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Design and Simulation of Multiple Coil Model for Wireless Power Transmission System

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Abstract

In Wireless Power Transfer (WPT) systems the proportion of energy received by the load is critical and the efficiency is the more significant parameter. WPT systems use resonant inductive coupling, where it is the near field wireless transmission of electrical energy between two coils that are highly resonant at the same frequency. This paper aims to propose a design of an optimal two dimensional (2D) structure of transmitter and receiver. Multiple overlapping coils structures in the transmitter side are proposed, in order to achieve higher efficiency than the typical single coil transmitter. Simulation results showed that the axial component of magnetic induction resulted from the overlapping coils structure has preferable homogeneous distribution. The proposed system achieved an efficiency value of 90 % for a receiver placed 20 cm away from a 4 coils transmitter comparing to an efficiency value of 75% for the same distance using a single coil transmitter.

Keywords*: wireless power transfer, resonant inductive coupling, multiple overlapping transmitter coils, magnetic field forming*

1. Introduction

Mobile and portable devices are gaining more and more popularity due to their ease of use and incremental computational power. One key issue regarding the comfortability of using such devices is the need to recharge them rapidly because of their limited battery capacity. In []the writer discussed the future of charging the mobile devices wirelessly and concluded that it is going to be a practical reality [1, 2].

Recently numerous electronic devices that use the wireless medium for different purposes have commercialized. Wireless power transfer (WPT) systems have also made significant advancements and many companies are currently active in development and research activities [4-7]. Some products have also been commercialized. However, the efficiency and the convenience of use of WPT systems still needs to improve to get mainstream recognition.

Wireless power transfer was established with the pioneering work on electromagnetism by the 19th century physicists, who showed that an alternating current produces a magnetic field and vice versa. Nikola Tesla made significant and well ahead of the time contributions to wireless power transfer in the late 19th century and at the early 20th century. He has demonstrated a successful WPT system that powered electronic devices [8-12]

The recent developments in 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 application in consumer electronics, sensors and robotics [13-16].

This paper is organized as follows, section II discusses the general wireless power transfer system design and the parameters needed to be adjusted to make the system work as expected. Section III presents the transmitter structures based on the field forming theory, while section IV shows the theoretical analysis of the power transfer system. Section V discusses the

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design steps, the parameters optimization and the simulation results. Finally, section VI concludes the work and results achieved in this paper.

2. WPT System

In this part a general overview about the designed wireless power transfer system will be presented, beside a brief discussion about the parameters in consideration. Figure 1 shows the general diagram for the designed WPT.

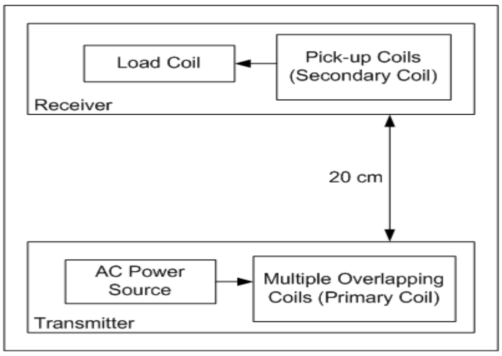


Figure 1. Wireless Power Transfer System Model

An alternative current (AC) power source will be connected to the transmitter, which consists of multi-overlapping coils that are arranged into symmetric distribution with the same radius. The receiver is assumed to be placed some distance away from the transmitter, up to 20 cm. The pick-up coils in the receiver side will induce the power from the radiated magnetic field and power the connected load which can be a mobile or another portable device.

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. To start with, it has been stated that increasing the number of turns at receiver coil results in an increase in the attainable efficiency []. When the number of turns is increased, the resistance of the coil increases linearly and the inductance of the coil increases in a squared fashion with the number of turns. Thus, increasing the number of turns results in a more increase in the inductance than the increase in the resistance which improves the system performance due to the increase in the quality factor of the coil.

Regarding the radius of the coil, the induced electromotive force in the receiver coil is caused by the uniform magnetic field of time-variation from transmitter. The more coverage area of the receiver the more induced electromotive force it will get leading to increasing in efficiency and load power. The receiver coil is chosen in such a way that it can conveniently fit into mobile devices. A value up to 2 cm for the outer radius has been chosen for the receiver coil.

The frequency has an obvious effect on the WPT system for the efficiency in the receiver antenna. On one hand, when higher initial induced electromotive force, the primary coil can get higher system frequency. On the other hand, the primary coil with high quality and the secondary coil are coupled and the equivalent impedance seen by primary coil is directly proportional to the frequency of the system.

3. Design of Multiple Coil Model

The transmitter consists of multiple overlapping coils, which are arranged into symmetric distribution in the same area of 2D space. There are many different structures of the transmitter that can be used to generate the various sorts and varieties of magnetic field forming intensity distribution. It is also possible to use single coil, three coils, four coils, nine coils structures and so on for the transmitter. Figure 2, Figure 3 and Figure 4show examples for single coil, four coils and nine coils structures of the transmitter respectively.

3.1. Single Coil Structure

Figure 2 shows a single circular coil transmitter structure and the calculation model for the magnetic induction in any place of the space. Equation (1) presents the magnetic induction in any point in the space for the circular coil. The space coordinate of point P is expressed as (r,θ,φ). Whereμ0is the vacuum permeability, the Initial electric current of the coil is I and the radius of the circular coil is α.ρ isthe distance between the center of the circle and the projective point of P. K(k) in (2) and E(k) in (3) are the first and the second kind of complete elliptic integral. The parameter k is the coefficient to calculate K(k) and E(k).

$$B_z = \frac{\mu_0 I}{2\pi}\cdot\frac{1}{\sqrt{(\rho+a)^2+z^2}}\cdot[K+\frac{a^2-\rho^2-z^2}{(\rho-a)^2+z^2}E] \tag{1}$$

$$K(k)=\int_0^{\pi/2}\frac{d\phi}{\sqrt{1-k^2\sin^2\phi}} \tag{2}$$

$$E(k)=\int_0^{\pi/2}\sqrt{1-k^2\sin^2\phi}\,d\phi \tag{3}$$

$$k=\sqrt{\frac{4\cdot a\cdot r\cdot\sin(\theta)}{r^2+a^2+2\cdot a\cdot r\cdot\sin(\theta)}} \tag{4}$$

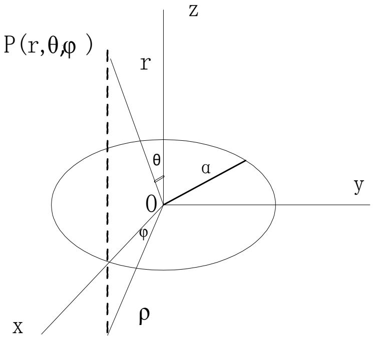


Figure 2. Single Coil Transmitter Structure

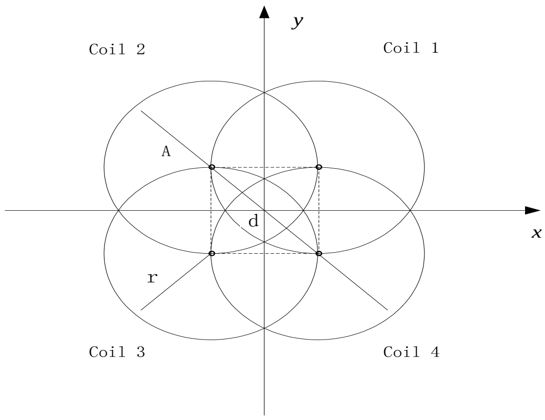


Figure 3. Four Coils Transmitter Structure

3.2 Four Coils Structure

Assume that the transmitter can sense where the mobile device is and the system can choose which four coils should be supply the power. *r* is the radius of each small coil and *d* is the maximal diagonal linedistance of opposite coils. The magnetic conduction of point *A* is calculated as follows,the center coordinates of the four coils are (x_1,y_1), (x_2,y_2), (x_3,y_3), and (x_4,y_4) respectively. The coordinate of point *A* in the space is (x_A,y_A,z_A). The magnetic conduction caused by coil one is shown in (1). Therefore, the magnetic conduction of each coil in four coils structure can be deduced by analogy in (5). And *n* represents the sequence number of the coils.

$$B_{zn}=\frac{\mu_0 I}{2\pi}\cdot\frac{1}{\sqrt{(\sqrt{(x_A-x_n)^2+(y_A-y_n)^2}+r)^2+z_A^2}}\cdot [K+\frac{r^2-((x_A-x_n)^2+(y_A-y_n)^2)-z_A^2}{(\sqrt{(x_A-x_n)^2+(y_A-y_n)^2}-r)^2+z_A^2}E] \tag{5}$$

K and *E* calculation method can be found in (2) and (3). Equation (6) shows the k_n calculation method for coil1, coil 2, coil3 and coil4 separately.

$$k_n = \sqrt{\frac{4r\sqrt{(x-x_n)^2+(y-y_n)^2}}{(r+\sqrt{(x-x_n)^2+(y-y_n)^2})^2+z^2}} \quad (6)$$

Then the total magnetic induction of point A generated by the transmitter is calculated by vector addition by each coil which is shown in (7). Therefore, the intersecting part area has the maximal power transfer because the direction of the magnetic induction of each coil is the same.

$$B_z = B_{z1} + B_{z2} + B_{z3} + B_{z4} \quad (7)$$

The coordinates of (x_1,y_1), (x_2,y_2), (x_3,y_3), and (x_4,y_4) can be expressed by *d* and *r*, which is shown in Equation (8).

$$\begin{aligned} x_1 &= \frac{d-2\cdot r}{2\sqrt{2}}, y_1 = \frac{d-2\cdot r}{2\sqrt{2}} \\ x_2 &= -\frac{d-2\cdot r}{2\sqrt{2}}, y_2 = \frac{d-2\cdot r}{2\sqrt{2}} \\ x_3 &= -\frac{d-2\cdot r}{2\sqrt{2}}, y_3 = -\frac{d-2\cdot r}{2\sqrt{2}} \\ x_4 &= \frac{d-2\cdot r}{2\sqrt{2}}, y_4 = -\frac{d-2\cdot r}{2\sqrt{2}} \end{aligned} \quad (8)$$

Substitute Equation (8) into Equation (6) and (7). Assume the radius *r* is a fixed value and point *A* (x_A,y_A,z_A) is also settled. Therefore, there is only one variable *d* in Equation (7). Then we can find the maximal magnetic induction value of any point in the space by adjusting the variable of *d*. The maximal *B* value can be shown in Equation (9).

$$B_{max} = \frac{\partial Bz}{\partial d} = \frac{\partial\left(B_{z1} + B_{z2} + B_{z3} + B_{z4}\right)}{\partial d} \quad (9)$$

3.2 Nine Coils Structure

Figure 4 shows the nine coils transmitter structure wherethe magnetic conduction of the nine coils transmitter structure is similar as the four coils transmitter structure.

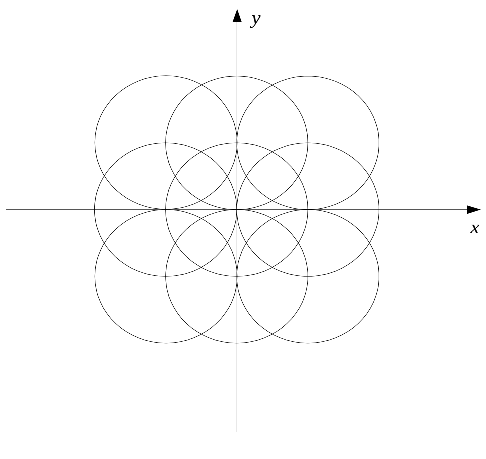


Figure 4. Nine Coils Transmitter Structure

Comparing with the traditional WPT system, this magnetic field former consists of multiple overlapping coils, whereas there is only one coil in the traditional transmitter. The proposed structure presents a viable and simple method to produce the magnetic field forming in the transmitter, which allows the mobile devices to be placed in free position in the defined spatial extent. The center of the mobile devices can move in the rectangle range of 600mm ×600mm in the horizontal level and with some distance away from the transmitter in the vertical direction up to 20cm.

However, there is only a single coil in the traditional transmitter; the receiver should be placed in the point where both centers of the receiver and the transmitter should be in the same axes. If the receiver moved discretionarily, the efficiency decreased very quickly.

4. Analysis of the Power Transfer System

Spiral coils provide low self-inductance and constrain the maximum achievable quality factor. Multi-layer helical coil is used and it can provide high quality factor, which has the advantages of positive effect on the area efficiency, easily build up and easy analysis. The AC resistance, self-inductance and stray capacitance of these coils have been studied very well, which makes it easy to make a thorough analysis of their efficiency. Figure 5 shows the technical drawing of such a coil.

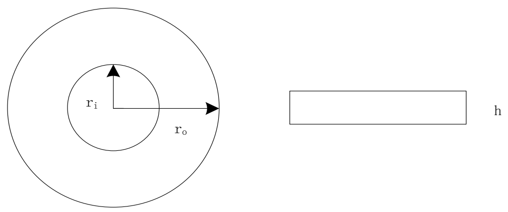


Figure 5**.** Multi-layer Helical Coil

The outer radius r_o, the inner radius r_i and the thickness of the coil $h$are the parameters to be optimized. The thickness of the coil determines the number of turns per layer $N_t$whereas the difference between the inner and the outer diameter determines the number of coaxial layers N_h.

4.1. Comparison between the Magnetic Coupling with Resonance and without Resonance

Figure 6 shows the simple wireless power transfer system model which includes the transmitter and the receiver.

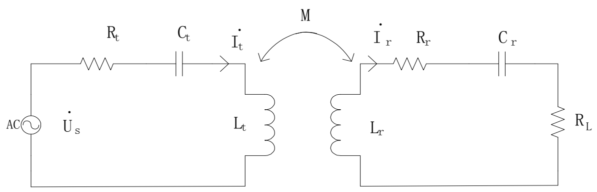


Figure 6. Simple Wireless Power Transfer System Model

It is easy to get the efficiency formula of simple WPT system according to Figure 6 which is given in (10). The angular frequency of system is ω. Z_t and Z_r are the impedance of the transmitter and the receiver respectively.

$$\eta = \frac{(\omega M)^2 R_L}{Z_r[Z_t Z_r + (\omega M)^2]} \tag{10}$$

$$Z_t = R_t + j\left(\omega L_t - \frac{1}{\omega C_t}\right) \quad (11)$$

$$Z_r = R_r + R_L + j\left(\omega L_r - \frac{1}{\omega C_r}\right) \quad (12)$$

There is no resonance in both the transmitter coil and the receiver coil. The current is flowing in one coil, which generates the magnetic flux as a medium. Then the induced electromotive force is caused in the other coil through the medium. But the energy transfer distance is restricted in grade of millimeter. The transfer efficiency is shown in Equation (13).

$$\eta_1 = (\omega M)^2 R_L \Big/ \left\{ (R_r + R_L + j(\omega L_r - \frac{1}{\omega C_r}))\cdot [(R_r + R_L + j(\omega L_r - \frac{1}{\omega C_r}))(R_t + j(\omega L_t - \frac{1}{\omega C_t})) + (\omega M)^2] \right\} \quad (13)$$

Equation (14) shows the resonance only in the transmitter

$$\eta_2 = (\omega M)^2 R_L \Big/ \left\{ (R_r + R_L + j(\omega L_r - \frac{1}{\omega C_r}))\cdot [R_t(R_r + R_L + j(\omega L_r - \frac{1}{\omega C_r})) + (\omega M)^2] \right\} \quad (14)$$

Equation (15) shows the resonance only in the receiver.

$$\eta_3 = \frac{(\omega M)^2 R_L}{(R_r + R_L)[(R_t + j(\omega L_t - \frac{1}{\omega C_t}))(R_r + R_L) + (\omega M)^2]} \quad (15)$$

Equation (16) shows the resonancefor both the transmitter and the receiver.

$$\eta_4 = \frac{(\omega M)^2 R_L}{R_t(R_r + R_L)^2 + (\omega M)^2 (R_r + R_L)} \quad (16)$$

Comparing (13), (14), (15) and (16), it can be observed that $\eta_4 > \eta_3 > \eta_2 > \eta_1$ because equivalent impedance is minimum and the current in the circuit is maximal. So the magnetic resonant coupling technology is beneficial to WPT system in the middle range transfer.

4.2. Circuit Diagram

The transfer system is constituted by several transmittercoils and a receiver coil, which have the same frequency by adjusting the interrelated parameters. The resonance coils are in the state of self-resonant to achieve the energy coupling. Magnetic coupling circuit is used only in the receiver antenna. L_t,L_{rp} and L_{rs} are the inductance of the transmitter, the primary coil and the secondary coil of the receiver respectively. C_t, C_{rp} and C_{rs} are the compensation capacitor of the transmitter, the primary coil and the secondary coil of the receiver which should be adjusted for appropriate value to make the system (transmitter and receiver) work in the resonance frequency as shown in Equation (17). R_t and R_{rp} and R_{rs} represent the internal resistances of the transmitter and the receiver coils respectively. R_L is the load resistance of the receiver coil.

M_{t1_2}, M_{t2_2}, M_{t3_2}, M_{t4_2} are the mutual inductancebetween each transmitter coil and the receiver respectively. M_{2_3} is the mutual inductance between the primary coil and the secondary coil in the receiver. U_s is the alternating current power supply with frequency ω_0 for the transmitter.

$$\omega_0 = \frac{1}{\sqrt{L_t C_t}} = \frac{1}{\sqrt{L_{rp} C_{rp}}} = \frac{1}{\sqrt{L_{rs} C_{rs}}} \tag{17}$$

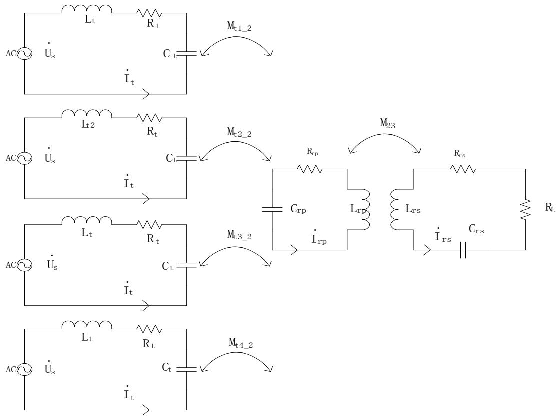


Figure 7. Wireless Power Transfer System Modelfor Four Coils Structure

Figure 7 shows the circuit diagram for the WPT system with four coils transmitter structure. Assume that the resistance, the inductance and the capacitance values are the same in all four coils. As in [], the four coils structure can achieve higher efficiency than the two coils structure due to the high quality factor of the primary and the secondary coil. Sinceinternal resistance of the source is not considered in this WPT model, there is no coupling in the transmitter.

4.3. WPT Efficiency Analysis

The circuit model provides an analysis reference for the WPT system characteristics of a magnetically coupling resonator system. The mutual inductance between the transmitter and the secondary coil of the receiver are neglected in the following analysis. Then the current in each resonant circuit is determined from (18) to (23) by using Kirchhoff's voltage law.

$$\dot{I}_{t1}\left(R_t + j\omega L_t + \frac{1}{j\omega C_t}\right) - \dot{I}_{rp} j\omega M_{t1\_2} = \dot{U}_s \tag{18}$$

$$\dot{I}_{t2}\left(R_t + j\omega L_t + \frac{1}{j\omega C_t}\right) - \dot{I}_{rp} j\omega M_{t2\_2} = \dot{U}_s \tag{19}$$

$$\dot{I}_{t3}\left(R_t + j\omega L_t + \frac{1}{j\omega C_t}\right) - \dot{I}_{rp} j\omega M_{t3\_2} = \dot{U}_s \tag{20}$$

$$\dot{I}_{t4}\left(R_t + j\omega L_t + \frac{1}{j\omega C_t}\right) - \dot{I}_{rp} j\omega M_{t4\_2} = \dot{U}_s \tag{21}$$

$$\begin{aligned} &\dot{I}_{rp}\left(R_{rp} + j\omega L_{rp} + \frac{1}{j\omega C_{rp}}\right) - \dot{I}_{t1} j\omega M_{t1\_2} - \dot{I}_{t2} j\omega M_{t2\_2} \\ &-\dot{I}_{t3} j\omega M_{t3\_2} - \dot{I}_{t4} j\omega M_{t4\_2} - \dot{I}_{rs} j\omega M_{2\_3} = 0 \end{aligned} \tag{22}$$

$$\dot{I}_{\mathrm{rs}}\left(R_{\mathrm{rs}}+j\omega L_{\mathrm{rs}}+\frac{1}{j\omega C_{\mathrm{rs}}}+R_{\mathrm{L}}\right)-\dot{I}_{\mathrm{rp}}\,j\omega M_{2\_3}=0 \tag{23}$$

The efficiency of WPT system model is calculated in Equation (24). It is obvious that the efficiency is related to the mutual inductance between the primary coil and the secondary coil, the secondary coil and the load coil. Rt, Rrp, Rrs, RL and system angular frequency ω also have an import effect on the efficiency. The values of Mt1_2, Mt2_2, Mt3_2, Mt4_2 and M2_3 give the index of strength of coupling between the primary coil and the secondary coil, the secondary coil and the load coil, which have an important effect on the efficiency of the system. The mutual inductance is in a relationship with the shape of the coil, the number of turns and the relative position of the two coils[]. The transmitter structure in this paper has a positive effect on the strength of coupling between the transmitter and the receiver. According to theoretical analysis, efficiency is in proportion to the operation angular frequency, the mutual inductance and the load resistance, but in an inverse ratio to the inner resistance of the primary coil, the secondary coil and the load coil. The efficiency will increase square times over the increase of angular frequency. What should be pay attention to is that the load resistance should match the inner resistance well in order to get the maximal 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 an effective way to increase the number of turns of the coil and its radius to increase the mutual inductance, but the number of turns and the radius should not be too large. One reason is that the design of the coils should fit the size of mobiles and portable devices. The other reason is the resistance of the coil will also get larger, which will lead to a waste of energy.

$$\begin{aligned}
\eta &= \omega^4 M_{\mathrm{tot}}^2 M_{2_3}^2 R_{\mathrm{L}} Z_{\mathrm{t}} \Big/ \Big\{\left(Z_{\mathrm{t}}Z_{\mathrm{rp}}Z_{\mathrm{rs}}+Z_{\mathrm{rs}}\omega^2 M_{\mathrm{tot}}+Z_{\mathrm{t}}\omega^2 M_{2_3}^2\right)\cdot \\
&\qquad \left[4\left(Z_{\mathrm{t}}Z_{\mathrm{rp}}Z_{\mathrm{rs}}+Z_{\mathrm{rs}}\omega^2 M_{\mathrm{tot}}+Z_{\mathrm{t}}\omega^2 M_{2_3}^2\right)-\omega^2 M_{\mathrm{tot}}^2 Z_{\mathrm{rs}}\right]\Big\} \\
M_{\mathrm{tot}} &= M_{\mathrm{t1_2}}+M_{\mathrm{t2_2}}+M_{\mathrm{t3_2}}+M_{\mathrm{t4_2}} \\
Z_{\mathrm{t}} &= R_{\mathrm{t}}+j\omega L_{\mathrm{t}}+\frac{1}{j\omega C_{\mathrm{t}}} \\
Z_{\mathrm{rp}} &= R_{\mathrm{rp}}+j\omega L_{\mathrm{rp}}+\frac{1}{j\omega C_{\mathrm{rp}}} \\
Z_{\mathrm{rs}} &= R_{\mathrm{rs}}+j\omega L_{\mathrm{rs}}+\frac{1}{j\omega C_{\mathrm{rs}}}+R_{\mathrm{L}}
\end{aligned} \tag{24}$$

Because the system works on the resonant frequency, then the efficiency can be modified as Equation (25).

$$\begin{aligned}
\eta &= \omega^4 M_{\mathrm{tot}}^2 M_{2_3}^2 R_{\mathrm{L}} R_{\mathrm{t}} \Big/ \Big\{\left(R_{\mathrm{t}}R_{\mathrm{rp}}R_{\mathrm{RL}}+R_{\mathrm{RL}}\omega^2 M_{\mathrm{tot}}+R_{\mathrm{t}}\omega^2 M_{2_3}^2\right)\cdot \\
&\qquad \left[4\left(R_{\mathrm{t}}R_{\mathrm{rp}}R_{\mathrm{RL}}+R_{\mathrm{RL}}\omega^2 M_{\mathrm{tot}}+R_{\mathrm{t}}\omega^2 M_{2_3}^2\right)-\omega^2 M_{\mathrm{tot}}^2 R_{\mathrm{RL}}\right]\Big\} \\
R_{\mathrm{RL}} &= R_{\mathrm{rs}}+R_{\mathrm{L}}
\end{aligned} \tag{25}$$

It is noticed that if the radius of the coil is increased, then the distance between the transmitter and the receiver can be larger which guarantees the high efficiency. Because the radius of the coil increases, the efficiency will also be raised.

5. Parameters and Simulation

By testing and simulating many cases and settings, the proper and optimized parameters for the WPT system are shown in Table 1.

Table 1. Optimized Coil Parameters for WPT System

	Parameter	Value
Transmitter 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
Primary 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
Secondary 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
	Number of isolated wires for a litz wire	10
Circuit	Load Resistance	50 ohm

5.1. Characteristics of the Different Transmitter Structures

The simulations start by determining the center point of the different models on *X-Y* plane, taking into account the symmetric and the arrangement mentioned before. Next steps are determining the radius of the coils, determining the number of turns used in the transmitter, and then the initial current in the transmitters.

On the receiver side, the parameters of the receiver coil and the secondary coil as well were defined, such as the radius of the single wire, the inner and the outer radius of the coil, the frequency, the number of turns in *r* and *z* directions, the thickness and the number of turns. Also, the parameters of the circuit were defined. The receiver is assumed to be placed from -300mm to 300mm in both *x* axis and *y* axis. The height of the receiver also needs to be defined before the simulation starts. A calculation of the inductance and resistance of the primary and secondary coil is done as well as a calculation of magnetic strength in the receiver coil area. Then a series of calculations on the receiver side achieved to determine the received power and the efficiency. In order to compare the characteristics of different structures, the simulation defines the transmitter overlap a 600mm × 600mm area. When a single coil structure is simulated, the radius of the single coil is 300mm, while when a four circular structure is used, if one of the coils center is (100mm, 100mm), the radius of the coil is 200mm.

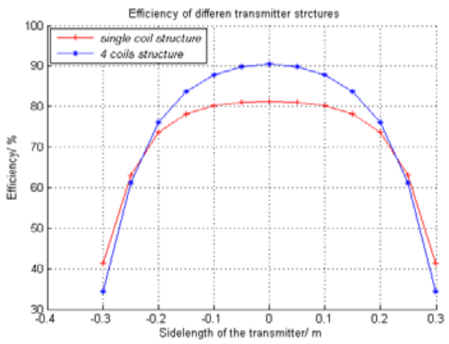


Figure 8. Comparison between Single Coil and Four Coils Structure (370KHz, 200mm Height)

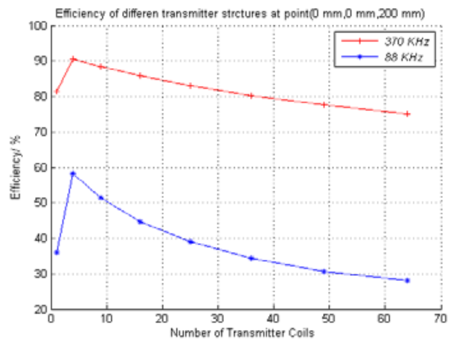


Figure 9. Received Power Efficiency for Different Multiple Coils Transmitter Structures

Through the results figures, it is obviously can be found that, the area that can received over 80% energy is from -0.18m to 0.18m for the multi-coil structure, while value for the single-coil structure is from -0.1m to 0.1m.

In Figure 10, the efficiency of 36 coil structure is nearly the same as the single coil model. Therefore, we suggest that the transmitter would better use no more than 36 coils structure.

In summary, we can conclude that the four coils structure is the most optimized structure for our transmitter in terms of both the efficiency and the received power.

5.2. Characteristics of the Different Transmitter Sizes

For single coil structure, the magnetic strength *H* is affected by the diameter of the transmitter and the distance between the transmitter and the receiver. In order to prove that the multiple coils structure also applies to Equation (1), the simulations of multiple coils structure of different size are given.

From the results of different sizes of the transmitter, we find that when the side length of the transmitter is 600mm the receiver will get the highest efficiency value. This is matches the results obtained by the theory calculation.

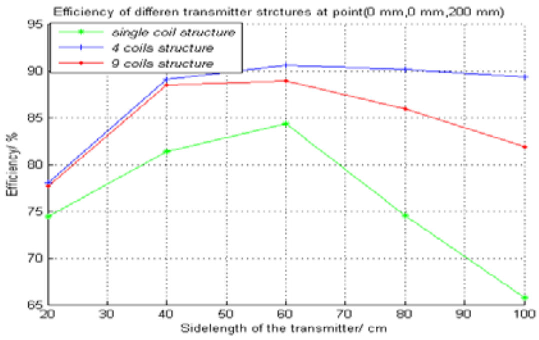


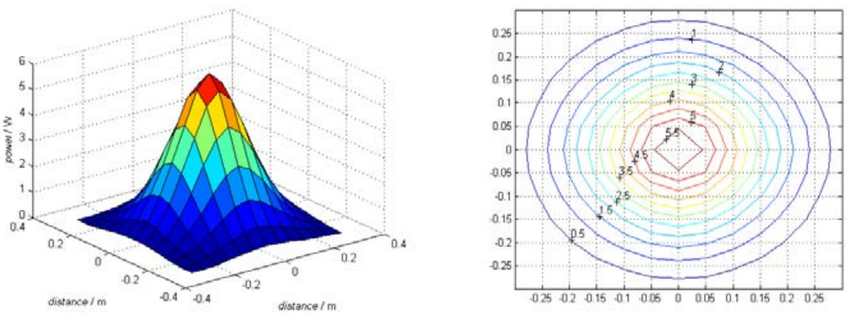
Figure 10. Received Power Efficiency for Different Transmitter Sizes

5.3. Optimized Simulation Results

The parameters of the receiver are defined and the system optimization is to find the most proper parameters of the transmitter, which can provide the highest received power and efficiency at 200mm height. The optimized parameters and simulations results are shown as follows:

Table 3. Optimized Configurations for the Four Coils Transmitter

Parameter	Value
Center Coordinates of Coil 1	(-100 mm, 100 mm)
Center Coordinates of Coil 2	(100 mm, 100 mm)
Center Coordinates of Coil 3	(-100 mm, -100 m)
Center Coordinates of Coil 4	(100 mm, -100 mm)
Coil Radius	200 mm
Number of Litz Wire Turns	200
Number of isolated wires for a Litz ire	60
Radius of an isolated wire	0.05 mm
Input Signal Amplitude for 370 KHz	0.25 A
Input Signal Amplitude for 88 KHz	1 A



(a) (b)

Figure 11. Received Power at 200mm Height (88KHz)

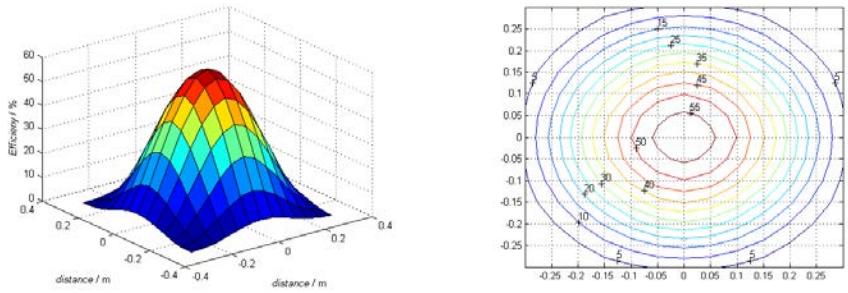
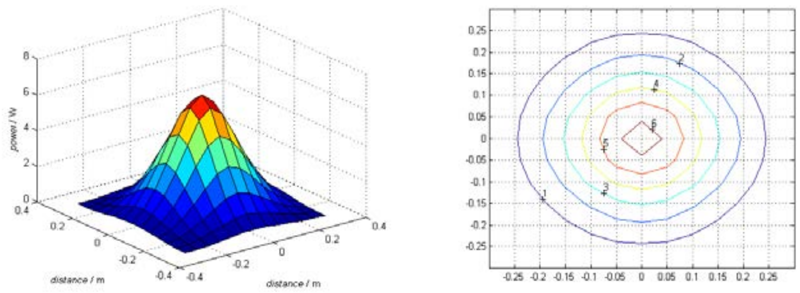
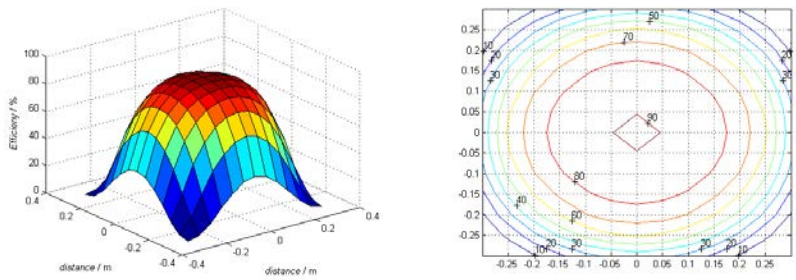


Figure 12. Power Efficiency at 200mm Height (88KHz)



(a) (b)

Figure 13. Received Power at 200mm Height (370KHz)



(a) (b)

Figure 14. Power Efficiency at 200mm Height (370KHz)

Figure 12 to Figure 15 show the received power and the efficiency distribution in a 300mm × 300mm area. Figure 12(a) and Figure 14(a) give a three dimensional (3D) plot of the energy distribution for different frequencies, while Figure 12(b) and Figure 14(b) clearly show that the received energy can get over 5W, when the receiver is placed around the center of the transmitter. The range that can receive over 5W for 370KHz is larger than the one obtained with 88KHz.

Figure 13 and Figure 15 show the received power efficiency. In Figure 13(b) and Figure 15(b), the contour map describes the area where the receiver can get higher efficiency value. For 370KHz, the area over 80% is nearly circular with radius of 0.15m, while for 88KHz, the area over 50% is a circular with radius of 0.05m.

From the results, we can conclude that the four coils structure transmitter is able to generate over a 5W energy and over 50% efficiency when the receiver is at a 0.2m height. This is satisfied with the design goals stated for this WPT system.

6. Conclusion

In this paper, the design and the optimization steps for the WPT system are described. The focus of this paper is to design an optimal two dimensional (2D) structure of transmitter and receiver. Simulation results show that significant advantages of multiple coils structure in the receiving efficiency. The four coils transmitter model provides a large range, which can receive higher power efficiency, comparing to the single coil model. When using the four coils model with a 600mm × 600mm transmitting area and 200mm receiving distance, the achievable power transfer efficiency is over 50% for 88KHz, while the efficiency is over 80% for 370KHz. The results confirm the robustness of the WPT system multiple coils based model when operating at longer transmitting distances, which also demonstrates that multiple coils model is of an advantage to consider and solve the field forming problem.

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