Magnetic Field Forming of Spatial Multiple Antennas for Wireless Power Transfer

Duan Zhao[1], Wei Chen[1], Rani Al-Maharmah[1], Shinjae Kang[2], Seung-Ok Lim[2], Guido Bruck[1], and Peter Jung[1]
1 Lehrstuhl für Kommunikations Technik, Universität Duisburg-Essen,
47048 Duisburg, Germany, duan.zhao@kommunikationstechnik.org
2 Korea Electronics Technology Institute (KETI) 9FL,
Sangam-dong, Mapo-gu Seoul, 121-835, Korea, sjkang@keti.re.kr

1. Introduction

Mobile and portable devices are gaining more and more popularity. One key issue regarding the comfortable use of such devices is the need to recharge them rapidly because of their limited battery capacity. In [1]the writer discussed the future of charging the mobile devices wirelessly and concluded that it is going to be a practical reality.

The recent developments in wireless power transfer (WPT) systems can be categorized as short-range, mid-range and long-range based on the distance between the transmitter and the receiver in relation to their dimensions. Mid-range WPT system, the focus of this paper, has shown significant developments and attention recently and it has potential applications [2][3][4][5][6].

There is a need to design a wireless mobile charging system, which takes into account the magnetic field forming in the transmitter side, beside a simple and suitable structure and dimensions for the receiver that can fit easily in mobiles or portable devises placed some distance away. This paper describes the work on designing an optimal two dimensional (2D) structure of transmitter and receiver where multiple overlapping coils used in the transmitter side, and the receiver is placed up to 20 cm away from the transmitter, taking into account the applications for cell phone in the pocket or PDA (personal digital assistant) in hand which could be expediently charging.

2. WPT System

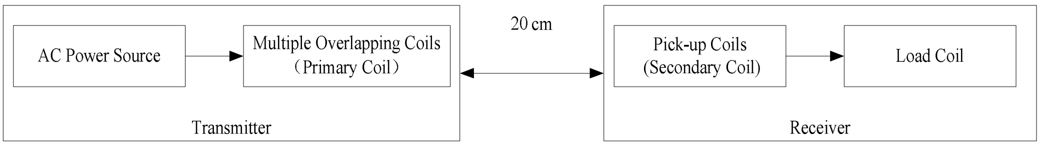

Figure 1: Wireless Power Transfer System Model

Figure 1 shows the general diagram for the designed WPT. An alternative current (AC) power source will be connected to the transmitter, which consists of multiple overlapping coils. The receiver is assumed to be placed 20 cm away. The pick-up coils in the receiver side will induce the power from the radiated magnetic field and power the connected load.

The WPT system constructed from several transmitter coils and a receiver coil which they have the same frequency by adjusting the interrelated parameters. The resonance coils are in the state of self-resonance to achieve the magnetic coupling. The efficiency of the WPT system can be defined as the ratio of the received power in the load resistance to the delivered power from the electric power source.

3. Transmitter Structures Based on the Field Forming Theory

3.1 Description of the Field Forming Theory

The novelty in this proposal is the field forming by different structures of transmitter coils. Field forming takes advantages of interference to change the directionality of the antenna array. When transmitting, a field former controls the phases of power supplied in the transmitter to create a pattern of constructive and destructive effect for spatial multiple coils. In other words, magnetic field forming is introduced in WPT, which enables spatially focused/dedicated power delivery to devices while keeping power levels in all the other locations minimal. It is efficient to use multiple overlapping coils structures, which can generate the magnetic field forming. The aim is to choose the optimized combination of different structures of multiple coils to transfer the magnetic energy to different positions of the receiver antennas as much as possible in the spatial domain. Each coil of the transmitter uses the same frequency to charge different mobile devices at different positions.

3.2 Example Structures

The transmitter consists of multiple overlapping coils, which are arranged into symmetric distribution with the same radius, and the coverage area of the different transmitter structures is also the same.

Also, there are many different structures of transmitter that can be used to generate the various sorts and varieties of the magnetic field forming intensity distribution. It is also possible to use one coil, three coils, four coils, nine coils structures and so on for the transmitter. Figure 2 shows examples for one coil, four coils and nine coils structures of the transmitter respectively. All the coils are symmetrically distributed in the same area in the 2D space.

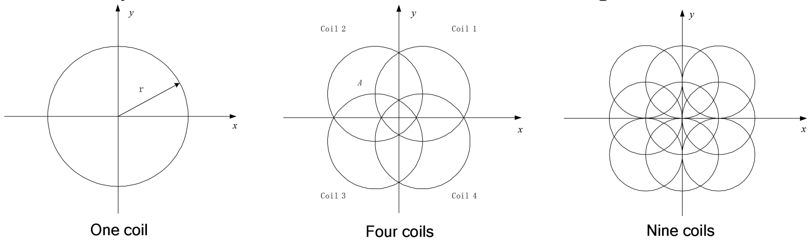

Figure 2: Transmitter Structures

Assuming that the transmitter can detect where the mobile device is, the overlapping coils structure transmitter transfers the effective power to the mobile device with the optimized or maximized way, according to the location of the receiver in the space. Therefore, the receiver can freely move in a rectangle range of 600 mm × 600 mm.

4. WPT Coupling System

4.1 Circuit Model

Figure 3 shows the circuit diagram of the WPT system with four coils in the transmitter and one coil in the receiver, which have the same resonant frequency by adjusting the interrelated capacitance parameter. Figure 3 shows only one coil and omits the other three coils in the transmitter. Assuming that the resistance, inductance and capacitance values are the same in all the four coils of the transmitter, as in [7] the four coils system can achieve higher efficiency than the two coils system due to higher quality factor of the primary and secondary coil. Since the internal resistance of the source is not considered in this WPT model, there is no coupling in the transmitter.

Let L_{t}, L_{rp} and L_{rs} be the inductance of the primary, secondary, and load coils respectively. Let C_{t}, C_{rp} and C_{rs} be the compensation capacitor of the primary, secondary, and load coils which should be adjusted for an appropriate value to make the system work in the resonant frequency as shown in equation (1). Let R_{t}, R_{rp}, and R_{rs} be the internal resistances of primary, secondary, and load coils respectively. Let R_{L} be the load resistance of the load coil. Let $M_{\mathrm{t1\_2}}$, $M_{\mathrm{t2\_2}}$, $M_{\mathrm{t3\_2}}$, $M_{\mathrm{t4\_2}}$ be the mutual inductance between each primary coil and the secondary coil respectively. Let M_{2_3} be the mutual inductance between the secondary and load coils in the receiver. Let U_{s} be the alternating current power supply with the frequency ω_0 for the transmitter.

$$\omega_0 = \frac{1}{\sqrt{L_{\mathrm{t}} C_{\mathrm{t}}}} = \frac{1}{\sqrt{L_{\mathrm{rp}} C_{\mathrm{rp}}}} = \frac{1}{\sqrt{L_{\mathrm{rs}} C_{\mathrm{rs}}}} \quad (1)$$

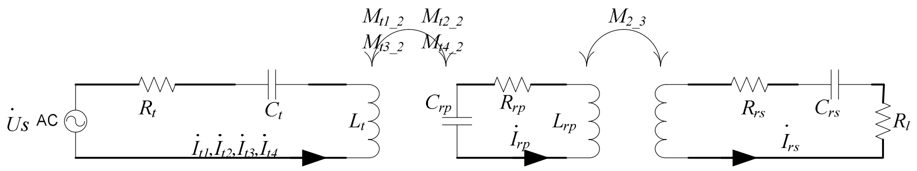

Figure 3: Wireless power transfer system model of four coils structure

4.2 WPT Efficiency Analysis

The efficiency of the WPT model is calculated in equation (2). The mutual inductance has a relationship with the shape and the size of coils, the number of turns, and the relative position of the two coils [8]. The transmitter structure proposed in this paper has a positive effect on the strength of coupling between the transmitter and the receiver.

According to the theoretical analysis, the efficiency is proportional to the mutual inductance and the frequency, and in direct ratio to the load resistance in certain scope, but inversely with the inner resistance. The efficiency will increase square times over the increasing of the frequency, taking into account that the load resistance should match the inner resistance well to get the maximum power of the receiver. Therefore, the best way to increase the efficiency is to raise the coupling strength as much as possible between the transmitter and the receiver. So it is sufficient to increase the coil's number of turns and its radius to increase the mutual inductance. But the number of turns and the radius shouldn't be too large. One reason is that the design of the coils should fit the size of the portable devices. The other reason is that the resistance of the coil will also get larger, which will lead to a waste of energy.

$$
\begin{aligned}
&\eta = \omega^4 M_{\mathrm{tot}}^2 M_{2\_3}^2 R_{\mathrm{L}} R_{\mathrm{t}} / 4\left(R_{\mathrm{t}} R_{\mathrm{rp}} R_{\mathrm{RL}} + R_{\mathrm{RL}}\omega^2 M_{\mathrm{t\_s}} + R_{\mathrm{t}}\omega^2 M_{2\_3}^2\right)\cdot\left[\left(R_{\mathrm{t}} R_{\mathrm{rp}} R_{\mathrm{RL}} + R_{\mathrm{RL}}\omega^2 M_{\mathrm{t\_s}} + R_{\mathrm{t}}\omega^2 M_{2\_3}^2\right) - \omega^2 M_{\mathrm{tot}}^2 R_{\mathrm{RL}}\right] \\
&R_{\mathrm{RL}} = R_{\mathrm{rs}} + R_{\mathrm{L}} \\
&M_{\mathrm{tot}} = M_{\mathrm{t1\_2}} + M_{\mathrm{t2\_2}} + M_{\mathrm{t3\_2}} + M_{\mathrm{t4\_2}} \\
&M_{t\_s} = M_{t1\_2}^2 + M_{t2\_2}^2 + M_{t3\_2}^2 + M_{t4\_2}^2
\end{aligned} \quad (2)
$$

5. The Optimized Parameters and the Simulation Results

5.1 The Optimized Parameters

The specific application requirements of the WPT system constrain the design parameters of the transmitter and the receiver. After testing and simulating many settings, the proper and optimized parameters for the WPT system are shown in Table 1.

Table 1: The Optimized Coil Parameters for the WPT System

	Parameter	Value
Primary Coil	Number of Litz Wire Turns (N_t)	200
	Number of isolated wires for a litz wire	60
	Radius of an isolated wire	0.05 mm
Secondary Coil	Inner Radius of Primary Coil	10 mm
	Outer Radius of Primary Coil	20 mm
	Thickness of Primary Coil	2 mm
	Number of Turns	200
	Number of isolated wires for a litz wire	10
Load Coil	Inner Radius of Secondary Coil	10 mm
	Outer Radius of Secondary Coil	20 mm
	Thickness of Secondary Coil	1.6 mm
	Number of Turns (N_s)	160

5.2 The Simulation Results

The receiver was placed from -300 mm to 300 mm in both x and y axis. The distance between the receiver and the transmitter is 200 mm. In order to compare the characteristics of different structures, the transmitter covers an area of 600 mm × 600 mm. When a single coil structure is simulated, the radius of the single coil is 300 mm. But when a four coils structure is used, if one of the coils center is (100 mm, 100 mm), the radius of the coil is 200 mm.

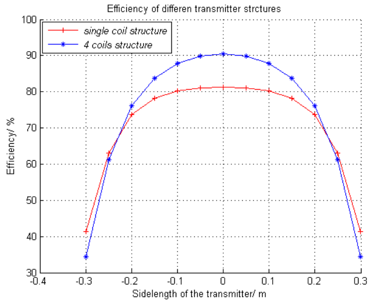

Figure 4: Comparison between Single Coil and Four Coils Structure (370 KHz, 200 mm Height)

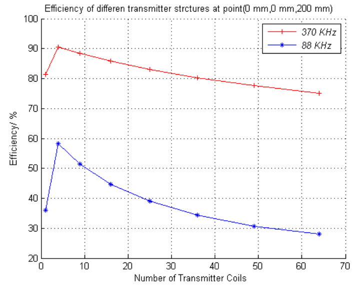

Figure5: Received Power Efficiency for Different Multiple Coils Transmitter Structures

The figures obviously show that the area that can receive over 80% energy is from -0.18 m to 0.18 m for the multiple coil structure, while the value for the single-coil structure is from -0.1 m to 0.1 m. In Figure 5, the efficiency of the 36 coil structure is nearly the same as the single coil. In summary, it can be concluded that the four coils structure is the most optimized, which is able to generate over 5W energy and over 50% efficiency when the receiver placed at 0.2 m away.

6. Conclusion

In this paper, the design and the optimization of WPT system are described. The focus of this paper is designing a 2D structure of the transmitter and the receiver. Simulation results show significant advantages of multiple coils structures in the efficiency. The four coils transmitter model provides larger range, which can obtain higher power efficiency, comparing to the single coil model. When using the four coils model within a 600 mm × 600 mm transmitting area, placed 200 mm away and no phase shift input signal, the power transfer efficiency is over 80% for 370 KHz. The results confirm the robustness of the multiple coils model based WPT system when operating at longer transmitting distances, which also demonstrate that multiple coils model is of advantage to solve the field forming problem.

References

[1] A R. Bansal, "The Future of Wireless Charging," IEEE Antennas and Propagation Magazine, vol. 51, no. 2, p. 153, April 2009.

[2] 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.

[3] J. D. Joannopoulos, A. Karalis, and. M. Soljacic,"Wireless Non-radiative energy transfer". U.S. Patent Patent 0222 542, 27 September 2007.

[4] A. Karalis, J. D. Joannopoulos, and. M. Soljacic,"Efficient wireless Non-radiative mid-range energy transfer," Annals of Physics, vol. 323, pp. 34-48, January 2008.

[5] S. J. Mazlouman, A. Mahanfar, B. Kaminska,"Mid-range Wireless Energy Transfer Using Inductive Resonance for Wireless Sensors," IEEE International Conference on Computer Design, vol. 323, pp. 517-522, 2009.

[6] B. L. Cannon, J. F. Hoburg, D. D. Stancil, S. C. Goldstein,"Magnetic resonant coupling as a potential means for wireless power transfer to multiple small receivers," IEEE Transactions on Power Electronics, vol. 24, no. 7, pp. 1819-1825, July 2009.

[7] A. K. RamRakhyani, S. Mirabbasi, M. Chiao,"Design and Optimization of Resonance-Based Efficient Wireless Power Delivery Systems for Biomedical Implants," IEEE TRANSACTIONS ON BIOMEDICAL CIRCUITS AND SYSTEMS, pp. 48-63, February 2011.

[8] C. M. Zierhofer, E. S. Hochmair,"Geometric Approach for Coupling Enhancement of Magnetically Coupled Coils," IEEE TRANSACTIONS ON BIOMEDICAL ENGINEERING, pp. 708-714, JULY 1996.