IOP Conference Series: Materials Science and Engineering

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To cite this article: Dongsheng Yang *et al* 2017 *IOP Conf. Ser.: Mater. Sci. Eng.* **199** 012008

IOP Conf. Series: Materials Science and Engineering **199** (2017) 012008 doi:10.1088/1757-899X/199/1/012008

Design of Range Adaptive Wireless Power Transfer System Using Non-coaxial Coils

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Abstract. Wireless Power Transfer (WPT) is a remarkable technology because of its convenience and applicability in harsh environment. Particularly, Magnetic Coupling WPT (MC-WPT) is a proper method to midrange power transfer, but the frequency splitting at over-coupling range, which is related with transfer distance, is challenge of transmission efficiency. In order to overcome this phenomenon, recently the range adaptive WPT is proposed. In this paper, we aim to the type with a set of non-coaxial driving coils, so that this may remove the connection wires from PA (Power Amplifier) to driving coil. And, when the radius of driving coil is changed, on the different gaps between driving and T_X coils, coupling coefficient between these is computed in both cases of coaxial and non-coaxial configurations. In addition, the designing steps for 4-coil WPT system using non-coaxial coils are described with the example. Finally, the reliability of this topology has been proved and simulated with PSPICE.

1. Introduction

Wireless Power Transfer (WPT) technology is concerned in many areas, specially charging of batteries which are used in the devices such as Electric Vehicle (EV), implantable device, and portable device as power source and delivering power to the device which working in harsh environment[1-6], due to being delivered without cord, and safety during high-power charging. And magnetically-coupled resonant becomes the most recommended method in wireless power transfer, since it's discovered by scientist Marin Soljacic of Massachusetts Institute of Technology[7]. The main concept of magnetically-coupled resonant WPT is based on the principle which if the coils of both sides of transmitter and receiver is highly resonant, the magnetic field generated by oscillating current of first coil which is connected to high frequency source, relatively slowly is vanished over very many cycles and in this situation, if a second coil is brought near it, the coil can pick up most of the energy before it is lost, even if it is some distance away.

There are two types of structure which are respectively called as 2-coil and 4-coil system in magnetically-coupled resonant WPT. Compared with the basic two-coil system[8-10], the 4-coils system is able to extend the transmission distance, because the existence of the two extra mutual coupling coefficients (one is a coupling between driving and transmitter coil, and another is one between receiver and load coil)[11-14]. Due to the advantages that the 4-coil system has relatively long transfer distance, it still be investigated rather than the 2-coils system for mid-range application when the transmission distance is more than the transmitter coil dimension. With this reason, 4-coil system is considered in this paper.

However, despite using 2-coil or 4-coil system, frequency bifurcation is observed under over-coupling range. Due to the frequency bifurcation, although a receiver is very close to the transmitter (distance between transmitter and receiver is small), power delivered to load may be dropped on the fixed frequency[11-13]. This is why in the prior works frequency tracking method is proposed[11]. In order to tune optimum frequency, this method is extended to a wide range of frequency band, but in fact the frequency band which assigned for studying, industrial and medical applications is pretty narrow, the frequency cannot be selected informally. The other method is to mechanically adjust the drive coil according to the distance between the transmitter coil and receiver coil. This method is mainly classified to two categories; one is to mechanically move a coil, thus the distance between two coils is changed and that means the change of coupling coefficient, and the other is that prepare some of coils that have various coupling factors and then according to transfer distances make to change the number of connected coils and connecting structure by using switches[14-15]. In these works, they have not need to tune frequency, but the cubic dimension of the transmitter is more than others. In previous work[14], the method that various single turn coils on the same plane is switched to adapt with the coupling between the transmitter and receiver were suggested. Beside frequency adapting methods, the majority of methods which use the coupling coefficient changing have used coaxial axis type, thus have the inconvenience in delivering the exciting power to the coil, moreover the influence of the longer cable for powering which bring about the disagreement with designs can’t be neglected in single turn coils.

The method described in this paper has the advantages of occupying smaller cubic size and directly delivering the high frequency power of exciting source to driving coil without any connection wires. In section 2, firstly, analysis of the 4-coil WPT system based on the circuit theory and calculations of the mutual inductance with lateral misalignment and the parameters of circular coil made of round wire is reviewed. Then, the topology of the variable sized coils is introduced and the designing steps for 4-coil WPT system using non-coaxial coils are described with the example. The simulation analysis is given in section 3, and section 4 is the conclusion.

2. Design of 4-coil WPT system using non-coaxial coils

In this section, the fundamental analysis for range adaptive WPT system[11] and mutual inductance with lateral displacement[16] is reviewed, and then the design steps for 4-coil WPT system using non-coaxial coils are described on the basis of this analysis.

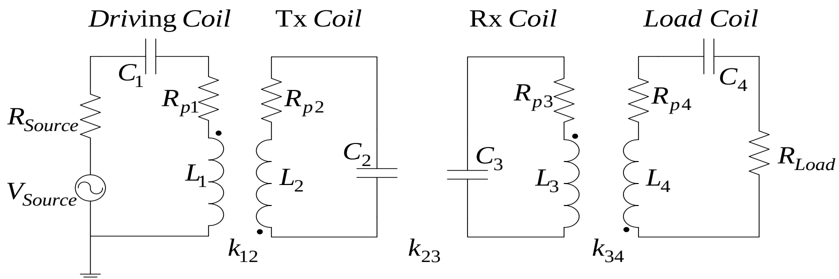

Figure 1. Equivalent circuit model of a 4-coil WPT system.

2.1. Analysis of 4-coil WPT system based on circuit theory

A typical 4-coil WPT system is composed of four resonators that have the same resonant frequency and can be represented by an equivalent circuit model. The equivalent circuit model of a 4-coil WPT system is presented in Figure 1, and it has four coils, namely, *driving coil*, *T_X coil*, *R_X coil* and *load coil*. R_{Source} and R_{Load} are the power source and load resistance, respectively. R_{pi} *(i=1,2,3,4)* and L_i *(i=1,2,3,4)* are the parasitic resistances and inductances of *driving*, T_X, R_X and *load* coil, respectively. C_i *(i=1,2,3,4)* are the resonance capacitances which are connected with aforementioned inductances and let each circuit to be resonated with the same resonant frequency. According to the KVL of circuit theory, we can obtain the following equation (1):

$$\begin{cases} V_S = I_1\left(R_{Source} + R_{p1} + j\omega L_1 + \dfrac{1}{j\omega C_1}\right) + j\omega I_2 M_{12} \\ 0 = I_2\left(R_{p2} + j\omega L_2 + \dfrac{1}{j\omega C_2}\right) + j\omega\left(I_1 M_{12} - I_3 M_{23}\right) \\ 0 = I_3\left(R_{p3} + j\omega L_3 + \dfrac{1}{j\omega C_3}\right) + j\omega\left(I_4 M_{34} - I_2 M_{23}\right) \\ 0 = I_4\left(R_{Load} + R_{p4} + j\omega L_4 + \dfrac{1}{j\omega C_4}\right) + j\omega I_3 M_{34} \end{cases} \tag{1}$$

Where I_1, I_2, I_3 and I_4 are the currents of driving, T_X, R_X and load circuit, respectively and M_{12}, M_{23} and M_{34} are the mutual inductances between adjacent coils. In general cases, the mutual inductances of nonadjacent coils like M_{13}, M_{14} and M_{24} are ignored, due to much smaller than the others. In order to facilitate analysis, make the following notation as equation (2)

$$\begin{cases} Z_1 = R_{p1} + R_{Source} + j\omega L_1 + \dfrac{1}{j\omega C_1} \\ Z_2 = R_{p2} + j\omega L_2 + \dfrac{1}{j\omega C_2} \\ Z_3 = R_{p3} + j\omega L_3 + \dfrac{1}{j\omega C_3} \\ Z_4 = R_{p4} + R_{Load} + j\omega L_4 + \dfrac{1}{j\omega C_4} \end{cases} \tag{2}$$

Generally, they are all magnetically coupled each other, whereas the main coupling coefficient are k_{12}, k_{23} and k_{34}, where $k_{mn}=M_{mn}/(L_mL_n)^{1/2}(0<k_{mn}<1)$represents the coupling strength between inductance L_m and L_n. Therefore, according to equation (1) and (2), following result is obtained as equation (3):

$$\frac{V_L}{V_S} = \frac{i\omega^3 k_{12}k_{23}k_{34}L_2L_3\sqrt{L_1L_4}R_{Load}}{k_{12}^2k_{34}^2L_1L_2L_3L_4\omega^4 + Z_1Z_2Z_3Z_4 + \omega^2\left(k_{12}^2L_1L_2Z_3Z_4 + k_{23}^2L_2L_3Z_1Z_4 + k_{34}^2L_3L_4Z_1Z_2\right)} \tag{3}$$

For analysing conveniently, the 4-coil WPT system is defined to be symmetrical, so the inductance, resistance and capacitor of the T_X coil are the same with the one of R_X coil, namely, $L_2=L_3$, $R_2=R_3$ and $C_2=C_3$. As we all know, inductance and quality factor of each coil can be described as equation (4), thus $Q_2=Q_3$. Similarly, the parameters of driving coil are equal to those of load coil, $L_1=L_4$, $R_{p1}=R_{p4}$, $C_1=C_4$. If R_{Source} equal to R_{Load}, the quality factors, taken into account of whole circuit resistances, become same, namely, $Q_1=Q_4$. And assumed that the coupling coefficient between driving and T_X coil, k_{12} is equal to the one between load and R_X coils, k_{34}, and all of the resonance frequency of the four closed circuits ($\omega_i=(L_iC_i)^{-1/2}$) are the same.

$$Q_i = \frac{1}{R_i}\sqrt{\frac{L_i}{C_i}} = \frac{\omega_i L_i}{R_i} = \frac{1}{\omega_i R_i C_i} \tag{4}$$

$$\left.\left(\frac{V_L}{V_S}\right)\right|_{\omega=\omega_0} = \frac{ik_{23}k_{12}^2Q_1Q_2^2}{k_{23}^2Q_2^2 + \left(1+k_{12}^2Q_1Q_2\right)^2} \tag{5}$$

From this symmetrical topology and the aforementioned relations, equation (3) can be simplified to equation (5). The relationship for maximizing efficiency transfer with respect to k_{23} had been derived from equation (5) and represented only with the quality factors and the coupling coefficients as shown in equation (6).

$$\left(k_{23}\right)_{critical} = \frac{1}{Q_2} + k_{12}^2 Q_1 \tag{6}$$

In equation (6), if Q_1, Q_2 and k_{12} have been fixed, optimum coupling coefficient $(k_{23})_{critical}$ is unique. Whereas leaving from this condition, transfer efficiency will decline significantly. In order to overcome this weakness, the method to control k_{12} or both k_{12} and Q_1 are presented.

Generally, WPT system may be considered as 2-port network, where one port is the side which includes V_{Source} and R_{Source}, and the other is covered with R_{Load}, meanwhile power transfer is represented by scattering parameters (S-parameter). Therefore further deriving, the forward voltage gain $|S_{21}|$ can be got as equation (7).

$$\left|S_{21}\right| = 2\frac{V_{Load}}{V_{Source}}\sqrt{\frac{R_{Source}}{R_{Load}}} \tag{7}$$

2.2. Calculations of the mutual inductance with lateral misalignment and the parameters of circular coil made of round wire

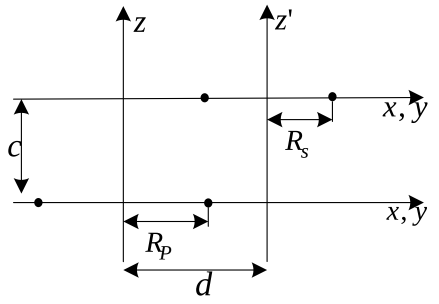

Figure 2. Filamentary circular coils with lateral misalignment

Generally, the mutual inductance (M) between coils relates to several factors, and in Figure 2, filamentary circular coils with lateral misalignment are depicted, where central axis z and z' are parallel. The mutual inductance (M) between two filamentary circular coils with lateral axes has been calculated by equation (8)[16]. R_p is the radius of the first coil, R_S is the radius of the second coil, c is the distance between the centres of coils, d is the lateral tolerance of coils.

$$M = \frac{2\mu_0}{\pi}\sqrt{R_P R_S}\int_0^{\pi}\frac{\left(1-\frac{d\cos\phi}{R_S}\right)\Psi(k)}{k\sqrt{V^3}}d\phi \tag{8}$$

Where $k^2 = 4\alpha V\left(\left(1+\alpha V\right)^2+\beta^2\right)^{-1}$, $\alpha = R_S R_P^{-1}$, $\beta = cR_P^{-1}$,

$V = \left(1+d^2R_S^{-2}-2dR_S^{-1}\cos\phi\right)^{1/2}$, $\Psi(k) = \left(1-k^2/2\right)K(k)-E(k)$,

$K(k) = \int_0^{\pi/2}\left(1-k^2\sin^2\theta\right)^{-1/2}d\theta$, $E(k) = \int_0^{\pi/2}\left(1-k^2\sin^2\theta\right)^{1/2}d\theta$.

$K(k)$ and $E(k)$are the complete elliptic integrals of the first kind and the second kind, respectively.

According to [17], the inductance of a circular coil of round wire, where coil radius is r and wire radius is a, is as equation (9):

$$L = \mu_0 a\left[\ln(8r/a)-1.75\right] \tag{9}$$

In a round conductor, the radial distribution of the current density is a Bessel function of argument proportional to the square root of frequency. At DC (Direct Current), the current density is uniform due to zero frequency, whereas at high frequencies the current is concentrated close to the surface. This is called as skin effect, and the available cross section which is able to flow current becomes decrease. Due to this phenomenon, AC resistance is much more than DC resistance at high frequency.

When the frequency is f, the length of winding wire is l_ω, the diameter of winding wire is d, the resistivity of winding conductor is ρ_ω and the permeability of free space is μ_0, the skin depth δ_ω and winding DC resistance $R_{\omega DC}$ of the winding wire can be got as equation (10) and (11):

$$\delta_\omega = \sqrt{\frac{\rho_\omega}{\pi \mu_0 f}} \tag{10}$$

$$R_{\omega DC} = \frac{4\rho_\omega l_\omega}{\pi d^2} \tag{11}$$

The ratio of the wire diameter to the skin depth is d/δ_ω, and if it is much more than 1, the ratio of the AC and DC winding resistance is

$$F_R = \frac{R_\omega}{R_{\omega DC}} \approx \left(\frac{\pi}{4}\right)^{3/4} \frac{d}{\delta_\omega} \sqrt{\frac{d}{p}} \frac{(2N_l^2+1)}{3} \tag{12}$$

Where d/p is the porosity factor, and N_l is the number of layers. So, the winding AC resistance for the sinusoidal current is

$$R_\omega = F_R R_{\omega DC} \tag{13}$$

2.3. Design of 4-coil WPT system without connection wires

In this subsection, we proposed the procedure of design of 4-coil WPT system without connection wires from PA to coil. In general, the greater the coils, the longer the transmission distance. But in practical applications, these coils unfortunately should be not such great dimension because of some limitations, or such dimension may not be needed. When using equation (5), k_{13} and k_{24} as well as k_{14}, should be smaller enough to be neglected, thus the radius of driving coil (r_1) should be smaller than the radius of T_X coil (r_2), and similarly $r_4<r_3$. In this design, resonance frequency is 13.56MHz, maximum size of r_1 and r_4 are 0.1m, r_2 and r_3 are 0.15m. The wire's diameter of coils is 2.5mm, and all coils are made up of copper wire. Under above conditions, in order to satisfy equation (6), the number of turns is decided as $n_1=n_4=2$, and $n_2=n_3=4$. System being designed is symmetric, so only driving coil and T_X coil are mainly considered in following part.

As is showed in Figure 3, according to the state of the Switch, different coil is connected to Driving Source. These four coils are placed on the same plane, but have not only different radii, but also different axes. Therefore, when the coupling coefficient is computed, the axis's offset is taken into account consideration, as well as coil's radius. All of following calculations is computed with MATLAB.

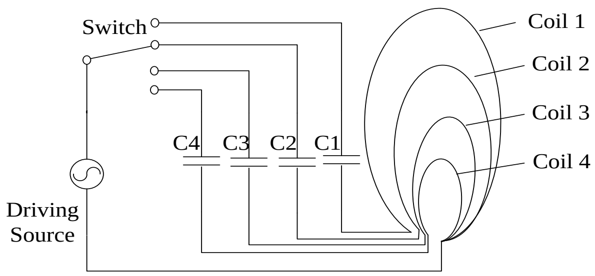

Figure 3. Topology of driving coils with non-coaxial axes

a. Base on equations (9)-(13), AC resistance (R_2) and inductance (L_2) of T_X coil are computed and then the quality factor of T_X coil (Q_2) is got from these values and the resonance frequency. Calculated values are added to Table 1. This closed circuit has only the parasitic resistance of T_X coil, and hence the quality factor of this is equal to one of T_X coil. But in case of driving circuit, besides parasitic resistance of coil, driving source's resistance also is considered.

Table 1. Parameters of T_X and R_X circuits

Parameter	*Frequency*	$R_2=R_3$	$R_{Source}=R_{Load}$	$L_2=L_3$	$C_2=C_3$
Value	13.56*MHz*	4.3*ohm*	50*ohm*	15.56*uH*	8.8543*pF*

b. Base on equation (8), mutual inductance between T_X and R_X coils (M_{23}) is computed as the function of the distance and then the coupling coefficient (k_{23}) is got from this relation and self-inductance (L_2). In Figure 4, the coupling coefficient (k_{23}) between T_X and R_X coils as a function of distance is plotted.

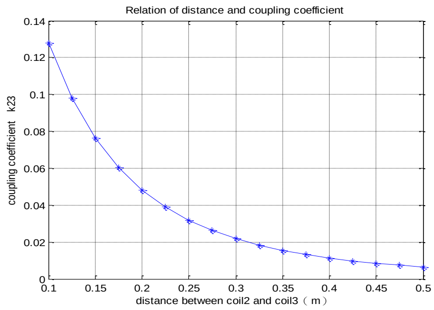

Figure 4. Coupling coefficient between T_X and R_X coils as a function of distance

c. Similar to a., AC resistance R_{p1}, inductance (L_1) and the quality factor (Q_1) of driving coil are computed as the function of radius, but this quality factor is considered by both of source and coil resistances. In Figure 5, parameters of the driving coil are plotted for the radius.

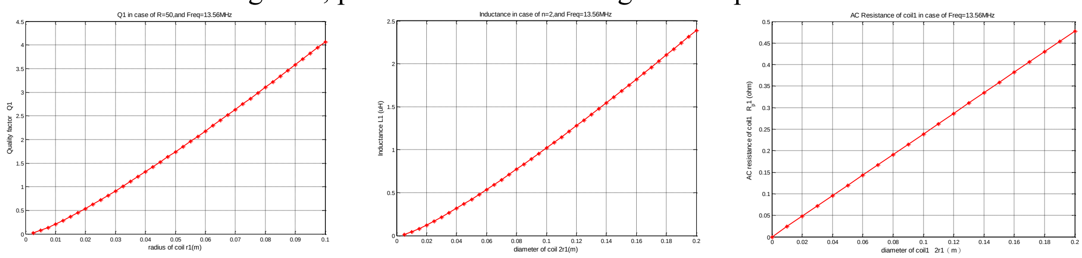

Figure 5. Parameters of the driving coil as a function of the radius.

d. When the radius of driving coil (r_1) is changed, on the different gaps (d_{12}) between driving and T_X coil, mutual inductance between these (M_{12}) is computed in both case of coaxial and non-coaxial configurations. In case of non-coaxial configuration, lateral misalignment is equal to difference between radii of driving coil and T_X coil (r_1-r_2), since two coils are inscribed. Using driving coil inductance (L_1) of a. and T_X coil inductance (L_2) of c., the coupling coefficient (k_{12}) is got. The result is plotted in Figure 6.

e. From k_{12} and Q_1 as the function of r_1, which have been obtained in step d., proper gap which can support the equation (6) over all interest range (k_{23}) should be selected. In this paper $d_{12}=0.03m$ is recommended.

f. Interest range of the system is uniformly divided into five gaps, and corresponding k_{23} with these equal diversion points is obtained from Figure 4. And then set of r_1 to satisfy these k_{23} is decided from Figure 6 (c) and Figure 5. In this paper, interval is 0.1m, and the distance range of interest is 0.5m. The parameters obtained according to distances are tabulated in Table 2.

g. Resonance capacitors are computed from L_1-L_4 and ω. These values are added to Table 2.

Table 2. Parameters of driving and load circuit

$d_{23}(m)$	k_{23}	$2r_1(cm)$	Q_1	k_{12}	$L_1(uH)$	$C_1(pF)$
0.1	0.128	19	3.8	0.181	2.245	61.363
0.2	0.048	15	2.8	0.131	1.683	81.853
0.3	0.022	12	2.2	0.1	1.279	107.71
0.4	0.012	10.5	1.75	0.082	1.084	127.08

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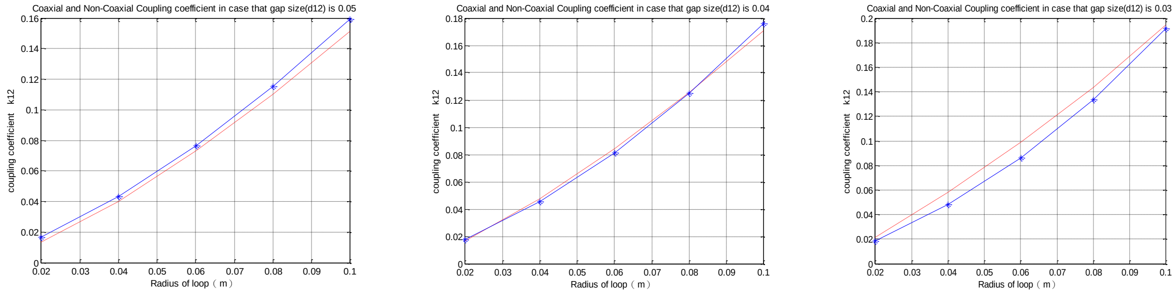

(a) (b) (c)

Figure 6. Coaxial and Non-coaxial coupling coefficient (k_{12}) as function of radius of driving coil (r_1) on the different gaps (d_{12}). (a) in case of $d_{12}=0.05m$, (b) in case of $d_{12}=0.04m$, (c) in case of $d_{12}=0.03m$. Solid line is the coaxial coupling coefficient and dotted line is the non-coaxial coefficient.

3. Simulation of the proposed method

The example configuration given in Section 2 is simulated to prove validation of the new method in PSPICE. The parameters listed in Table 1 are about to T_X and R_X coils, thus these parameters are fixed in whole simulation process and inputted into elements of Figure 1. But Table 2 is listed as sets of parameters, that should be changed according to which driving coil is connected to power source. For example, if driving coil1 ($2r_1=0.19m$) is selected, the parameters of column2 of Table 2 are inputted into elements of Figure 1. According to equation (7), $|S_{21}|$ is obtained as the function of k_{23} in case that driving coil1 is selected. In the same way, in the other cases $|S_{21}|$ is obtained and all of the simulation results are plotted in Figure 7. As showed in Figure 7, the peak points are exactly matched with calculated value based on equation (6), so the correctness of this method is proved and able to be used for range adaptive WPT system.

If we are able to measure the distance to be transferred, proper driving coil is be selected by using proposed method, thus the high efficiency transmission is maintained in whole range.

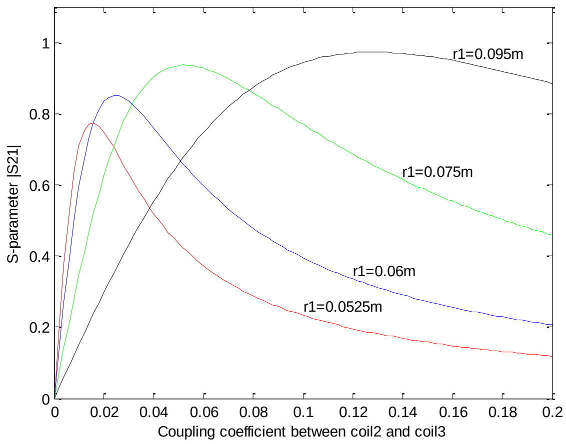

Figure 7. $|S_{21}|$ as function of k_{23} in case of different driving coil's radius

4. Conclusion

In this paper wireless power transfer system without any connection wires from high frequency power source to driving coil has been proposed and simulated. It has been confirmed that the proposed methods can be used to overcome the frequency bifurcation phenomenon and non-coaxial coil is able to remove the connection wires. The coupling coefficient between driving and T_X coils in case of using coaxial coils is different with one in case of using non-coaxial coils, but non-coaxial coils are also used for range adapting. Moreover, as shown in Figure 6 the change of the coupling coefficient with lateral misalignment is nearly proportional to coil radius, thus this advantage makes it easy for designer to design a WPT system with high transmission efficiency.

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