Cooperative Transmitter Structure for Improving Efficiency in Wireless Power Transfer

Wei Chen, Sebastian Rickers, Guido H.Bruck, Peter Jung
Lehrstuhl für KommunikationsTechnik
University of Duisburg-Essen, 47057 Duisburg Germany
info@kommunikationstechnik.org

***Abstract* – Wireless power transfer (WPT) is widely used in portable devices with the advantage of flexibility and conveniences. This paper aims to design a cube transmitter structure, which generates a spatially focused magnetic field providing effective power transfer. The phase shift in multiple coils has been optimized for maximum power transfer efficiency and free positioning in the charging spatial domain. The performance of out-phase multiple coil cube (OPMC) antenna has been compared to that of in-phase multiple coil cube (IPMC) transmitter and traditional single coil. Simulation results show that the OPMC is better and provides higher efficiency wherever the receiver is located inside the cubical region above the cube base.**

***Index Terms* — Wireless power transfer, resonant coupling, magnetic field forming, cube transmitter structure.**

I. Introduction

Wireless power transfer (WPT) systems employ no direct electrical connection between the transmitter (TX) and the receiver (RX). Resonant magnetic coupling technology in the near field is the pivotal role to realize WPT systems [1]. The key performance for WPT systems are the transmission mode with long distance, high efficiency, dynamic use of energy and safety between the transmitter and the receiver. Mobile devices are enabled to be placed and charged on a pad in a free-positioning manner presented in [2]. This paper designs the out-phase multiple coil cube (OPMC) transmitter structure. This system has the advantage of high efficiency and convenience even when the mobile device is placed arbitrarily in the charging region.

II. Magnetic Field Forming Based on Cube Transmitter

A. Magnetic Field Forming

Magnetic field forming is an energy processing technique that used in antenna arrays for directional energy transmission or reception. It is efficient to use multiple coil structure, which can generate the magnetic field forming. When transmitting, a field former controls the phases of power supply in the transmitter to achieve spatial selectivity. Combination of phases in antenna arrays creates a pattern of constructive and destructive interference effect for spatial multiple coils. The aim is to choose the optimized directionality phases in multiple coil cube transmitter structure, which can transfer the magnetic field energy to different positions of the receiver antenna as much as possible in the spatial domain.

B. Cube Transmitter Structure

The cube transmitter structure consists of five circle coils which are fixed on the four sides and the bottom of the cube. The five circle coils are same in size and number of turns. Fig. 1 shows the three dimensional and profile sketch of the cube transmitter structure. The receiver is placed positioning in the cube charging spatial domain.

Because the bottom coil is connected to every side of four coils, the phase of the bottom coil and phase of other four coils on sides should be configured. The phase of each coil is observed from inside of the cube transmitter. Two scenarios are proposed in this paper, which are out-phase multiple coil cube (OPMC) and in-phase multiple coil cube (IPMC) transmitter separately.

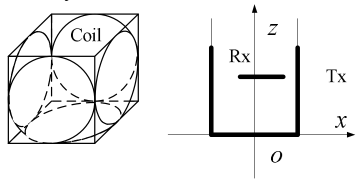


Fig. 1. Three-Dimensional and profile sketch of the five coil cube transmitter structure.

III. Analysis of Improvement Power Transfer System Efficiency

A. Diagram of Resonant WPT System

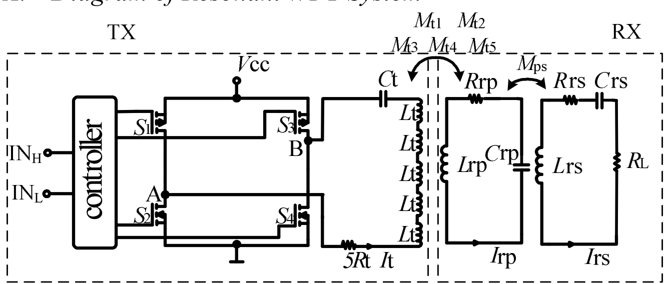


Fig. 2. Wireless power transfer system model for 5 coil cube structure.

Fig. 2 shows the circuit diagram for the WPT system with a 5 coil cube transmitter structure and a receiver. The values of M_{t1}, M_{t2}, M_{t3}, M_{t4}, and M_{t5} are the mutual inductance between the each coil in the transmitter and the receiver. The resonance circuit of TX and RX are tuned to the angular frequency of voltage source in (1). The adjoined inductance L_{adj} of five coils which are series connected is shown in (2). m is the number of coils in the transmitter. M_{ij} is the mutual inductance between each two coils in the transmitter. Plus and minus signs are in-phase and out-phase connection between each two coils in the transmitter side.

$$\omega_0 = \frac{1}{\sqrt{L_{adj}C_t}} = \frac{1}{\sqrt{L_{rp}C_{rp}}} = \frac{1}{\sqrt{L_{rs}C_{rs}}}. \quad (1)$$

$$L_{adj} = 5L_t \pm \sum_{i=1}^{m}\sum_{j=1\neq i}^{m} M_{ij}. \quad (2)$$

B. *Analysis of Improvement Efficiency*

The circuit model is used to analyze the performance of the proposed WPT system using magnetically coupling resonators. Equation (3) gives the efficiency of the WPT system model. The efficiency of the WPT system is proportional to total mutual inductance M_{tot} between the transmitter and the receiver.

$$\eta = \frac{\omega^4 M_{tot}^2 M_{ps}^2 R_L}{(5R_t R_{rp} R_{rsL} + R_{rsL}\omega^2 M_{tot}^2 + 5R_t\omega^2 M_{ps}^2)\cdot(R_{rp}R_{rsL} + \omega^2 M_{ps}^2)}. \quad (3)$$

$$M_{tot} = \sqrt{M_{t1}^2 + M_{t2}^2 + M_{t3}^2 + M_{t4}^2 + M_{t5}^2}, R_{rsL} = R_{rs} + R_L$$

The coupling factor k between transmitter and the receiver, which is defined in (4), depends on the shape of the coil, the number of turns and the relative position of TX and RX. So k is same in the OPMC and IPMC transmitter structure. The larger value of L_{adj} leads to larger M_{tot}.

$$M_{tot} = k \cdot \sqrt{L_{adj}L_r}. \quad (4)$$

IV. Simulation Results

A. *The Optimized Parameters*

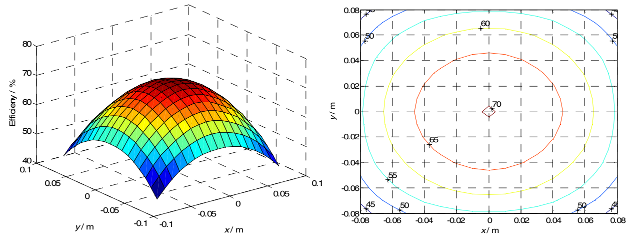
The optimized parameters for WPT system is shown in Table I. L_{adj} is maximal if the bottom coil has π phase shift with other four coils on sides. From (3) and (4), it is easy to observe the efficiency is improved by the OPMC transmitter structure.

TABLE I
The Optimized Parameters for WPT Systems

Coil	Outer Radius (cm)	Inductance (μH)	Resistor (Ω)	Quality Factor
TX(IPMC)	10.5	592.7	3.878	96.5
TX(OPMC)	10.5	977.4	3.983	154.2
RX	3	464.7	3.3	88.3

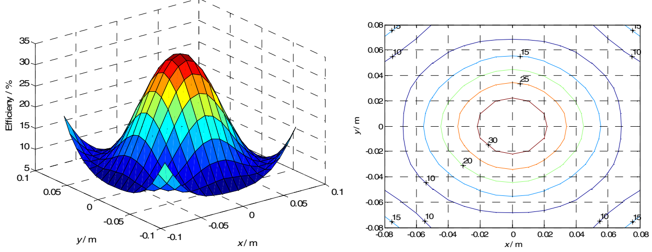
B. *Results Comparison*

The receiver coil is assumed to be placed from – 8 cm to 8 cm in both x-axis and y-axis. The height of the receiver above the bottom coil of transmitter is 5 cm. Fig. 3 (a) and Fig. 4 (a) shows 3D plots of efficiency distribution with OPMC and IPMC transmitter structure, while Fig. 3 (b) and Fig. 4 (b) gives contour lines of the efficiency for 100 kHz.



(a) (b)

Fig. 3 Efficiency of OPMC at 100 kHz. (a) 3D. (b)Contour.



(a) (b)

Fig. 4 Efficiency of IPMC at 100 kHz. (a) 3D. (b)Contour.

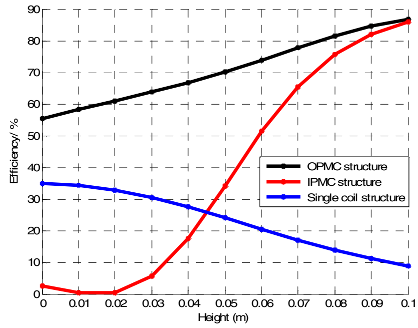


Fig. 5 Efficiency comparison of different receiver positions.

Fig 5 shows the efficiency comparison for OPMC, IPMC and traditional single coil transmitter. The sing coil transmitter has same turns as cube transmitter structure. The receiver is located in (0, 0) in xy-plane with different height above the bottom of the transmitter coil.

V. Conclusion

This paper proposes a cube transmitter structure with phase shift to generate focused magnetic field forming in the transmitting area. From simulation results, the efficiency of OPMC is better than that of both IPMC and the traditional single coil transmitter.

References

[1] A. Kurs, A. Karalis, R. Moffatt, J. D. Joannopoulos, P. Fisher and M. Soljacic, "Wireless Power Transfer via Strongly Coupled Magnetic Resonances," Science Magazine, vol. 317, pp. 83-86, July 2007.

[2] W. X. Zhong, X. Liu and S. Y. Hui, "A novel single-layer winding Array and receiver coil structure for contactless battery charging system with free-positioning and localized charging features," IEEE Transactions on Industrial Electronics, vol. 58, no. 9, pp. 4136-4144, September 2011.