Research on Parameter Optimization of Double-D coils for Electric Vehicle Wireless Charging Based on Magnetic Circuit Analysis

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Abstract Compare with circular coils, Double-D coils are widely used in the wireless charging system of electric vehicles for its high coupling coefficient and excellent offset tolerance. In order to obtain higher coupling coefficient and reduce the leakage magnetic flux in the central part of the coils, this paper proposes a method that optimizing stray parameters, which can achieve more than 95% of transmitting efficiency. The investigation is performed by joint simulation for the choice of experimental devices concerning current-withstanding characteristic. According to simulations and experiments, more than 11 kW output power can be achieved for a wide range of frequency.

key words: Double-D coils, wireless charging system, electric vehicles, coupling coefficient, stray parameter, joint simulation.

Classification: Electron devices, circuits, and systems

1. Introduction

Wireless power transfer (WPT) technology has gained more and more attention due to its unique advantages [1,2], with the characteristics of green, convenience, safe and non-contact. It has been widely used in implantable medical devices [3], Electric vehicles(EVs) [4] and other applications [5, 6, 7, 8]. It is also available for both stationary and dynamic charging [9, 10, 11]. Accordingly, some outstanding contributions to improve the transfer efficiency and output power of WPT devices have been made by researchers [12, 13, 14, 15, 16]. The WPT system is composed of control devices [17], magnetic coupling structure [18, 19]and compensation network [20, 21, 22]. With the continuous development of WPT technology, the structure of transmission coils is diverse. Among them, circular coil is the most researched[23, 24]. However, the DD type has been recently proposed as the EV’s charging magnetic coupler design, which already has been proven to have the better performance in the stationary and misalignment charging than circular coils [25]. The WPT system of DD coils achieved the efficiency at 94.07% while delivering 4.73 kW to the load with a vertical air gap of 150 mm [26]. Non-dominated sorting genetic algorithms II is applied to optimize the DD coil structure with coupling coefficient and maximum leakage magnetic flux density [27]. However, to data, the current work is almost seldom done to optimize the horizontal spacing of DD coils on the coupling coefficient.

In the shorted-resource world, economizing on resources has become particularly important, especially for the mass production of wireless charging system. Therefore, the optimization of wireless charging system not only focuses on improving the transfer performances, but reduces the costs. For instance, the ferrite is removed from a roadway DD pad while the reflection winding requires careful design [28]. The researchers of Shinshu University in Japan proposed a magneto plated aluminum pipe, which is lighter and cheaper than litz wire except for slightly lower transfer efficiency [29]. This paper focuses on economizing the WPT system costs on the basis of increasing the coupling coefficient.

In this paper, the physical parameters of magnetic cores are optimized and the structure of DD coils is slightly adjusted based on large coupling coefficient by the theory of the finite element method (FEM) and experiments, enabling a less expensive WPT system based on considerable efficiency. Moreover, a method of optimizing stray parameters of DD coils considering the unique flux path is proposed. Besides, the distribution of DD inductance is also discussed in this paper. Finally, the optimized system can achieve more than 95% of the efficiency.

2. Theoretical analysis of WPT

Series-series (SS) resonant compensation topology is adopted as Fig. 1 shown, where the maximum efficiency would be obtained in the resonant angular frequency \( \omega \).
The efficiency of the WPT is presented as follows when
\[ k = M / \sqrt{L_1 L_2} . \]
\[ \eta = \frac{\omega^2 k^2 L_1 L_2 R_c}{R_c (R_c + R_l) + \omega^2 k^2 L_1 L_2} (R_2 + R_l) \]  
(1)

The expression of the output power can be derived as
\[ P = I^2 R_L = \frac{\omega^2 k^2 L_1 L_2 U_m^2}{R_c (R_c + R_l) + \omega^2 k^2 L_1 L_2} R_L \]  
(2)

Where \( E_1 \) is the voltage with peak value of 750 V, \( L_1, L_2 \) are self-inductance of transmitter (Tx) and receiver (Rx), \( M \) is the mutual inductance. \( k \) is the coupling coefficient. \( R_1 \) and \( R_2 \) represent the resistances of the two coils. \( R_L \) is the resistive load. \( I_1 \) and \( I_2 \) are the primary and secondary current respectively. The output power increases linearly with load before efficiency arrives at its maximum point as shown in Fig. 2.

Besides, the maximum efficiency can be higher and decrease more smoothly versus load as \( M \) increases. And the load is lower when \( P \) arrived at its maximum point as \( M \) decreases. Additionally, an optimum resistance for the maximum efficiency can be derived from Eq. (1) that
\[ R_c = \frac{1}{\omega^2 k^2 L_1 L_2 R_c} \]  
(3)

the optimum resistance for the maximum output power can also be derived from Eq. (2).
\[ R_c(P) = R_2 + \frac{\omega^2 k^2 L_1 L_2 / R_L}{R_2} \]  
(4)

Once the coil shape is determined, usually, the self-inductance \( L_1 \) and \( L_2 \) will not change. It can be concluded from Eq. (1) that efficiency is almost proportional to mutual inductance and coupling coefficient when \( R_L \) is constant. In the case of ultra-power transmission, high transmission efficiency can alleviate the loss of the coil, therefore, increasing coupling coefficient is the premise of optimizing the transmitting efficiency of WPT.

3. Optimization design of WPT

3.1 Typical Magnetic Coupling System for EVs

The magnetic coupling system using DD structure is composed of magnetic cores, litz wires and shield plate as shown in Fig. 3. The direction of coordinate system is also indicated, where X-axis is parallel to the direction of long side of DD coil. The aluminum shield plays a role of EVs’ chassis, which facilitates magnetic shielding. The typical magnetic coupling system indicates that the length of the cores is consistent with the DD coils and the horizontal spacing between single coils is equal to the turn spacing. Define \( b \) and \( w \) as the height and width of the cores, which are 8 mm and 50 mm. Outer diameters of Tx and Rx are both 7.4 mm, and coil turns are 15 and 13, respectively. Inner rectangles of Tx and Rx are 200 mm*52.6 mm and 150 mm*52.6 mm. The transfer distance is designed as 166 mm, which should meet WPT/Z2 of the SAE standard J2954 with Z range of 140-210 mm [30].

3.2 Optimization of Horizontal Spacing of DD Coils

Based on the coupling principle, the magnetic flux of YZ section can be divided into mutual coupling region and self-coupling region. Fig. 4(a) shows the magnetic field distribution of DD coils. As shown in Fig. 4(b), the cross section of the electromagnetic coupling mechanism for WPT in EVs is presented. Fig. 4(c) shows the equivalent magnetic circuit model.

According to symmetry, the reluctances of the mutual coupling area and self-coupling area are equivalent to \( R_{m1} \sim R_{m2} \) and \( R_{s1} \sim R_{s3} \), where \( F \) is the magnetomotive force. \( R_{m2}, R_{s3} \) are maintained when the variation of \( d_1 \) is equal to \( d_2 \). The coupling coefficient is defined as \( k \), which is determined as follows.
\[ k = \frac{\Phi_m}{\Phi_m + \Phi_{m1} + \Phi_{m2} + \Phi_{m3}} = \frac{2F}{R_{m2} + R_{m1} + 2R_{m2} + \frac{4F}{4F + R_{m1} + 2F}} \]  
(5)

Any magnetic resistance is given by \( R = l/\mu A \), where \( \mu_0 = 4\pi \times 10^{-7} \text{H/m} \), \( l \) is magnetic length, and \( A \) is an effective area. In order to keep system aligned during the variation on horizontal spacing, the distance from the alignment line to the...
inner edge of the Tx and the Rx are denoted as \(d_1\) and \(d_2\) respectively. In other words, \(d_1\) and \(d_2\) are the half of the horizontal spacing between each coil of the DD Tx and the DD Rx respectively. The length of circuit in the Self-coupling area 2 is equal to the Self-coupling area 1, defined as \(d\). Besides, the Mutual coupling area 1 is set as \(d-2t\), where \(2t\) is the gap between the Mutual coupling area 1 and the Self-coupling area 2. Define \(w_1\) and \(w_2\) as the width of each coil in the DD Tx and the DD Rx as Fig. 4(a) shown. The relationship among \(d\), \(d_1\), \(d_2\) and \(t\) can be presented as

\[
d=2w_1 + 2d_1 = 2w_2 + 2d_2 + 2t
\]  
(6)

On the basis, \(k\) can be expressed as

\[
k = \frac{1}{\Gamma_1d + \frac{\Gamma_2}{d} + \Gamma_3} = \frac{d}{\Gamma_1d^2 + \Gamma_3d + \Gamma_2}
\]  
(7)

The following equations are applied to simplify the expression of \(k\)

\[
\begin{align*}
\Gamma_1 &= \frac{A_{\alpha} + A_{\alpha|m|}}{\mu_0 A_{\alpha}R_{\alpha^3}} \\
\Gamma_2 &= \frac{4\mu_0 R_{\alpha|m|}A_{\alpha|m|}A_{\alpha|m} - 2A_{\alpha|m|}A_{\alpha|m}t}{A_{\alpha} + A_{\alpha}} \\
\Gamma_3 &= \frac{2A_{\alpha|m}A_{\alpha} + 2A_{\alpha|m}A_{\alpha|m}I_{\alpha|m} R_{\alpha^3} \frac{t}{A_{\alpha|m} R_{\alpha^3} k_0}}{A_{\alpha} + A_{\alpha}} + \frac{2R_{\alpha|m}}{R_{\alpha^3}} + 2
\end{align*}
\]  
(8)

Where \(A_{\alpha}, A_{\alpha|m}, A_{\alpha|m}\) are the effective area of self-coupling area 1, self-coupling area 2 and self-coupling area 1, which are constants. Similarly, \(R_{\alpha}, R_{\alpha|m}\) will not change along with \(d\). The derivative of \(k\) with respect to \(d\) are derived as

\[
k'(d) = \frac{\Gamma_2 - \Gamma_3d^2}{(\Gamma_1d^2 + \Gamma_3d + \Gamma_2)^2}
\]  
(9)

In order to simplify the analysis and calculation, \(t\) can be ignored as the magnetic flux leakage in the central part of the receiving coil is neglected. Therefore, \(\Gamma_1, \Gamma_2 \) and \(\Gamma_3\) are positive. By Eq. (9), \(k\) has a maximum value when \(d = \sqrt{\frac{\Gamma_2}{\Gamma_1}}\). However, it is difficult to obtain effective area of magnetic flux in addition to determining that the maximum value of \(k\) exists.

It should be noted that above results about \(k\) is analyzed under the condition of the variation of \(d_1\) is equal to \(d_2\). Accordingly, Newman formula as Eq. (10) is used to calculate mutual inductance and to discuss the changes of \(k\) with \(d_1\) and \(d_2\).

\[
M = N_1N_2 \frac{\mu_0}{4\pi} \int \int \frac{dl_1dl_2}{r}
\]  
(10)

Where \(l_1\) and \(l_2\) are integral loops, \(r\) is the distance between integral element \(dl_1\) and \(dl_2\). \(N_1, N_2\) are the turns of Tx and Rx. Denote the coil at the left part and the right part of the Tx, the left part and the right part of the Rx as \(T_1, T_2, R_1\) and \(R_2\) respectively. Fig. 5(a) shows the diagram of DD coils. Where \(M_{\text{RT11}}, M_{\text{RT22}}, M_{\text{RT21}}\) and \(M_{\text{RT22}}\) are mutual inductance between \(R_1\) and \(T_1, R_1, T_2, R_2\) and \(T_1, R_2\) and \(T_2\) respectively. \(M_T\) and \(M_R\) are mutual inductance between each rectangular coils of the Tx and the Rx respectively. \(L_{T1}, L_{T2}, L_{R1}\) and \(L_{R2}\) are the self-inductance of \(T_1, T_2, R_1\) and \(R_2, d_1, d_2\) are also marked on both sides of the alignment line. Besides, there are two schematic diagrams shown below. One is the three-dimensional relations between \(k\) and \(d_1, d_2\), shown in Fig. 5(b), which proves the existence of the maximum value of \(k\) in theoretical analysis. Another one in Fig. 5(c) expresses the condition when \(k\) reaches its maximum that is \(d_1 = d_2\). Fig. 5(d) illustrates the equivalent electrical circuit that two coils are connected in series with the identical current direction. \(I_1\) and \(I_2\) are currents flowing out of \(T_1\) and \(R_1, I_1'\) and \(I_2'\) are currents flowing into \(T_2\) and \(R_2\) respectively.

![Fig. 5. DD coils. (a) The diagram of inductances distribution. (b) The three-dimensional relations between \(k\) and \(d_1, d_2\). (c) Top view of the three-dimensional relationships. (d) Equivalent circuit of DD coils](image)

Mutual inductance between Tx and Rx

\[
M = M_{\text{RT11}} + M_{\text{RT22}} = M_{\text{RT21}} + M_{\text{RT22}}
\]  
(11)

Self-inductance of Tx

\[
L_T = L_{T1} + L_{T2} + 2M_T
\]  
(12)

Self-inductance of Rx

\[
L_R = L_{R1} + L_{R2} + 2M_R
\]  
(13)

The above analysis shows that \(k\) reaches the maximum value when variation of \(d_1\) is equal to \(d_2\), which greatly reduces the computation and simulation time of FEM. To simplify, the variation curve of \(d\) and \(k\) is drawn in Fig. 6, where \(2d_1 = 2d_2 = d'\). \(d'\) is the horizontal spacing of the DD coil.

![Fig. 6. Horizontal spacing of coils. (a) magnetic distribution under \(d'=2\) mm. (b) magnetic distribution under \(d'=35\) mm. (c) magnetic distribution under \(d'=105\) mm](image)

It can be seen that the value of \(k\) changes with \(d'\) in Fig. 6, which is consistent with the theoretical derivation of reluctance. As supplement legends, the magnetic field
distributions under \(d' = 2\) mm, \(d' = 35\) mm and \(d' = 105\) mm are illustrated by Fig. 6(a), (b) and (c). Note that \(d' = 2\) mm means that the horizontal spacing between each coil of one DD coil is equal to the turn spacing. When \(k\) arrived at its maximum, \(d' = 105\) mm. However, the coupling coefficient and the transmission efficiency are relatively lower when \(d' = 2\) mm and the transmission efficiency is less than 95%. Besides, the system of WPT with \(d' = 105\) mm is unacceptable due to its excessive size while the efficiency is close with \(d' = 35\) mm. Considering the cost of WPT system, coupling coefficient and transmission efficiency comprehensively, it is better to set \(d' = 35\) mm.

### 3.3 Optimization of magnetic cores

The cores play the role of short flux, which greatly reduce the leakage of the central part. It is essential to reduce the reluctance in the magnetic flux path by adding cores. On the basis, the placement of strip cores is parallel to the two rectangular coils separated by DD coils, which can eliminate the influence between adjacent coils. Additionally, \(k\) would significantly increase by adding the cores. Furthermore, the cores would only affect the magnitude of reluctance but not the topological structure of the equivalent magnetic circuit. \(\Phi_m\) and \(\Phi_C\) are almost shorted by the cores as \(R_{\phi_2}\) and \(R_{\phi_1}\) are much smaller relative to air reluctance. \(k\) increases as \(R_{\phi_1}\) decreases. It can be concluded from Eq. (4) that in order to increase \(k\), \(R_{\phi_2}\) should be increased, thus the cores should not be arranged at both sides of Tx. LP9 ferrite bars are used in the DD coils, whose properties are given in TABLE I.

| Name                  | Value | Units          |
|-----------------------|-------|----------------|
| Relatively Permeability | 3300  |                |
| Bulk Conductivity     | 0.167 | Siemens/m      |
| Mass Density          | 4900  | w/m^3          |

The relationships between \(k\) and the length of cores can be verified by FEM as shown in Fig. 7.

Fig. 7. Length of the cores. (a). Change direction of Tx cores. (b). Change direction of Rx cores.

Note that both cases are discussed respectively, where the cores are placed on Rx and Tx. The lengths of the cores increase in directions of Fig. 7 (a) and (b) are depicted. When the cores are on the Rx, \(k\) reaches a peak value of 0.172 with the length of the cores 350 mm. When the cores are on the Tx, \(k\) reaches a peak value of 0.161 with the length of the cores 400 mm. By comparison, it also can be observed that \(k\) is significantly improved without the cores on the margins in the X-axis direction.

### 4. Performance verification

#### 4.1 Joint simulation

In this design, Ansys Maxwell and Ansys Simploer are employed to achieve current of WPT system. Fig. 8 depicts the joint simulation circuit diagram.

Fig. 8. Joint simulation circuit diagram.

Where W1 and W2 are the wattmeter, \(C_1.I\) and \(C_2.I\) are the primary and the secondary current respectively. VM1 and VM2 are the voltages of the transmitting and the receiving coil. The resonant frequency of the circuit is 85 kHz. The mutual inductance between Tx and Rx simulated by Maxwell is 40.69 \(\mu\)H, the self-inductances of Tx and Rx are 214.12 \(\mu\)H and 127.59 \(\mu\)H respectively, \(C_1\) and \(C_2\) can be determined by resonance formula \(f = \frac{1}{2\pi\sqrt{LC}}\), then \(C_1 = 16.4\) nF, \(C_2 = 27.5\) nF. When the load is 18.8 \(\Omega\), the output power is above 11 kW that meets the Class 3 Power of the SAE standard [30]. Meanwhile, the variations of \(C_1.I\) and \(C_2.I\) are presented in Fig. 9.

Fig. 9 Current of WPT system

From Fig. 9, we can observe the characteristic that both current of the Tx and the Rx increase gradually until they stabilize. Besides, the phase difference between the stable current of the Tx and the Rx is 90°. The maximum current peak of the \(C_1.I\) is 31.81 A, when that of the \(C_2.I\) is 36.27A. The simulation results can also make guidance for the selection of experimental devices, such as the dimension of litz wire for overcurrent. As a result, the litz wire with 7 mm diameter is selected, which the characteristic of current- withholding is 50 A.
4.2 Experimental verification
An experimental prototype for electric vehicle wireless charging is built up to validate the performance of WPT system. Fig. 10 shows the experimental setup.

![Experimental prototype](image)

Fig. 10. Experimental prototype. (a) High power DC source. (b) High frequency inverter. (c) Electronic load. (d) WPT system.

The mutual inductance, the self-inductances of Tx and Rx measured by U2836 LCR meter are 36.9 $\mu$H, 196.7 $\mu$H and 117.42 $\mu$H, respectively. Meanwhile, the compensation capacitances of Rx and Tx are 17.8 nF and 30.0 nF, respectively. The current and voltage are distributed equally by tuning system composed of four identical capacitors, as Fig. 10(b) shown. Accordingly, the heating of capacitors can be well relieved. By experiment, the measured WPT system efficiency, the input power and the output power in different frequencies are compared with the simulation results in Fig. 11. It can be seen that the efficiency curve is almost unchanged while the frequency is from 82.5 kHz to 90 kHz. Meanwhile, the output power is almost more than 11 kW for a wide range of the working frequencies. The experimental results are consistent with the simulation results.

![Comparison of experimental results and simulation results at different frequencies](image)

Fig. 11. Comparison of experimental results and simulation results at different frequencies.

In addition, the unoptimized system in Fig. 3 and the optimized system in Fig.10 are built up to make a comparison on the coupling coefficients measured by LCR meter, which the results are presented in TABLE II.

| Parameters | Length of cores (mm) | Coupling coefficient |
|------------|---------------------|----------------------|
| Unoptimized system | 630 | 555 | 0.237 |
| Optimized system | 400 | 350 | 0.246 |

Compared with the typical DD coils presented in Fig. 3, the coupling coefficient is improved by reducing the length of cores, which are also more economic. In general, the result shows that the optimized WPT system could achieve better transmitting performance with less costs. Furthermore, the system efficiency shall be tested for X and Y offset tolerance based on a plane horizontal to the ground. As a result, the experiment is conducted to test the offset tolerance of WPT system at the specific locations according to SAE standard J2954, which are shown in TABLE III.

| Offset Position | Position |
|-----------------|---------|
| X offset/mm     | ① 0 75 0 0 100 75 100 |
| Y offset/mm     | ② 0 0 75 100 0 100 75 |

...Fig. 11 shows the relationship between efficiency and the offset position. The correctness of the simulation is verified by experiments results. Besides, because the cores are adopted by hand, some errors between simulation and experimental results are normal and acceptable. Comparisons are made between position ② and ③, ④ and ⑤. The conclusions can be summarized from Fig. 11 that the requirement of high tolerance of WPT system can be satisfied well. Especially, the optimized DD coils have better tolerance in Y-axis offset.

![Efficiency](image)

Fig. 12. Measured and simulated efficiency

5. Conclusion

In this paper, the method of optimizing the horizontal spacing of DD coils and the length of cores according to the magnetic coupling principle have been proposed. Theoretical results show that the coupling coefficient can be improved by designing the connection spacing between coils of Tx or Rx and configuring the length of the cores. By comparison, the performance of the optimized system is verified well. Besides, the DD coils are proved with better
tolerance in Y-axis offset. Finally, the cores can be saved by optimization with higher transmitting efficiency, which is of great significance to mass production of EVs.

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