Investigation of power transfer efficiency: utilizing different coil designs in wireless charging of electric vehicles

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Abstract
EV battery can be wirelessly charged by inductive coupling method between two electromagnetic couplers. In this study, the transmitter and receiver coils are designed. The effect of the number of turns for transmitter and receiver coils are studied. The results show that efficiency is decreased with the reduction of turns for both coils. Next, the spacing between each turn of coils is analyzed by 1mm of increasing for each simulation and the increased efficiency is only 2.6% for every 1mm spacing. Then, the power transfer efficiency is investigated for different coil designs. The efficiency can be improved with the proper consideration of air gap length, operation frequency, suitable coil designs and coil properties. Five coil designs such as circular, rectangular, double-D, double-D quadrature (DDQ) and bipolar designs are selected. The best design for maximum power transfer efficiency is DDQ design but the structure is complex since more wires are used in this design. The air-gap length between two coils is selected as 120mm and frequency is 85 kHz in this study.

Keywords: Inductive coupler, Power Transfer Efficiency, Wireless Charging, Electric Vehicles

1. Introduction
Electric Vehicles (EV) has been significantly popular in recent years since the required electric energy is obtained from various sources such as nuclear power and renewable energy sources [1]. However, one biggest problem is the time required for driving EV to a charging station and waiting for the battery to be fully charged. Wireless charging or Wireless Power Transfer (WPT) system brings an ultimate
solution to that problem [2]. WPT is based on inductive coupling in which electrical energy is transmitted from a power source to an electrical load using two electromagnetic coils. The magnetic field is created between the coils and transferred over distance. Wireless charging for EV can be categorized into stationary, semi-dynamic and dynamic charging system. In dynamic charging, the transmitter/primary coil is installed under the ground connecting to the grid electricity and the receiver/secondary coil under the chassis of EV. The primary system consists of a grid network power supply, a cascade of AC-DC and DC-AC rectifier increasing the AC power line frequency (50Hz or 60Hz) to a high-frequency AC power (<100kHz) to energize the primary transmitter coils and a compensation circuit. The VA ratings of power electronics are reduced and the leakage inductance for magnetically coupled power transfer are neutralized to achieve the higher frequency by the compensation circuit. The secondary side includes AC-DC rectifier converting the induced high-frequency AC into DC and a secondary compensation circuit providing constant current, constant voltage, or step power to charge an onboard battery. The in-road transmitter must be delicately constructed to achieve the necessary power transfer efficiency and performance [3].

In order to design an efficient WPT system, the effect of significant operating parameters such as operating frequency, physical airgap spacing between transmitting and receiving charging coils, wire property used for coil and coil configuration must be primarily analyzed [4]. Moreover, the following parameters such as power level, maximum charging distance, charging tolerance, size and weight and efficiency are critical when WPT system for EV is designed [5]. Power level determines the required amount of time for full charging of the battery. The maximum charging distance is a distance between transmitter and receiver according to the ground clearance of EV to be charged. The charging tolerance is where a driver needs to park EV to adjust the horizontal and vertical position according to the charging equipment. The size and weight are for a receiver pad to be installed in EV. The receiver part was designed with the effect of shape, size of the wire, number of turns and size of the coil [6]. The efficiency of the WPT system could be compared with the plug-in system. In order to reduce the weight of the receiver pad and enhance the power transfer efficiency, this paper focuses on three parametric studies with the following criteria. The first parametric study is that the number of turns for transmitter and receiver coils were alternated in a way of 10 transmitter turns and 10 receiver turns, 10 transmitter turns and 5 receiver turns, and 5 transmitter turns and 5 receiver turns. The second one is the spacing of 1mm, 2mm and 3mm between consecutive turns that were compared for both coils simultaneously. Finally, the five coil designs for both transmitter and receiver coils were analyzed for maximum power transfer efficiency.

2. Methodology

During the design process of primary and secondary coils, the main parameters that should be maximized are quality factor $Q$ and coupling coefficient $k$ with the increasing air-gap lengths. Ferromagnetic materials (cores) can be used to guide magnetic flux to improve coupling [7]. Losses within the system contain core losses of the ferrite material and ohmic losses of the coils including proximity and skin effect losses. Litz wire can reduce skin effect losses while the flux density was lower than the saturation flux density of the material decreases core losses. However, limitations of power and space requirements are still challenging for the available design options. The efficiency of the power transfer can be enhanced by three design parameters coupling coefficient $k$ or mutual inductance $M$, self-inductance of the coils $L$ and frequency $\omega$. An induced voltage in the secondary coil can be improved by increasing frequency but frequency-dependent losses will be also increased. Therefore, selecting the design frequency is also important. Increasing coil dimensions and the number of turns can be improved the self-inductance of the coils. However, there is also a limitation for maximum coil size which depends on the size of the underbody of EV. To obtain a higher coupling coefficient, decreasing the air-gap length between the coils, increasing the coil dimension, and having equally sized coils can be performed. The coupler size, coupling coefficient, quality factor of coils and maximum power transfer efficiency are calculated with the following equations.
\[ d_{xo} = d_{xi} + 2 \cdot [N \cdot d_w + (N - 1) \cdot \gamma] \]  
\[ k = \frac{M}{L_1 \cdot L_2} \]  
\[ Q = \frac{\omega \cdot L}{R} \]  
\[ \eta_{max} = \frac{1}{1 + 2 \cdot \frac{k^2 Q_1 Q_2}{k^2 Q_1 Q_2 + 1} + \frac{2}{k^2 Q_1 Q_2} + 1} \]

3. Conceptual model  
This paper is only based on a simulation study using Ansys Electronics Suite software. Circular-circular coil design is selected as a base model for parametric studies. The outer coil diameter is chosen as 300 mm and the wire diameter is 7mm. Frequency of 85kHz is used and current is excited as 10A. An air gap between transmitter and receiver coils is chosen as 120mm. For the first parametric study which is the impact of the number of turns on efficiency, three different cases which are 10 turns for both transmitter and receiver coils, 10 turns for transmitter coil and 5 turns for receiver coil and 5 turns for both coils are analyzed. For the spacing between consecutive turns, 1mm, 2mm and 3mm spacings are examined for power transfer efficiency. For different coil designs, circular, rectangular, double-D, double-D quadrature (DDQ) and bipolar designs are observed.

4. Simulation results and discussion  
To compare the power transfer efficiency of different coil designs, they are designed to be as analogous to each other as possible. This study ultimately aimed to investigate the efficiency of power transfer, so some received parameters such as coupling coefficient \( k \), the quality factor of both transmitter \( Q_1 \) and receiver coils \( Q_2 \) are mainly compared. The software gives 6 decimal places for all results. The parameter that effects the efficiency is coupling coefficient \( k \), so \( Q_1 \) and \( Q_2 \) are taken as only two decimal places. By comparing the power transfer efficiency given by different decimal places of \( k \), it was discovered that the result with four decimal places of \( k \) is almost the same as six decimal places of \( k \). Therefore, the important parameter coupling coefficient was taken as four decimal places and others are taken as only two decimals for every simulation result.

4.1 Number of Turns for transmitter and receiver coils  
As a first step, the number of turns for transmitter and receiver coils are alternated as shown in Figure 1. A most general design (Circular-Circular) is chosen for simulation. Here, three cases are simulated and compared the power transfer efficiency. The spacing between consecutive turns is selected as 2mm for all three models to ensure a fair comparison. The magnetic coupling as well as efficiency increase dramatically with the increase in the number of turns for both coils as presented in Table 1. It can be
concluded that designing wireless charger coils with the highest possible number of coil turns is beneficial to achieve strong coupling between the coils. However, increasing the number of turns in a receiver coil will raise the weight of EV, and the resistance also increases. The effect of change in the number of turns affects significantly on the voltage in the secondary side since the ratio of the primary to secondary turn change. This effect is much more obvious than the effects due to parasitic capacitances or changes in the values of inductance and coupling.

Figure 1. Models of circular coil design (a) 10-10 turns (b) 10-5 turns (c) 5-5 turns.

Table 1. Power transfer efficiency of three circular coil designs for a different number of turns.

| Results                        | Transmitter turns – 10 Receiver turns – 10 | Transmitter turns – 10 Receiver turns – 5 | Transmitter turns – 5 Receiver turns – 5 |
|-------------------------------|-------------------------------------------|------------------------------------------|------------------------------------------|
| Coupling coefficient $k$      | 0.0275                                    | 0.0230                                    | 0.0179                                    |
| Quality factor $Q_1$          | 147.1                                     | 146.62                                    | 128.85                                    |
| Quality factor $Q_2$          | 255.05                                    | 224.76                                    | 206.91                                    |
| Power Transfer Efficiency $\eta_{max}$ | 68.85%                                   | 62.22%                                   | 51.09%                                   |

4.2 Spacing Between Consecutive Turns
The spacing between consecutive turns in coils is also crucial in wireless charging of EV. The power transfer efficiency depends on the spacing between turns as seen in Table 2. Here also, circular-circular coil design is simulated. For the second case, the spacing between turns is alternated while the number of turns for both transmitter and receiver coils are chosen as 5 turns. The reason for choosing 5 turns for both coils is because of less computational time. It is obviously seen that the efficiency can be improved by increasing the spacing between consecutive turns while maintaining the coil size constant. That makes the inner coil radius smaller. Inner coil radius has a significant influence on the magnetic coupling of the two coils [8]. If the coil size is not kept constant, increasing the spacing between turns of the coil makes the coil bigger. The coupling coefficient, as well as the mutual inductance also rise since the coupling coefficient is directly proportional to the radii of the coil.

Table 2. Power transfer efficiency of different spacing between consecutive turns.

| Results                        | 1mm Spacing | 2mm Spacing | 3mm Spacing |
|-------------------------------|-------------|-------------|-------------|
| Coupling coefficient $k$      | 0.0183      | 0.0179      | 0.0205      |
| Quality factor $Q_1$          | 115.44      | 128.85      | 119.58      |
| Quality factor $Q_2$          | 188.12      | 206.91      | 199.87      |
| Power Transfer Efficiency $\eta_{max}$ | 48.4%       | 51.09%      | 53.74%      |
4.3 Different Coil Designs

4.3.1 Circular – Circular Coil Designs (C-C)
In the early times, circular coil design was common due to simple design. Figure 2 shows the B-field of the circular coil design. For receiver coil which is mounted on vehicles, size and weight are preferred to be decreased. In addition, circular design can reduce the quantity of ferrite and maintain a critical coupling between the primary and the secondary coils [9]. Circular coil design has low non-directional misalignment tolerance. With a lateral offset, the magnetic flux comes into the coil from either side resulting in a null in power distribution. There is also a limitation in the achievable flux height. However, circular coils still display the highest magnetic coupling when compared to other equally sized coil configurations [8]. Hence, circular coils are best suitable for stationary wireless charging system where the coil performance can maximize using multi-objective optimization methods. In a single-coil design, circular pad shows the highest magnetic coupling and highest magnetic field for any number of turns comparing with other designs.

![Figure 2. B-field of circular-circular coil design.](image)

4.3.2 Rectangular – Rectangular Coil Designs
For dynamic wireless power transfer, rectangular design as presented in Figure 3 is the most common design for high longitudinal misalignment tolerance and efficient space using on the vehicle [10]. Rectangular coils are more preferable for a cost-effective option than circular and hexagonal designs [11]. Moreover, with a provided material allowance, rectangular pads transmit maximum power over a limited region. When the distances between coils increase, the coupling coefficient does not significantly change. However, the minimum power is shown in the center of the rectangular-rectangular coil and almost half of the leakage flux was lost in the bottom of the coil.

![Figure 3. B-field of the rectangular-rectangular coil.](image)
4.3.3 Double-D – Double-D Coil Designs (DD-DD)
DD is one of the most popular advanced coil structures producing a single-sided flux. The geometry is two rectangular coils on top of core material guiding magnetic flux and re-directing it to the front [12]. Thus, the magnetic flux is not produced from the backside of the coil. DD pad has a lower magnetic leakage field than rectangular pad [13] and higher coupling coefficient. DD coil only couples the horizontal flux while circular pad couples the vertical flux component when aligned centrally. The magnetic flux density plot is as shown in Figure 4. The input current directions are same with output current directions in the following figures. The magnetic coupling is significantly higher in multi-coils pad compared with circular and rectangular. Moreover, the coil resistances also increase since more wires are used. However, the efficiency is relatively high and the DD pad is assumed as the best suitable for primary coil.

![Figure 4. B-field of DD-DD coil design.](image)

4.3.4 Double-D Quadrature – Double-D Quadrature Coil Designs (DDQ-DDQ)
DDQ is created by adding the quadrature coil to DD design as displayed in Figure 5 so not only the horizontal but also the vertical flux can be coupled [14]. DDQ pad combines two windings thus using more wires and having twice the flux height of a circular coil. DDQ has better performance than DD with different secondary topologies and is commonly used in secondary. DDQ pad has a higher tolerance to misalignment but a drawback is increased cost and space since the number of coils is increased. The coupling is highest from the simulation results and the efficiency is highest among all coil designs.

![Figure 5. B-field of DDQ-DDQ coil design.](image)

4.3.5 Bipolar – Bipolar Coil Designs (BP-BP)
Bipolar pad design has two windings like the DD design, but the coils are overlapped with each other as demonstrated in Figure 6. The two coils should be mutually decoupled as much as possible to obtain the appropriate overlapping distance. The using wire is 25% lower than DDQ pad but the power transfer
abilities are quite similar [15]. DDQ pad has also a higher tolerance to misalignment. As the different current direction, the bipolar pad can act as a circular pad, a single coil or DD pad. Hence bipolar pad design is most suitable for multi-mode secondary pad design. Since the coils are overlapped, the available coil space can be reduced more than DD pad. All multi-coil design (DD, DDQ and Bipolar) require an independent power supply and synchronized converter [16].

![Figure 6. B-field of bipolar-bipolar coil design.](image)

### Table 3. Comparison of power transfer efficiency for different coil designs.

| Results                      | C-C   | R-R   | DD-DD | DDQ-DDQ | BP-BP |
|------------------------------|-------|-------|-------|---------|-------|
| Coupling coefficient $k$     | 0.0179| 0.0135| 0.0269| 0.0345  | 0.0121|
| Quality factor $Q_1$         | 128.85| 1674.05| 2064.33| 2485.72 | 1973.45|
| Quality factor $Q_2$         | 206.91| 1882.77| 1812.01| 2073.97 | 1595.39|
| Power Transfer Efficiency $\eta_{max}$ | 51.09%| 92%   | 96.23%| 97.48%  | 91.11%|

5. Conclusion

In this study, the impact of a number of turns for transmitter and receiver coils and spacing between each turn is investigated and power transfer efficiency of different lamped coil designs are simulated and analyzed. Increasing the number of turns for both coils and spacing between turns can enhance the power transfer efficiency. The increased efficiency is only 2.6% for rising 1mm spacing between turns. DDQ coil design has the highest power transfer efficiency, but it is not suitable for use as a receiver coil because of weight on the vehicle. The circular design is most simple, but the efficiency is not so high. Rectangular can transfer maximum power but the leakage of the magnetic field can occur from the other side of the pad. The bipolar design has the highest tolerance for misalignment, so it is appropriate for dynamic charging of EV along the road.

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