Coil Design and Efficiency Analysis for Dynamic Wireless Charging System for Electric Vehicles

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Wireless charging electric vehicles (EV) is the development trend of EV. However, the battery taken by EVs has the disadvantages of big volume, long time to recharge, and limited driving distance. In this paper, an innovative dynamic wireless charging system based on magneticcoupled resonant power transmission is presented. The transmitting coil of this charging system can selectively turn ON/OFF for charging vehicles while driving. The structures of the transmitting coil and receiving coil are researched and improved. In addition, the dispersed coupling structure named grouped periodic series spiral coupler is proposed, and its characteristics are described. A simulation of coupling coefficients at different \(D\) values is carried out. A prototype is built to experiment on the dynamic wireless charging process of EV. Meanwhile, the coil coupling and variation of transmission efficiency are analyzed. The comparison of the experiment indicated that the EV can obtain a stable charging process under 25 mm transmission distance using the improved receiving coil with \(R: H: D = 4:5:13\). Moreover, the dynamic charging process is relatively stable without an obvious fluctuation while passing the interval between two transmitting coils, and the transmission efficiency is promoted by 50%.

Index Terms—Coil design, dispersed coupling, dynamic wireless charging, grouped periodic series spiral coupler (GPSSC).

I. INTRODUCTION

In recent years, the electric vehicle (EV), which is low-carbon green and energy efficient \([1], [2]\), has widely been used as mass transit. However, charging stations, the traditional charging way for EVs, are time-consuming, few and far between, and easily affected by environment, and the security is poor \([3]\). Besides, the plug must insert into the socket so the battery can be charged and one charging pile can only charge one EV simultaneously, which is neither flexible nor convenient. Wireless power transmission (WPT) technology \([4]\) avoids the risks of electric shock, short and spark, and the demands of users can be responded to promptly. With the development of WPT technology, the trend of wireless charging for EVs is irreversible \([2], [3], [5]\).

The wireless charging for EVs consists of stationary mode and dynamic mode. The stationary wireless charging needs EVs to park in a specific position. However, the battery capacity and energy density limit the development of stationary charging \([5], [6]\). By installing the cable lines under the roads, EVs with receiver coils can be charged while driving, which is called dynamic wireless charging technology. In \([7]–[9]\), the transmitting coil is designed to be two parallel straight wires. There is energy waste due to line loss when the coil is conducted for long time. Its service life will be decreased because of continuous working. Besides, the transmission efficiency will decline due to the current density standing wave. In \([10]\), the economical allocation of the power transmitters and the right battery capacity is achieved using the particle swarm optimization algorithm. However, there is some fluctuation during the dynamic charging process.

In this paper, an innovative dynamic wireless charging system is proposed. In this system, the dispersed coupling structure named grouped periodic series spiral coupler (GPSSC) is used. This paper emphatically analyzes the structures of GPSSC, in which the transmitting coils are buried under the road at certain distances and can selectively turn ON/OFF for charging vehicles, while EVs are in motion. This paper further deduces the transmission efficiency expression of GPSSC. Simulation studies and experiments on different spacings of receiving coil are carried out to achieve the best dynamic charging state. At the optimal spacing of the two row coils of the receiving coil, an experiment was established to verify the design.

II. SELECTIVE ON/OFF PRINCIPLE AND COIL STRUCTURE RESEARCH

A. Working Principle of Selective ON/OFF Transmitting Coil

The transmitting coil of the dynamic wireless charging system can selectively turn ON/OFF for charging vehicles while driving, as shown in Fig. 1.

The transmitting coils are pre-embedded under the road, which are connected by the relays to the cable. The in-vehicle communication module will connect with the interface of the road entrance communication module automatically when the EV with receiving coil drives up to the road. Then, the entrance communication will signal the operation of the sensors installed on all the transmitting coils. However, the relay connected with each of transmitting coils is open. When the EV runs to the transmitting coil \(L_1\), the sensor will signal the contact of the relay \(S_1\) to ON, and the transmitting coil \(L_1\) will be energized, resonating with the receiving coil, transmitting energy wirelessly to the EV. Meanwhile, transmitting coil \(L_2\) is standby. When the EV runs on the interval between two transmitting coils, \(L_1\) and \(L_2\) will be connected in series. This charging method can avoid the impact caused by suddenly energizing of transmitting coils on the wireless charging system. While the EV pulls away, \(S_1\) will be open and \(L_1\) will be de-energized. By analogy, the transmitting coils can stage charge the EV by selective ON/OFF process.

B. Coil Structure and Efficiency Analysis of GPSSC

To avoid the impact of current density standing wave of two parallel straight wires at high frequencies, spiral coils
are adopted in the coupled structure called GPSSC, which is characterized by dispersed coupling in this paper. As shown in Fig. 2(a) and (b), according to the ratio of the road width and the EV size in practical application, the transmitting coil is made up of eight coils connected in series, which are divided into two rows. The structure of the receiving coil is the same as the transmitting coil, except that it has only four coils. By using this structure, the ability of anti-positional offset will be improved. For example, when there is a coil diameter of offset, there is still a row of coils right above the transmitting coils, so the dramatic decline of transmission efficiency can be avoided. In order to strengthen the magnetic field density within the area of coupling structure, all the coils are featured magnetic shielding [12], [13].

The topology of GPSSC is shown in Fig. 2(c). In the process of dynamic wireless charging for EV, the coupling coefficient is constantly changing. To ensure the normalized compensation capacitance of transmitting coil is not affected by coupling coefficient, the magnetic coupler of the EV adopts the series compensation [14] method.

In Fig. 2(c), $U_S$ is the source voltage, and $I_{1i}$ ($i = 1, 2, \ldots, n$) and $I_2$ are primary current and secondary current, respectively. $M_i$, $M_{i+1}$, $M_{i+2}$, and $M_{i+3}$ ($i = 1, 2, \ldots, n$) are defined as the mutual inductance, $R_0$ is the inner resistance of source, $R_L$ is the load resistance. $R_{1i}$, $L_{1i}$, and $C_{1i}$ ($i = 1, 2, \ldots, n$) refer to the transmitting coil’s values of resistance, inductance, and compensation capacitance, respectively, while $R_2$, $L_{21}$, $L_{22}$, and $C_2$ refer to the receiving coil’s values. In addition, $S_i$, $S_{1i}$, and $S_{12}$ ($i = 1, 2, \ldots, n - 1$) denote relay contact. When the EV is passing the interval between two transmitting coils, $S_{1i}$, $S_i$, and $S_{i(i+1)}$ will be ON, and the other relays will be OFF. At this time, $I_{1i} = I_{1(i+1)} = I_1, r$, $L_{1i} = L_{1(i+1)} = L_1, C_{1i} = C_{1(i+1)} = C_1$, and $L_{21} = L_{22} = L/2$. According to the working principle of selective ON/OFF transmitting coil, the loop voltage equation in matrix form is induced, as shown in (1) at the bottom of this page.

The input power and load power are defined as $P_{in}$ and $P_L$. Then, in terms of the loaded $Q$ factor, the transmission efficiency can be derived as

$$
\eta = \frac{P_{in}}{P_L} = \frac{\text{Re}\{I_2^*R\}}{\text{Re}\{U_I^*\}} = \frac{(k_i + k_{i+1} + k_{i+2} + k_{i+3})^2 Q_1 Q_2/2}{1 + \left(\frac{R_0 + R_1}{R_L}\right)^2 + (k_i + k_{i+1} + k_{i+2} + k_{i+3})^2 Q_1 Q_2/2},
$$

(2)

Here, the coupling factors $k_{i-1}$ and $k_i$, the transmitting coil’s loaded $Q_1$, and the receiving coil’s loaded $Q_2$ are defined as

$$
k_i = \frac{M_i}{\sqrt{L_1 L_2/2}}, \quad k_{i+1} = \frac{M_{i+1}}{\sqrt{L_1 L_2/2}}, \quad k_{i+2} = \frac{M_{i+2}}{\sqrt{L_1 L_2/2}}, \quad k_{i+3} = \frac{M_{i+3}}{\sqrt{L_1 L_2/2}}.
$$

(3)

When the EV is in motion, as shown in Fig. 3, according to the Neumann formula, the mutual inductance $M_1$, $M_{i+1}$, $M_{i+2}$, and $M_{i+3}$ can be calculated using

$$
M = \frac{\mu_0 N_1 N_2}{4\pi} \int_0^{2\pi} \int_0^{2\pi} \frac{r^2 \cos(\theta - \phi) d\theta d\phi}{\rho},
$$

$$
\rho = \sqrt{(r \cos \theta - r \cos \phi)^2 + (r \sin \theta + y_1 - r \sin \phi)^2 + z_1^2}.
$$

(4)

When $S_1$ and $S_i$ are OFF and $S_{i(i+1)}$ is ON, the EV runs on a group of transmitting coils, (2) can be written as

$$
\eta = \frac{(k_i + k_{i+3})^2 Q_1 Q_2/2}{1 + (k_i + k_{i+3})^2 Q_1 Q_2/2} \cdot \frac{R_L}{R_2 + R_L}, \quad (i = 1, 2, \ldots, n).
$$

(5)

During dynamic wireless charging, the coupling coefficient $k$ will vary with the movement of the receiving
Fig. 4. Curves of coupling coefficient and transmission efficiency varying with the movement distance of receiving coil.

Fig. 5. Structural comparison of different receiving coils. (a) Front view. (b) Top view of improved receiving coil.

Fig. 6. Simulation of coupling coefficient at different $D$ values.

Fig. 7. Experimental device of dynamic wireless charging.

Fig. 8. Comparison of system performance at different $D$ values of improvement receiving coil. (a) Received current. (b) Received voltage. (c) Transmission efficiency.

C. Coupling Coefficient Calculation and Efficiency Analysis

In [15], the wireless charging frequency can range from 81.38 to 90.00 kHz by international standards. In this paper, the system working efficiency is set to 87 kHz. Both the transmitting coil and the receiving coil use the method of series capacitor compensation.

By (2) and (4), the transmission efficiency of dynamic wireless charging can be obtained. The waveforms of coupling coefficient and transmission efficiency varying with the
movement of receiving coil in one cycle period are shown in Fig. 4. The results indicate that the transmission efficiency expression is correct. The coupling coefficient \( k \) and transmission efficiency \( \eta \) increase as the receiving coil moves into transmitting coil. When the receiving coil is completely moved into, \( k \) remains stable, and \( \eta \) can be stabilized at about 71%. However, \( k \) will decline markedly and \( \eta \) will reduce from 71% to 5% so there will be drastic fluctuations when the receiving coil moves on the transmitting coils.

III. IMPROVEMENT OF RECEIVING COIL

Aiming to solve the fluctuations of dynamic wireless charging, the structure of the receiving coil is improved, as shown in Fig. 5.

To solve the decline of the coupling coefficient while the EV is passing the interval of transmitting coils improves the transmission stability and reduces the fluctuations, the two rows of coils of the receiving coil are separated, and the spacing is defined as \( D \). Setting the ratio of \( R \) and \( H \) at 4:5, the value of \( D \) is researched by simulation.

The coupling coefficient \( k \) varying with the movement distance of receiving coil at different \( D \) values is shown in Fig. 6. When the value of \( D \) is equal to 65 mm, the change of \( k \) is relatively stable. Therefore, the EV will have a steady dynamic charging progress.

IV. EXPERIMENT AND DISCUSSION

A dynamic wireless charging system is fabricated, and an experiment is operated to test the performance of the system with an improved receiving coil. The experimental device of dynamic wireless charging for EV is shown in Fig. 7.

In Fig. 7, a bulb is used as the system load. The current, voltage, and transmission efficiency are recorded by precision power scope. The power of the frequency tracing power supply is constant in 20 W.

The waveforms are recorded from the precision power scope when each movement distance of receiving coil is 2.5 cm. The resonance frequency of the system reasonably maintains at 87.7 kHz, which meets the wireless charging criteria.

The received current, voltage, and transmission efficiency of dynamic wireless charging are shown in Fig. 8. The comparison of system performance at different \( D \) values indicates that there is an optimal value of \( D \) for the stable charging process. When \( D = 65 \) mm, the system has a stable charging current. The charging voltage is relatively stable, and the transmission efficiency is 52% when the receiving coil passing the interval between the two transmitting coils. The experimental results demonstrate a reasonably good agreement between the simulation and the experiment.

V. CONCLUSION

The presented selective breaking structure of transmitting coils can reduce the circuit loss caused by excessive lines. It makes the dynamic wireless charging more energy efficient. The structure of GPSSC has an advantage of greater offset, and it avoids the problem of current density standing wave. It is good for EV charging.

In this paper, by modeling and analyzing, the nonlinear relationship between transmission efficiency and coupling coefficient of GPSSC is deduced. The transmission efficiency can be raised by increasing the coupling coefficient. Moreover, using the optimization design of a receiving coil with \( R:H:D = 4:5:13 \), which is a dispersed coupling structure, there is a stable charging current, voltage, and power. In addition, the transmission efficiency can be raised by 50% at maximum while passing the interval between the two transmitting coils. Furthermore, the dynamic charging process is relatively stable.

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