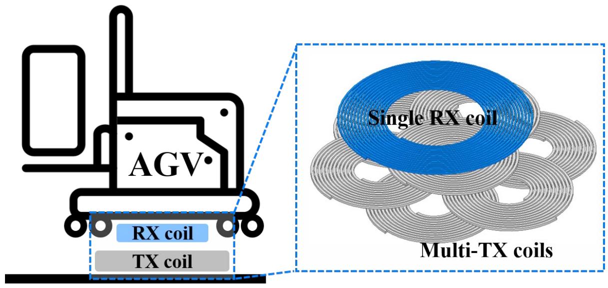



Fig. 1 A WPT system with multiple transmitter coils for AGV

A method to solve these problems is configuring a charging pad using multiple coils. When multiple coils are used rather than a single coil, the degree of freedom of the position of the RX coil is greatly improved, and power loss and leakage electromagnetic field can be reduced by forming a magnetic field only in a necessary area. Therefore, even if the size or position of the RX coil is different, the magnetic field is formed accordingly so that it is possible to have high efficiency and power transmission amount.

Coupling coefficients between each TX coil and RX coil ($k_{TXRX}$) are required to operate the multiplex TX coil, depending on the location or size of the RX coil. The $k_{TXRX}$ is calculated by sending a small signal from the transmitter and sensing the voltage induced in the RX coil. The information is transmitted to the MCU of the transmitter using a communication protocol, and the input voltage and current are adjusted accordingly. Recently, many studies have been conducted on a method of extracting a coupling coefficient through a change in the input impedance of the transmitter without using a communication protocol, as in [4]-[6].

In particular, [6] studied a TX coil current adjustment method according to the ratio of $k_{TXRX}$ values in the multi-TX WPT system. However, in [6], all TX coils should be activated. In order to effectively use the multi-TX WPT system, only specific TX coils are operated according to the position and size of the RX coil, and some TX coils that are not helpful for power transmission should be deactivated to reduce the power loss and the leakage EMF. In addition, regardless of the activation state of the TX coil, it is necessary to know all coupling coefficients to control the operation of the transmitter in real-time.

In this paper, we propose a coupling coefficient extraction method for optimal transmitter operation in a multi-TX WPT system for wireless charging of 300 W class AGV. The proposed method has the advantage of extracting the coupling coefficient even when the TX coil is deactivated.

This paper is organized as follows. Section II presents the mathematical derivation process of the proposed coupling coefficient extraction method. Section III describes the process and results of experiments to verify the proposed system, and Section IV concludes the paper.

## 2. COUPLING COEFFICIENT EXTRACTION METHOD ACCORDING TO THE TX ACTIVATION STATE

A simplified multi-TX WPT system can be represented as shown in Fig.2. The multi-TX WPT system is composed of the $N^{th}$ TX coils, $m^{th}$ TX coils transmit power to the RX coil in an active state, and $(N-m)^{th}$ TX coils are inactive because the coupling coefficient with the RX coil is too small.

At this time, if the RX coil is moved, every $k_{TXRX}$ will be changed, and the combination of the activated TX coil can be changed accordingly. Therefore, it should be possible to monitor all coupling coefficients regardless of the operating state.

The relative magnitudes of coupling coefficients $k_{A1}$ and $k_{A2}$ between the activated TX coil and RX coil in Fig. 2 can be calculated as follows through the method proposed in [6].

$$\frac{k_{A2}}{k_{A1}} = \frac{1/\left\{\omega^2 C_{lcc}^2\left(\left|\frac{V_{in,FH}}{I_{in,A2}}\right|-R_{lcc}\right)\right\}-R_{tx}}{1/\left\{\omega^2 C_{lcc}^2\left(\left|\frac{V_{in,FH}}{I_{in,A1}}\right|-R_{lcc}\right)\right\}-R_{tx}} \quad (1)$$

However, a method for calculating the coupling coefficient $k_D$ between the deactivated TX coil and the RX coil has not yet been presented. Therefore, in this paper, the relative value of $k_D$ was calculated by comparing the magnitude of the current flowing through the compensation inductor ($L_{lcc}$) in the deactivated state and the current flowing through the compensation inductor of the activated TX coil.

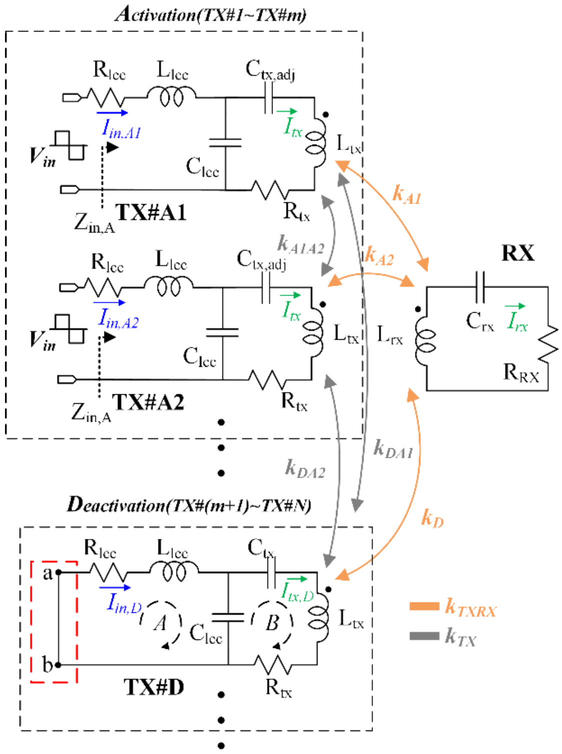



Fig. 2 A simplified WPT circuit with multiple transmitter coils

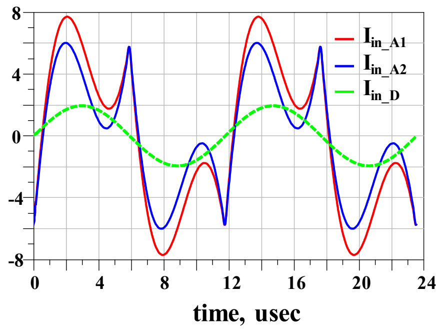



Fig. 3 Input current of each TX unit.

Each current equation calculated through impedance analysis is as follows.

$$I_{in,m} = \frac{\omega^2 C_{lcc}^2 (Z_{refl,m}+R_{tx}) V_{in,FH}}{R_{lcc}(\omega^2 C_{lcc}^2)(Z_{refl,m}+R_{tx})+1} \quad (2)$$

$$I_{in,D} = \frac{\omega^3 C_{lcc}^2 L_{tx} V_{in,FH}\left(\frac{\omega L_{rx} k_D \sum_{\chi=1}^{m} k_\chi}{Z_{rx}}\right) + j\sum_{\tau=1, \tau\neq D}^{m} k_{D\tau}}{\omega^2 C_{lcc}^2 R_{tx}+1} \quad (3)$$

Using (2) and (3), the ratio of the coupling coefficient can be derived as in (4).

$$\frac{k_D}{k_{A1}} = \frac{\sqrt{(\omega C_{lcc})^{-2}\left|I_{in,D}\right|^2 + \left(\omega^2 C_{lcc} V_{in,FH} L_{tx} \sum_{\tau=1, \tau\neq D}^{m} k_{D\tau}\right)^2}}{\frac{\left|I_{in,A1}\right|}{\omega C_{lcc}} - \omega C_{lcc} R_{tx} V_{in,FH}} \quad (4)$$

In (4), all other terms except for the magnitude of input current of each TX unit are known values and do not include information about the receiver. Therefore, it is possible to calculate the coupling coefficient between each TX coil and RX coil without communication technology with the receiver.

Although (4) is a relative size, if it is used, the ratio of the coupling coefficient between each TX coil and the RX coil can be calculated by the proposed equation. Through the information, it is possible to select a TX coil combination to operated depending on a change in the position of the RX coil.

All input current equations analyzed in this paper were analyzed by the Fundamental harmonic approximation method (FHA). The input current of the deactivated TX unit has a shape close to a sine wave, but the input current of the TX unit operating as shown in Fig. 3 is not a clean sine wave due to some high-order harmonic components by the LCC-S topology. Figure 3 shows the input current waveform when the coupling coefficients of TX_A1, A2, and D are set to 0.15, 0.1, and 0.05, respectively. If the coupling coefficient of the activated TX unit is rapidly reduced by an external force, the harmonic component becomes larger than the fundamental component, causing an error in coupling coefficient extraction. However, since the coupling coefficient of an activated TX unit with a large harmonic component in the input current generally has a large value, this paper does not consider the error.

The rms value of the AC input current can be extracted using an RMS-to-DC converter such as Linear Technology's LTC1966, and the proposed coupling coefficient extraction method can be applied to the information using an MCU such as Texas Instrument's TMS320F28335.

## 3. EXPERIMENTAL VERIFICATION

To verify the proposed method of extracting the coupling coefficient of the deactivated TX coil, the coil was arranged as shown in Fig. 4. We measured the input current changes according to the position of the RX coil, which can be calculated (2) and (3). The measured values were converted to extract the coupling coefficient by (4). They were compared with the results measured by the direct measuring instrument VNA.

First, among the 7 TX coils, TX7, TX3, and TX1 are activated to transfer power to the RX coil located at (80,0) in Fig. 4. Tables 1 and 2 show the geometry and electrical characteristic values of each coil. Therefore, these three TXs are in an activated state, and the remaining four TXs are in a deactivated state. At this time, the input currents of each TX corresponding to (2) and (3) were measured, and the results are shown as the black graph in Fig. 4(a).

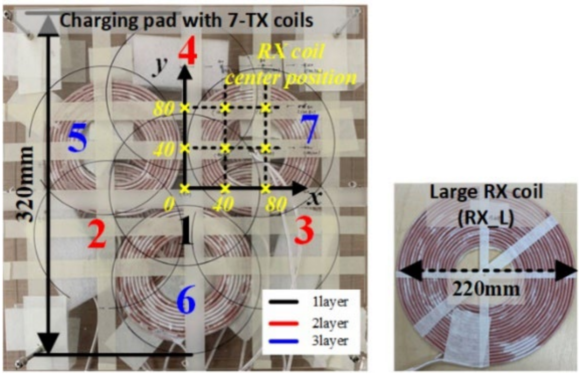



Fig. 4 Experiment setup for 7-TX and 1-RX MTSR WPT system

Table 1 Geometrical parameters of TX coil and RX coil

| Parameters | TX coil | RX coil |
|---|---|---|
| Outer diameter | 150 mm | 220 mm |
| Inner diameter | 86 mm | 76 mm |
| Litz wire (Diameter/strands) | 0.05 mm/2625 | |
| Turn | Top: 8 turns<br>Bottom: 9 turns | 18 turns |
| Overlap | 65 mm | - |
| Airgap | 50 mm | |

Table 2 Electrical parameters of TX coil and RX coil

| Parameters | TX coil | RX coil |
|---|---|---|
| Operating frequency | 85 kHz | |
| Inductance | 40.83 μH | 49.13 μH |
| Parasitic resistance | 50 mΩ | 80 mΩ |
| Output power | - | 300 W |

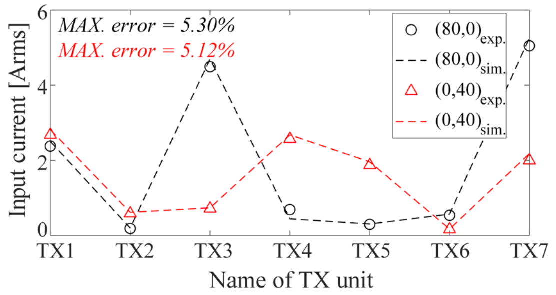
Also, the change in the current magnitude when the RX coil is moved to (0,40) is shown in the red graph in Fig. 4(a).

By substituting these input current values into (4), the change in coupling coefficient of each TX coil and RX coil can be calculated, and the result is shown in Fig. 4(b). It was confirmed that this result has a small error of up to 2.53% from that measured by VNA.

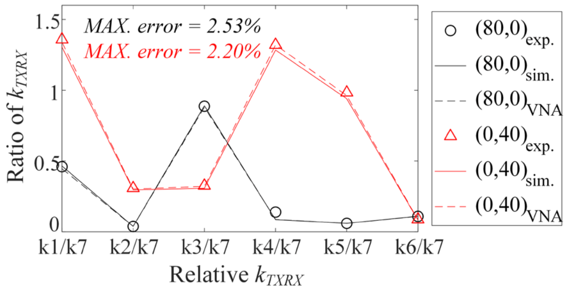
Using this result, it is possible to select a suitable TX coil again according to a change in the position of the RX coil and operate it to have maximum efficiency.

## 4. CONCLUSION

This paper proposes a method for extracting the coupling coefficient between each TX coil and RX coil in a multiple TX WPT system for AGV. Using the proposed method, even if some TX coils are deactivated, the relative size of coupling coefficients




(a)




(b)

Fig. 4 Experiment results (a) Each TX coil current (b) Calculated coupling coefficients by proposed method

between all TX coils and RX coils can be extracted. Since the current ratio of each TX coil can be determined only by the relative size, not the absolute value, the multiple TX WPT system can be efficiently operated by applying the proposed method. The proposed method was verified by targeting a 300 W class AGV, and the result extracted using the proposed method had a small error of 2.5%, with the result obtained using the dedicated measuring equipment. The small error does not affect the operation of the TX unit. This manuscript is an extended summary manuscript, and the process of derivation and verification of the proposed method for the final manuscript will be presented in detail later.

## ACKNOWLEDGMENT

The authors would like to thank the technical support from ANSYS Korea and KEYSIGHT Korea

## REFERENCES

(1) Z. Yan et al., "Efficiency Improvement of Wireless Power Transfer Based on Multi-transmitter System," in IEEE Transactions on Power Electronics, vol. 35, no. 9, pp. 9011-9023, Sept. 2020.

(2) S. Liu et al., "Efficiency Improvement of Dual-Receiver WPT Systems Based on Partial Power Processing Control," in IEEE Transactions on Power Electronics, vol. 37, no. 6, pp. 7456-7469, June 2022.

(3) B. Yang et al., "Analysis and Design of a T/S Compensated IPT System for AGV Maintaining Stable Output Current Versus Air Gap and Load Variations," in IEEE Transactions on Power Electronics, vol. 37, no. 5, pp. 6217-6228, May 2022.

(4) S. Zhou and C. Chris Mi, "Multi-Paralleled LCC Reactive Power Compensation Networks and Their Tuning Method for Electric Vehicle Dynamic Wireless Charging," in IEEE Transactions on Industrial Electronics, vol. 63, no. 10, pp. 6546-6556, Oct. 2016.

(5) B. Esteban, M. Sid-Ahmed and N. C. Kar, "A Comparative Study of Power Supply Architectures in Wireless EV Charging Systems," in IEEE Transactions on Power Electronics, vol. 30, no. 11, pp. 6408-6422, Nov. 2015.

(6) D.-H. Kim, S. Kim, S.-W. Kim, J. Moon, I. Cho, and D. Ahn, “Coupling extraction and maximum efficiency tracking for multiple concurrent transmitters in dynamic wireless charging,” IEEE Transactions on Power Electronics, vol. 35, no. 8, pp. 7853–7862, Dec. 2020.