Design and Implementation of Near-Field Spatial Wireless Power Transfer Using Orthogonal Multiple Coils

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***Abstract*— In this paper, we propose a three-dimensional (3D) wireless power transfer (WPT) system using highly isolated orthogonal coils for expanding spatial freedom. The proposed transmitting coil is arrayed with highly isolated orthogonal coils. The proposed 3D WPT coil can transmit the power to the receiving coil regardless of lateral and angular misalignments of receiving coil through all directions magnetic fields generated by isolated coils. For the performance verification, the power transfer efficiency (PTE) under the lateral and angular misalignments in the operating area is measured and compared with the conventional WPT system and the proposed 3D WPT system. The proposed 3D WPT system is matched at 6.78 MHz and achieves approximately 50% or more PTE regardless of all lateral and angular misalignments when the receiving coil is set to 180 $\times$ 180 mm^2 and the PTE is measured in the operating area of 300 $\times$ 300 $\times$ 300 mm^3.**

***Keywords*— highly isolated orthogonal coils, lateral and angular misalignments, three-dimensional wireless power transfer.**

I. Introduction

Wireless power transfer (WPT) technology has become a key technology with the development of a variety of mobile devices, because of the significant advantage of being able to provide full mobility to diverse systems that require power. WPT can be divided into the near-field and far-field technologies. The far-field WPT technology uses radiated energy through the antennas having high efficiency. This technology can transmit high power up to a long distance, but the power transfer efficiency (PTE) of the system is very low. Also, far-field technology for use is difficult because far-field technology has the problem of electromagnetic interference on electric devices and the electromagnetic field about human safety. Near-field WPT technology can be divided into two methods, magnetic induction and resonance. The magnetic induction method uses magnetic induction between the first and second coils and uses frequencies of hundreds of kHz, the transmission distance is several mm or less, and the transmission efficiency is about 90% in areas below 1 mm. This approach has a very high PTE but is very sensitive to transmitter-receiver alignment. Most of the commercially available products currently use a method of magnetic induction. The magnetic resonance method is a special case of electromagnetic induction and is a method using a resonance coil to use a resonance phenomenon between transmitting and receiving coils. It uses frequencies of several MHz and has a transmission distance of 1 m or less. The magnetic resonance method has high PTE, a mid-range operating distance, and relatively low sensitivity to the alignment. However, magnetic resonance technology's efficiency varies greatly depending on lateral and angular misalignments of transmitting and receiving coils. To resolve these concerns, coil structures that can generate magnetic fields in all directions are required.

Various research has been proposed to improve the efficiency under the misalignment [1]–[22]. To improve the efficiency due to lateral misalignment, a hybrid array resonator structure [1]–[2], a coil with metamaterials [3], stacked coils with different size coils [4], and coils with extended transmission areas [5] were proposed. To improve efficiency according to the operating distance, module integrated coil with metal-plated for eddy current [6], the antiparallel loop with constant mutual inductance [7], transmitting coil with an auto-matching system [9], and three coil WPT system with surface resonator [10]. However, although these studies have improved PTE in distance or lateral misalignment, the efficiency under the angular misalignment does not improve. Helmholtz coil with automatic frequency tracing technique [13], phase-shift controlled multiple coils [14], orthogonal coils [15], cylinder and cube shape coils [16]–[21], and overlapping coils [22] have been proposed to increase transfer efficiency under lateral and angular misalignments.

In this paper, the 3D WPT system for improved spatial freedom using highly isolated orthogonal multiple coils is proposed. Each orthogonal coil generates magnetic fields in the x-, y-, and z-direction and can transfer power under the angular misalignment of receiving coil. The proposed 3D WPT system that operates at 6.78 MHz improves the transfer efficiency under lateral and angular misalignments for the receiving coils within the charging area. The improved transfer efficiency is shown by comparing the PTEs of the conventional WPT system and the proposed 3D WPT system.

II. Proposed Highly Isolated Multiple Coils

A. *Operating principle of the proposed 3D WPT system*

Fig. 1 shows the concepts of the 3D WPT system for improved lateral and angular misalignments. The proposed 3D WPT system supports power transmission under lateral and angular misalignments of the receiving coil using highly isolated orthogonal coils. The proposed WPT system has five coils with two cases of configuration. Coils 1–4 are located on the xz or yz plane and coil 5 is located on the xy plane. In Figs. 2(a)–(c), the transmitting coil 5 generates the H_z field, whereas transmitting coils 1, 3 and coils 2, 4 generated

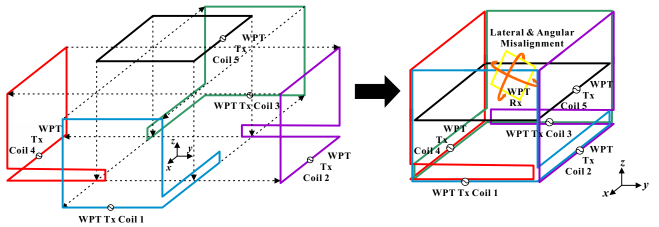

Fig. 1. Concept of the proposed 3D WPT system using highly isolated multiple coils.

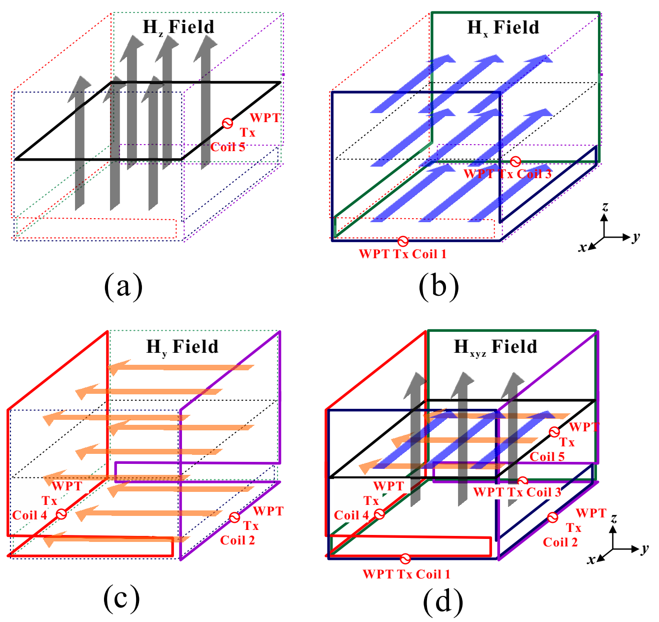

Fig. 2. Magnetic field of each operating case of the highly isolated coils: (a) H_z field, (b) H_x field, (c) H_y field, and (d) H field

the H_x and H_y fields, respectively. The orthogonal coils can transfer the power regardless of angular misalignment because each transmitting coil generates the x-, y-, z-axis magnetic field. Fig. 2(d) shows the magnetic field distribution. In this case, the x-, y-, z-axis magnetic fields are generated when all transmitting coils are operated at the same time. In order to radiate the magnetic field of each axis without mutual interference, it is necessary to secure high isolation between coils. In this paper, to design a transmitting coil having high isolation between transmitting coils, the overlap interval between each coil with minimal mutual inductance was calculated by setting parameters of the 2D and 3D multi-coils structures as shown in Fig. 3. In Fig. 3, each coil was divided into respective conductors. Each conductor of each coil was grouped into a–e. In Fig. 3(a), the width of the coil and the gap between the two coils used in the calculation are 300 mm and 2 mm, respectively. As shown in Fig. 3(b), the coil structure in which a part of one side extends from one planar coil and is folded and overlapped along the outer surface of one adjacent coil is proposed. Each coil's width and length are 300 mm.

The calculated and simulated results of the mutual inductance of each structure are shown in Fig. 4. The mutual

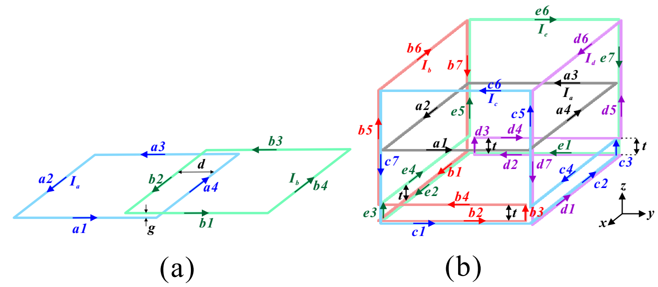

Fig. 3. Coil configuration for the mutual inductance calculation: (a) 2D coil and (b) 3D proposed coil

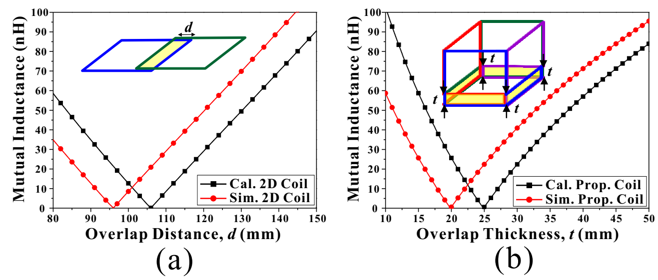

Fig. 4. Mutual inductance depending on the overlap distance and thickness: (a) 2D coil and (b) 3D proposed coil.

inductance is calculated by Neumann formula of

$$M = \frac{\mu_0}{4\pi} \oint_{C_1} \oint_{C_2} \frac{dl_1 dl_2}{r} \tag{1}$$

where C_1 and C_2 are the integral path of the conductor element of each coil, dl_1 and dl_2 are the lines of C_1 and C_2, respectively, and r is the distance between dl_1 and dl_2. As shown in Fig. 4(a), if the 2D coils are overlapped by 96 mm, the mutual inductance is minimized, and the coils are isolated. Fig. 4(b) is the result of analyzing the minimum mutual inductance by adjusting the length of the conductor corresponding to thickness (t). The proposed 3D coil satisfies the minimum mutual inductance even if the overlap interval t is only about 20 mm, which is a reduction compared to the 2D overlapping coil analyzed earlier. In Fig. 4, the difference in the overlap between the simulation and calculation was caused by the coupling between the coils not considered in the calculation

B. Proposed WPT system for improved lateral and angular misalignments

Fig. 5 shows the configuration and parameters of the conventional and proposed 3D WPT system using highly

Table 1. Parameter of the conventional and proposed WPT system

Parameter	l_{c1}	w_{c1}	l_{c2}	w_{c2}	h_c	l_r	w_r
Unit (mm)	300	300	298	298	300	180	180
Parameter	l_{t1}	w_{t1}	l_{t2}	w_{t2}	h_{t1}	h_{t2}	t
Unit (mm)	300	300	298	298	300	160	20

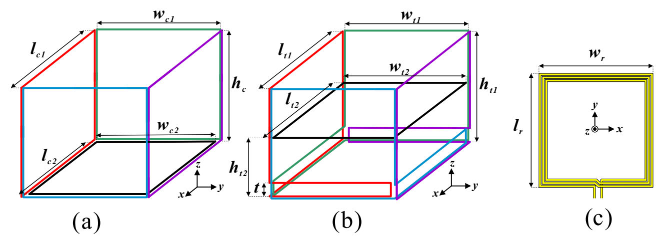

Fig. 5. Configuration of the (a) conventional WPT coil, (b) proposed highly isolated WPT coil, and (c) receiving coil.

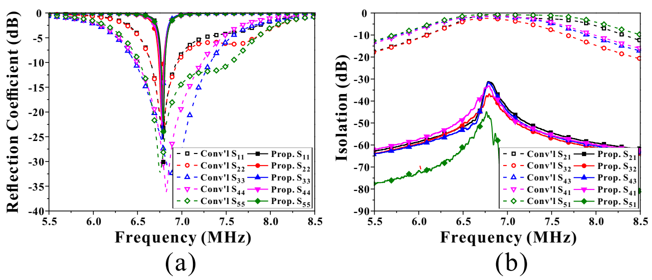

Fig. 6. Characteristic of the proposed WPT system: (a) reflection coefficients of the conventional and proposed transmitting coils, (b) isolation between each coil of the conventional and proposed transmitting coils.

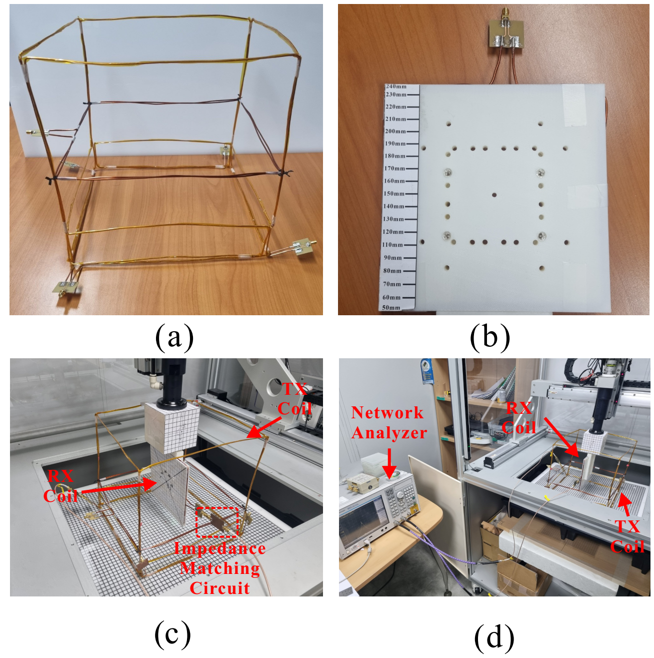

Fig. 7. Implemented proposed 3D WPT system: (a) proposed transmitting coil, (b) receiving coil, and (c)–(d) measurement setup of transfer efficiency with regard to angular misalignments.

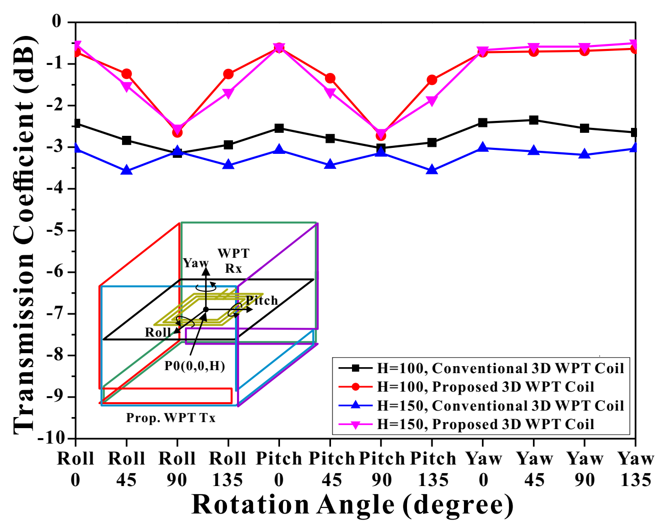

Fig. 8. Measured transmission coefficient with respect to the state of the receiving coil

isolated coils. Fig. 5(a) shows the conventional 3D WPT coil. Figs. 5(b)–(d) show the proposed highly isolated transmitting coil and receiving coil. The conventional and proposed transmitting coils consist of five coils. In Fig. 5(b), coil 5 of the proposed coil is perpendicular to coils 1–4 and is arranged to have isolation by ensuring a distance from the overlapping area. The transmitting and receiving coils were manufactured using 2 mm copper wire. The proposed 3D WPT system was optimized using Advanced Design System 2021. The parameter of the conventional and proposed coils are shown in Table 1. The proposed coil was impedance matched to 6.78 MHz using an impedance-matching circuit.

Fig. 6(a) shows the reflection coefficient of the proposed transmitting and receiving coils. Each coil of the proposed 3D WPT system was matched to less than -20 dB at 6.78 MHz through the matching circuit. The proposed coil is more frequency selective because they are not affected by coils in adjacent areas due to the high isolation. Fig. 6(b) shows the isolation of each coil of the convention and proposed transmitting coils. The isolation of the conventional transmitting coil between each coil is approximately -1 dB, but the isolation of the proposed transmitting coil between each coil is -30 dB or less. As the result, the proposed 3D WPT system has high isolation.

III. Results and Discusstions

To verify the performance under lateral and angular misalignments in the proposed 3D WPT system, the characteristics according to the rotation of receiving coil were compared with the conventional WPT system and the proposed 3D WPT system. The operating area of conventional and proposed 3D WPT systems is 300 × 300 × 300 mm^3. Figs. 7(a)–(b) show the proposed transmitting and receiving coils. To compare the transfer efficiency of the WPT system in charging where the receiving coils are arranged, the transmission coefficients of the conventional and proposed 3D WPT systems were measured using the network analyzer. Fig. 7(c)–(d) shows measurement setup for transfer efficiency due to a misalignment in the operating area using measuring equipment.

Fig. 8 shows the measured transmission coefficient of the conventional and proposed 3D WPT systems for each angle when the receiving coil rotates on the roll, pitch, and yaw angle. The conventional 3D WPT system has a maximum efficiency of 58.27% (-2.345 dB) and minimum efficiency of 43.92% (-3.573 dB) in the charging area. The proposed 3D WPT system has a maximum efficiency of 88.53% (-0.529 dB) and a minimum efficiency of 53.44% (-2.721 dB) in the charging area. In comparison with the conventional WPT system, the proposed system has a high isolation of -30 dB or more between each coil and enables power transmission with high efficiency of approximately 88.53% in the lateral and angular misalignments of receiving coil without an auto-matching circuit.

IV. Conclusion

The proposed 3D WPT system using multiple highly isolated coils for spatial freedom in the operating area has the uniform PTE for lateral and angular misalignments of the receiving coil. The proposed 3D WPT system has a PTE of approximately up to 50% when the receiving coil is disposed and rotates at any angle in all sections of the operating area of $300 \times 300 \times 300$ mm^3. The proposed 3D WPT system can be used in markets and companies where wireless charging methods with spatial freedom are used.

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References

[1] Q. Wang, W. Che, M. Mongiardo, and G. Monti, "Wireless Power Transfer System With High Misalignment Tolerance for Bio-Medical Implants," in *IEEE Transactions on Circuits and Systems II: Express Briefs*, vol. 67, no. 12, pp. 3023–3027, Dec. 2020.

[2] B. Wang, K. Teo, S. Yamaguchi, T. Takahashi, and Y. Konishi, "Flexible and mobile near-field wireless power transfer using an array of resonators," *IEICE Tech. Rep. WPT 2011-16*, 2011

[3] S. Wang, C. Jiang, X. Tax, F. Chen, C. Rong, C. Lu, Y. Zeng, X. Liu, R. Liu, B. Wei, and M. Liu, "Enhancing the Stability of Medium Range and Misalignment Wireless Power Transfer System by Negative Magnetic Metamaterials", *Materials*, vol. 13, no. 24, Dec. 2020.

[4] T. Lim and Y. Lee, "Stacked-coil technology for compensation of lateral misalignment in non-radiative wireless power transfer systems," *IEEE Trans. Ind. Electron.*, vol. 68, no. 12, pp. 12771–12780, Dec. 2021.

[5] W. Lee, S. Park, J. Lee, and M. Tentzeris, "Longitudinally misalignment insensitive dual-band wireless power and data transfer systems for a position detection of fast-moving vehicles," *IEEE Trans. Ant. Propag.*, vol. 67, no. 8, pp. 5614–5622, May 2019.

[6] S. Ahn and W. Lee, "A compact module-integrated wireless power transfer system with a square metal plate," *Microw. Opt. Technol. Lett.*, vol. 61, no. 5, pp. 1235–1239, May 2019.

[7] W. Lee, W. Son, K. Oh, and J. Yu, "Contactless energy transfer systems using antiparallel resonant loops," *IEEE Trans. Ind. Electron.*, vol. 60, no. 1, pp. 350–359, Jan. 2013.

[8] X. Chen, L. Chen, W. Ye, and W. Zhang, "Three-coil Magnetically Coupled Resonant Wireless Power Transfer System with Adjustable-position Intermediate Coil for Stable Transmission Characteristics," *Journal of Power Electronics*, vol. 19, no. 1, pp. 211–219, Jan. 2019.

[9] D. Seo, S. Ahn, J. Kim, S. Khang, S. Chae, J. Yu, and W. Lee, "Power Transfer Efficiency for Distance-Adaptive Wireless Power Transfer System," *Applied Computational Electromagnetics Society Journal*, vol. 33, no. 10, pp. 1171–1174, Oct. 2018.

[10] L. Dong, Y. Zhao, T. Shi, Y. Chen, Y. Liu, G. Deng, L. Liu, and Y. Shi, "Surface resonator for wireless power transmission systems with stable working frequency and high quality factor," *AIP Advances*, vol. 11, no. 5, May 2021.

[11] K. Chen and Z. Zhao, "Analysis of the double-layer printed spiral coil for wireless power transfer," *IEEE J. of Emerg. and Selec. Topics in Power Elec.*, vol. 1, no. 2, pp. 114–121, Jul. 2013.

[12] W. Wei, Y. Kawahara, N. Kobayashi, and T. Asami, "Characteristic analysis of double spiral resonator for wireless power transmission," *IEEE Trans. Ant. Propag.*, vol. 62, no. 1, pp. 411–419, Oct. 2014.

[13] W. Zhang, T. Zhang, Q. Guo, L. Shao, N. Zhang, X. Jin, and J. Yang, "High-efficiency wireless power transfer system for 3D, unstationary free-positioning and multi-object charging," *IET Electric Power Applications*, vol. 12, no. 5, May 2018

[14] N. Kang, C. Ma, and M. Liu, "A linear extendable phase-shift controlled multi-coil transmitter architecture for wireless power transfer with 3D magnetic field shaping," in *IEEE PELS Workshop on Emerging Technologies: Wireless Power Transfer (WoW)*, pp. 170–177, Nov. 2020.

[15] W. M. Ng, C. Zhang, D. Lin, and S. Y. Ron Hui, "Two- and Three-Dimensional Omnidirectional Wireless Power Transfer," in *IEEE Transactions on Power Electronics*, vol. 29, no. 9, pp. 4470–4474, Sep. 2014.

[16] J. Feng, Q. Li, and F. C. Lee, "Coil and circuit design of omnidirectional wireless power transfer system for portable device application," in *IEEE Energy Conver-sion Congress and Exposition (ECCE)*, pp. 914–920, Sep. 2018.

[17] R. Kuo, P. Riehl, and J. Lin, "3-D wireless charging system with flexible receiver coil alignment," in *IEEE Wireless Power Transfer Conf. (WPTC)*, pp. 1–4, May 2016.

[18] Q. Zhu,H.Han, M.Su, and A. Hu, "A 3D wireless charging cube with externally enhanced magnetic field for extended range of wireless power transfer," *Wireless Power Transfer*, vol. 6, no. 1, pp. 67–76, Apr. 2019.

[19] J. Kim, D. Kim, J. Choi, K. Kim, and Y. Park, "Free-positioning wireless charging system for small electronic devices using a bowl-shaped transmitting coil," *IEEE Trans. Microw. Theory Techn.*, vol. 63, no. 3, pp. 791–800, Feb. 2015.

[20] A. Chida, S. Shimokawa, K. Matsui, and H. Oshima, "Three-dimensional wirelesspower transfer method to realize efficient charging of IoT devices," *FUJITSU Sci. Tech. J*, vol. 53, no. 2, pp. 51–56, Feb. 2017.

[21] H. Nam, L. Hoang, M. T. Le, K. Park, and C. Seo, "Free-Positioning Wireless Power Transfer Using a 3D Transmitting Coil for Portable Devices," *Journal of Electromagnetic Engineering and Science*, vol.20, no. 4, pp. 270–276, Oct. 2020.

[22] J. Song, H. An, Y. Li, C. Zhang, and G. Liu, "Modeling and Experimental Analysis of Three-Dimensional Crossed Coil Structure for Misaligned Wireless Power Transfer System," *Progress In Electromagnetics Research C*, vol. 106, pp. 89–103, 2020.