Method of Moments Electromagnetic Field Analysis for Wireless Power Transfer Efficiency Improvement using Reverse-Coil Configuration for Magnetic Field Coupled WPT

Akari KAMADA[†], Tamami MARUYAMA[†], Noa EBITA[†], Masashi NAKATSUGAWA[†],
Masaya TAMURA [‡], and Noriharu SUEMATSU[†‡]

†National Institute of Technology, Hadakote College 14-1 Tokura, Hakodate-shi, Hokkaido, 042-8501 Japan
‡Toyohashi University of Technology, 1-1, Hibarigaoka, Tempaku-cho, Toyohashishi, Aichi, 441-8580 Japan
[†‡]Tohoku University 2 Chome-1-1 Katahira, Aoba Ward, Sendai, Miyagi, 980-0812 Japan

E-mail: †{23703, maruyama, 23702 }@hakodate.kosen-ac.jp, †nakatsugawa@hakodate-ct.ac.jp ‡tamura@ee.tut.ac.jp,
†‡noriharu.suematsu.a3@tohoku.ac.jp

Abstract It has been theoretically reported that reversing the orientation of coils in magnetic field-coupled Wireless Power Transfer (WPT) systems changes the direction of current flow and the sign of the electromagnetic field, thus altering the value of the coupling coefficient. Therefore, in this study, we used electromagnetic field analysis with the Moment Method (WIPL-D) to elucidate the relationship between the coil orientation, kQ product, wireless power transmission efficiency (η), and maximum wireless power transmission efficiency (η_{max}). By reversing the orientation of the transmitting and receiving coils, we revealed that the coupling coefficient k becomes stronger, resulting in an increase in the kQ product and the η_{max}. On the other hand, we also found that the S_{12} characteristics and the η calculated based on them do not differ significantly from the maximum value in the in-phase configuration. This is because excessive coupling in the out-of-phase configuration causes the peak to break.

Keyword Wireless Power Transmission, WPT, Magnetic coupling, kQ products, Wireless power transmission efficiency.

1. INTRODUCTION

In magnetic field-coupled Wireless Power Transfer (WPT), we have proposed to insert a parasitic coil between the transmitting and received coils to improve the wireless power transmission efficiency (η) [1]. It has also been reported through simulations [2] and measurements [3] that the η and maximum wireless power transmission efficiency (η_{max}) can be further improved by loading inductance onto the transmitter, receiver, and relay coils for wireless power transfer,. Besides, the authors have reported the effects of impedance loading when applying the symmetry of the magnetic field generated on both sides of the power supply coil for simultaneous wireless power delivery to multiple devices with a single power supply [4]. The coupling coefficient k, which is also found in the kQ product, an important factor in the calculation of η, can be calculated using the difference between the integrals of the electric and magnetic fields. Therefore, the value of the coupling coefficient k also changes when the sign of the integrals of the electric and magnetic fields changes depending on the direction of the current flowing in the coil, and theoretical analysis has reported that reverse winding is more efficient [5]. In this study, we conducted electromagnetic field analysis using the Moment Method (WIPL-D) in order to apply this concept to further enhance the efficiency of magnetic field-coupled WPT, for both cases where the coils had the same orientation and where they had opposite orientations. The comparison calculated results kQ product and S-parameters for each case are shown.

2. ANALYSIS RESULTS

The analysis model is shown in Fig. 1. In this design, we followed the specifications based on reference [5], with a frequency of 25 MHz, coil diameter D=245mm, coil pitch of 10mm, coil-to-coil distance of 50mm, and a total of 11 turns. These coils were analyzed using the WIPL-D for both cases where they were in-phase (as shown in Fig. 2) and out-of-phase configurations. The kQ product was calculated using the methods described in references [6] and its frequency characteristics were illustrated in Fig. 3. The out-of-phase is shown by the red line and the in-phase by the blue line in the graphs. As seen from Fig. 3, , the kQ product is significantly higher over nearly the entire range from 10 MHz to 90 MHz when the coils are out-of-phase with the current direction reversed. In particular, at the design frequency of 25 MHz, the kQ product of the out-of-phase is the largest, approximately 3.3 times larger than that of the in-phase. The frequency response of the S_{21} characteristic is shown in Fig. 4. As can be seen from

Fig. 4, the maximum value of S_{21} at the peak frequency is approximately the same for both in-phase and out-of-phase configurations. However, it is noticeable that the peak of the maximum value is shifted further away, indicating a stronger coupling, when in the out-of-phase configuration,.

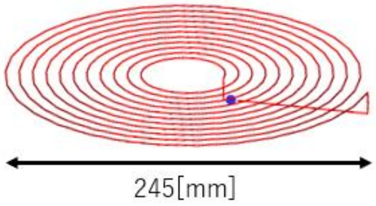

Fig.1. Analysis model of coil for magnetic coupling WPT.

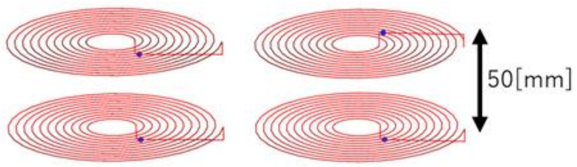

Fig.2. Coil arrangement and distance between coils.

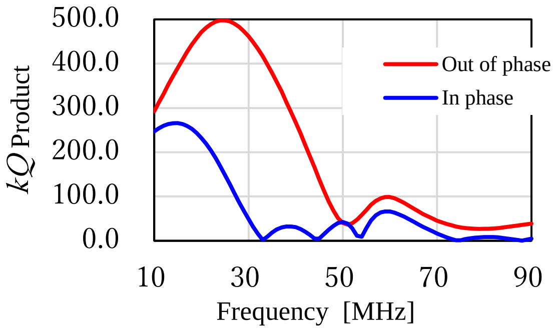

Fig.3. kQ product vs. Frequency.

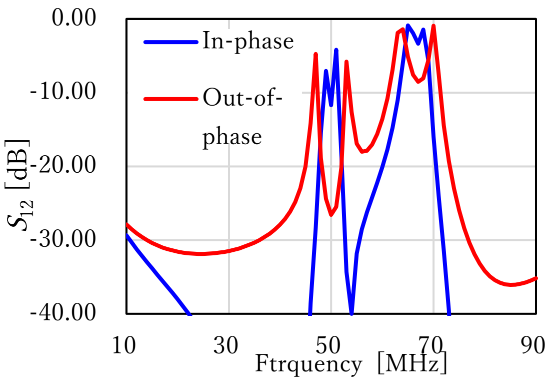

Fig.4. S_{12} vs. Frequency.

The formula for calculating the k is shown in Equation (1) [5].

$$k=\frac{\left|\int_V\left(\mu \boldsymbol{H_1}^{*}\cdot\boldsymbol{H_2}-\varepsilon \boldsymbol{E_1}^{*}\cdot\boldsymbol{E_2}\right)dV\right|}{\sqrt{\int_V \mu_1|\boldsymbol{H_1}|^2 dV\int_V \mu_2|\boldsymbol{H_2}|^2 dV}} \quad \ldots(1)$$

As shown in reference [5], it is evident from Equation (1) that the signs of the the magnetic and electric fields' integrals in the numerator influence the value of the coupling coefficient. In other words, it is understood that the sign of the electric and magnetic field, which changes depending on the direction of the current in the coil, affects the calculation results of the k.

The η and η_{max} from the S-parameter values were calculated. Here, the η and η_{max} can be determined from equations (2) and (3), respectively, as derived from references [6], [7].

$$\eta=|S_{21}|^2\times 100\ [\%] \quad \ldots(2)$$

$$\eta_{max}=(tan\theta)^2\times 100\ [\%] \quad \ldots(3)$$

Here,

$$\theta=\frac{1}{2}Tan^{-1}(kQ) \quad \ldots(4)$$

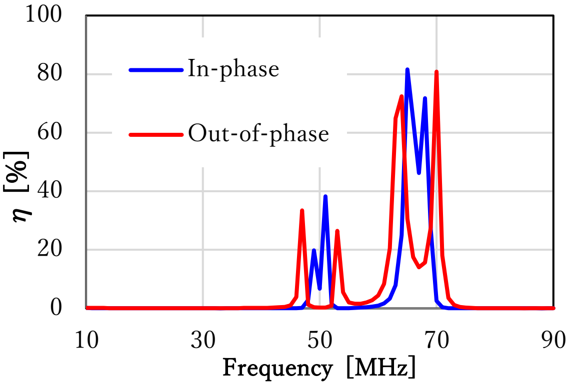

Fig.5. WPT efficiency η vs. Frequency.

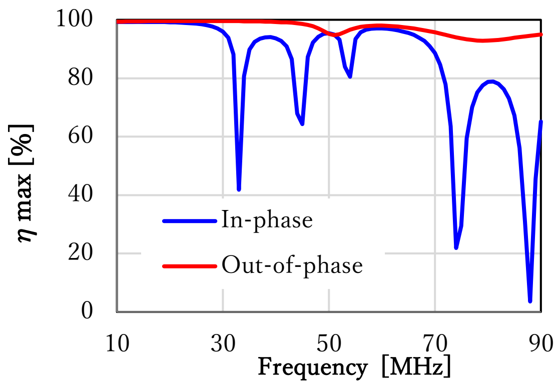

Fig.6. η_{max} vs. Frequency.

The frequency characteristics of the η and η_{max} are shown in Fig. 5 and 6, respectively. It can be observed that this coil resonates near 50 MHz and 65 MHz. The kQ product shown in Fig. 3 takes its minimum value at the resonance frequency of 50 MHz, where the coils are arranged in out-of-phase, and the explanation for this phenomenon is a subject for future investigation. Furthermore, Fig. 6 confirms that the η of over 90% is achieved in the frequency range from 10 MHz to 90 MHz by reversing the phase of the coils.

3. CONCLUSION

In this study, we investigated how the characteristics of the kQ product and η in magnetic field-coupled WPT change when the orientation of the transmitting and receiving coils is in-phase or out-of-phase. This investigation was conducted through electromagnetic field analysis using the moment method and theoretical calculations. By reversing the orientation of the transmitting and receiving coils, we discovered that the coupling becomes stronger, leading to an increase in the kQ product and η_{max}. On the other hand, we also revealed that the S_{12} characteristics and the η calculated based on them do not differ significantly when the coils are out-of-phase, as increasing the coupling too much causes the peak to break. In the future, we plan to apply these findings to relay-element insertion and inductance-loaded magnetic field-coupled WPT, which we have been studying, aiming for further efficiency improvements.

Acknowledge

This work was supported by JSPS KAKENHI Grant Number C21K04050, and the Research Institute of Electrical Communication, Tohoku University. This work was partially supported by Collaborative Research Program 2023 Information Initiative Center, Hokkaido University, Japan. This work was partially supported by Collaborative Research on Toyohashi University of Technology, Japan. This study was supported in part by Grants-in-Aid for Regional R&D Proposal-Based Program from Northern Advancement Center for Science & Technology of Hokkaido Japan.

References

[1] K. Furuta, R. Baba, S. Endo, K. Nunokawa, W. Takahashi, and T. Maruyama, “Effect of mutual coupling and positional deviation between the coil on wireless power transfer,” in *AIP Conf. Proc.*, 2017, vol. 1865, No. 07003, pp.1-3; doi/abs/10.1063/1.4993385.

[2] T. Maruyama, T. Kimura, and M. Nakatsugawa, “Magnetic coupling WPT efficiency improvement by inserting relay coil with optimized load impedance,” in *Proc. 2021 IEEE Int. Symp. Antennas Propag. and USNC-URSI Radio Sci. Meeting* (APS/URSI), Dec., 2021.

[3] T. Maruyama, K. Shibata, and M. Nakatsugawa, “Experimental study of efficiency with inductance load and relay coil for magnetic field coupling WPT,” in *Proc. ISAP 2022*.

[4] A. Kamada, T. Maruyama, M. Nakatsugawa and M. Tamura, “Analysis on the wireless power transmission efficiency of the moving objects simultaneously fed by a single coil for the magnetic field coupled WPT,” in *Proc. AWPT 2022* pp.134-136, 2022.

[5] I. Awai, Y. Zhang, T. Komori and T. Ishizaki, “Coupling coefficient of spiral resonators used for wireless power transfer,” in *Proc. APMC2010*, TH3G-16, pp.1328-1331.

[6] T. Ohira, “What in the world is Q,” *IEEE Microwave Magazine*, vol.17, no.6, p.42-49, May, 2016.

[7] Q. Yuan, Q. Chen, and K. Sawaya, “Numerical analysis on transmission efficiency of evanescent resonant coupling wireless power transfer system," *IEEE Trans. Antennas Propag.*, vol. 58, no. 5, pp. 1751-1758, May, 2010.

[8] T. Ohira, “Angular expression of maximum power transfer efficiency in reciprocal two-port systems,” in *Proc. IEEE WPTC* 2014, 2014, pp.228-230.

[9] Q. Yuan, Q. Chen, and K. Sawaya, “Numerical analysis on transmission efficiency of evanescent resonant coupling wireless power transfer system,” *IEEE Trans. Antennas Propag.*, vol. 58, no. 5, pp. 1751-1758, May, 2010.