A Coil Design Method for EV’s Wireless Power Transfer from the Perspective of Engineering Purpose and Application Environment

Ruying Zhong1, a, Linlin Tan1, 2, *, Zongyao Tang1, b, Xueliang Huang1, 2, c, Tao Meng1, d
1School of Electrical Engineering, Southeast University, Nanjing, 210096 China
2Key Laboratory of smart grid technology and equipment in Jiangsu province, Zhenjiang, 212000 China

*Corresponding author e-mail: tanlinlin@seu.edu.cn, amirandazry@163.com, btzy19950717@163.com, cxlhuang@seu.edu.cn, dlmtmttt@163.com

Abstract. When electric vehicles are loaded with wireless charging coils, engineering targets such as efficiency and power have always been the most significant targets for designers. In the previous research work, researchers designed and optimized the above relevant targets from the aspects of coil structure and magnetic core. However, the majority of these design and optimization schemes adopt a single-size coil to verification work, and the size often don’t take the actual application environment into consideration, so it don’t have engineering guidance significance and practical application value. In order to solve the gap and cooperate better with the application in engineering, this paper carries out a complete coil design method from the perspective of engineering design purposes and application environment. Firstly, the coil design conditions are constrained from the aspects of electric vehicle loading environment and design purpose, then the circuit and coil structure are analysed and selected, all the losses that may exist in reality are calculated, and the calculation method of the maximum winding length and minimum mutual inductance requirement of the coil is introduced. Finally, the maximum winding length index of the coil winding corresponding to the design purpose and application environment is formed, and the minimum mutual inductance design requirement is formed too. The design method of this paper is complete, and it can form different design schemes for different engineering design purposes (such as different power and efficiency). It has strong guidance to practical engineering and has high practical application value.

1. Introduction

In recent years, energy shortage has become a major issue in the history of human development. The development of a low-carbon economy has become an indispensable trend [1]. As a significant part of the low-carbon economy, electric vehicles (EV) have gradually developed towards industrialization and specialization. The wireless power transfer technology (WPT) can realize the transmission distance of several centimeters to several meters, and the transmission power is several watts to several tens of kilowatts, relying on the technology of induction and magnetic coupling resonance [2-
It can fully satisfy the demand of charging and discharging for electric vehicles. All major automobile manufacturers in the world have proposed to launch various series of models with wireless charging function into the market in recent years. However, due to the constraints of technology and related standards, it is difficult to promote their product series quickly and extensively. As the crucial component of energy transmission in WPT system, the transmission capability of the coil has always been a concern of researchers. The design and optimization of coils have been ongoing for years, including optimizing coil structure, optimizing coil layout, and optimizing design algorithms [5-7].

In the formulation work of related standard in WPT field, the feasible high power and high efficiency coil design is required as the reference. In the current design of wireless charging coils at home and abroad, most researches focus on improving the efficiency by changing the circuit topology and coil type. Literature [6] analyzed and compared the advantages and disadvantages of the DDQ coil rectangular circular coil in the electric vehicle road power supply system. The verification experiment unifies the dimensions of different coils, but its size does not consider the actual car loading environment, and design details can only provide theoretical rather than practical guidance. Literature [7] proposed a circular coupler applied to the dynamic charging system of electric vehicles, but its experimental transmission distance and size do not correspond to the actual application environment, so there is no practical significance. Therefore, in order to support the development of related standards for EV in WPT system, accelerate standardization work, and accelerate the industrialization of wireless charging electric vehicles, this paper proposes a complete method of coil design for electric vehicles from the perspective of engineering purpose and application environment, including engineering purpose analysis, vehicle environment analysis, coil topology and coil winding method selection, loss analysis, etc., and finally formed a design scheme including wire selection, mutual inductance requirements and maximum winding length requirements. The method proposed in this paper can be closer to the actual application environment, has good engineering value, and can guide the formulation of standards practically.

2. Design methodology and process

The overall scheme design flow diagram is shown in Fig. 1, which is mainly divided into four steps. This section mainly describes the detailed design process and the formula used.

2.1. Step1: Application environment and purpose parameter analysis

Before designing the coil, we always need to know where the coil application (loading) is, which means that the coil is loading on a small or medium-sized private car/medium commercial vehicle/large commercial vehicle. Then the target parameters including classic size limit $V$, transmission distance $Z$, target power $P_{out}$, size ratio $k$ and output (battery) voltage $U_1$ are determined by Table 1. In addition, we need to know the charging efficiency $\eta_0$ of the engineering requirements, the maximum input voltage $U_2$ that the power supply can provide, the possible offset $\Delta XY$ and Coil resonance frequency $f_0$. 
Table 1. Application environment and purpose parameter analysis.

| Purpose parameter                      | Application environment                     | Value                                      |
|----------------------------------------|---------------------------------------------|--------------------------------------------|
| Chassis size limit (typical value)     | small or medium-sized private car           | \(a_1 \times b_1 \times c_1\) (length × width × height) |
|                                        | medium commercial vehicle                   | \(a_2 \times b_2 \times c_2\)              |
|                                        | large commercial vehicle                    | \(a_3 \times b_3 \times c_3\)              |
| Chassis height (typical value)         | small or medium-sized private car           | \(Z_1\) (mm)                               |
|                                        | medium commercial vehicle                   | \(Z_2\) (mm)                               |
|                                        | large commercial vehicle                    | \(Z_3\) (mm)                               |
| Target power                           | small or medium-sized private car           | WPT1 (3.3kW)                               |
|                                        | medium commercial vehicle                   | WPT2 (7.7kW)                               |
|                                        | large commercial vehicle                    | WPT3 (11kW) or higher                      |
| Size ratio of primary and secondary    | WPT1                                        | \(k_1\)                                    |
| coil                                   | WPT2                                        | \(k_2\)                                    |
|                                        | WPT3                                        | \(k_3\)                                    |
| battery voltage                        | small or medium-sized private car           | \(U_a\)                                    |
|                                        | medium commercial vehicle                   | \(U_b\)                                    |
|                                        | large commercial vehicle                    | \(U_c\)                                    |

The size ratio is obtained by reference to the coil size of the corresponding power level in the standard SAE J2954 [8].

Figure 1. Flow chart of design methodology.
S denotes series and P denotes parallel. The primary compensation capacitor depends on the mutual inductance \( M \) in SP, PP, and PS compensations. To charge the vehicles, the system must be tolerant of unavoidable offset, so SS compensation is selected. In the SS topology, the current \( I_1 \) and \( I_2 \) of the primary and secondary coils can be calculated by input and output power and voltages as equation (1) and (2). The primary and secondary resonant coil losses are replaced by equivalent resistors \( R_1 \) and \( R_2 \), and \( R_L \) is the equivalent load resistance. \( \omega \) is the angular frequency at the resonant frequency and the mutual inductance is represented by \( M \).

\[
I_1 = \frac{U_1}{Z_{11} + \left(\frac{\omega M}{Z_{22}}\right)^2}
\]

\[
I_2 = \frac{j\omega M U_1}{Z_{11}Z_{22} + (\omega M)^2}
\]

The efficiency formula under the SS topology is

\[
\eta = \frac{(\omega M)^2 R_2}{\left[R_1(R_1 + R_2) + (\omega M)^2\right](R_2 + R_L)}
\]

2.2. Step2: Calculate the coil equivalent resistance

Calculate the maximum total loss value \( W \) under the efficiency condition. Then calculate the other loss \( W_2 \) except the coil resistance loss, including the capacitance loss \( W_c \) and the magnetic loss \( W_e \), and the coil resistance loss \( W_R \) can be calculated. So the theoretical value of equivalent resistance \( R_1, R_2 \) can be calculated. The ratio \( k \).

Use \( W = (P_{out}/\eta_0) - P_{out} \) to calculate the maximum total loss \( W \). Calculate the capacitance loss \( W_c \) using (4), where \( \tan \sigma \) is the capacitance loss angle and can be selected by frequency, and use the resonance relationship \( \omega^2 LC = 1 \) and \( U_C = 1/\omega C \) to obtain the capacitor loss optimization formula (5), \( L \) refers to the maximum inductance value in the corresponding power level SAE standard.

\[
W_c = 2\pi f\times \frac{1}{\omega^2 C}\times \tan \sigma
\]

\[
W_c = 2\pi f\times I^2 \times L\times \tan \sigma
\]

Through the core selection, the unit volume power loss value \( P_{cv} \) of the magnetic core at a certain frequency \( f_1 \) can be known, and the calculation formula is (6). \( Z \) and \( m \) are constants, and \( B_{max} \) represents the maximum value in the hysteresis loop. Convert \( P_{cv} \) to the resonant frequency \( f_0 \) as (7). Calculate the magnetic loss \( W_e \) by the equation (8), and the \( V_e \) represents the volume of the core.

\[
P_{cv} = Z f_1^2 B_{max}^m
\]

\[
P_{cv(f_0)} = P_{cv(f_1)} \times \frac{f_1^{1.2}}{f_0^{1.2}}
\]

\[
W_e = P_{cv(f_0)} \times V_e
\]
2.3. Step3: Determine the resonant coil design indexes
We can determine maximum size constraint $V$ (including length, width, height) based on coil type and chassis limit, at the same time, one of the maximum winding length $L_2$ can be obtained. The calculation method is introduced as follows: Firstly, it is necessary to determine the parameters of the litz wire used for winding the coil. According to the resonant frequency $f_0$ in step 1, we could select the single line diameter $d$ of the multi-strand litz wire and obtain the DC resistivity $\rho_{dl}$ and sectional area $S_d$ of the corresponding single line. According to the current $I_1$ and $I_2$, the limiting current of the litz wire is determined. The sectional area $S$ of the required litz wire is calculated according to the limiting current of per square millimeter of copper’s sectional area. At last, the number $n$ of litz wire is calculated by equation (9), and then through the formula (10) - (12), overall DC resistivity $\rho_d$ and AC resistivity $\rho_{ac}$ of the multi-strand litz wire are calculated.

$$n = \frac{S}{S_d}$$  \hspace{1cm} (9) \\
$$\rho_d = \frac{\rho_{dl}}{n}$$  \hspace{1cm} (10) \\
$$\rho_{ac} = \rho_d (1 + y_s)$$  \hspace{1cm} (11) \\
$$y_s = \frac{x^4}{192 + 0.8x^4}$$  \hspace{1cm} (12)

The equivalent AC resistances $R_1$ and $R_2$ has been calculated by step 2, and the total is set as $R_t$. The other one maximum winding length $L_1$ of the primary and secondary coil wire is:

$$L_1 = \frac{R_t}{\rho_{ac}}$$  \hspace{1cm} (13)

Compare $L_1$ and $L_2$ and acquire the small value which will become the maximum winding length $L$ design index of the coil. According to the maximum winding length and resistivity, the actual equivalent loss resistance $R_{11}, R_{22}$ can be obtained. Finally combined with (3) and $R_{11}, R_{22}$, we can obtain the minimum mutual inductance $M$ index.

2.4. Step4: Coil scheme design
Since the maximum size and the wire type have been set, the winding turn’s number, winding layers number and the winding pitch can be set autonomously within the size. If the designed scheme does not satisfy any one design indexes, repeat step d.

3. Design example and experimental verification
This part mainly introduces actual design parameters, results and simulation verification.
Table 2. Design example specification.

| Process | Design parameter | Value |
|---------|------------------|-------|
| Step 1: Application environment and purpose parameter analysis | transmission power $P_{out}$ | 30kW |
| | coil spacing $Z$ | 190mm |
| | deviation condition | $\pm 150$mm of XY axis |
| | transmission efficiency under the condition un-migrated | 95% |
| | transmission efficiency under condition of maximum XY axis deviation | 85% |
| | system resonance frequency $f$ | 85kHz |
| | coil size $V$ | 800mm×800mm×20mm(transmitting coil) 400mm×400mm×20mm (receiving coil) |
| | coil topology | series-series(SS) |
| | input voltage $U_1$ | 653V |
| | input current of the system $I_1$ | 48.36A |
| | output voltage $U_2$ (battery voltage) | 600V |
| | output current $I_2$ | 50A |
| | equivalent output impedance $R_L$ | 12 |
| | input power $P_{in}$ | 31.58kW |
| | system maximum allowable total loss $W_0$ | 1.58kW |
| | maximum reference value (primary side inductance) $L_1$ | 300μH |
| | secondary side inductance value $L_2$ | 150μH |
| | primary side capacitance loss $W_{C_1}$ | 200.276W |
| | secondary side capacitance loss $W_{C_2}$ | 400.553W |
| | power loss value per unit volume $P_{cv}$ (PC95 magnetic performance) | 350kW/m³ |
| | $P_{cv(85k)}$ calculated by equation (6)-(7) | 287.9kW/m³ |
| | total volume of the original secondary ferrite $V_e$ | $10^3$m³ |
| | total magnetic loss $W_e$ calculated by the equation (8) | 287.9W |
| | the maximum value of the coil resistance loss $W_R$ | 692.1W |
| | Theoretical total coil’s equivalent AC loss resistance maximum $R_t$ | 0.277Ω |
| Step 2: Calculate the coil equivalent resistance | sectional area $S_d$ of corresponding single line | 0.00785mm² |
| | sectional area $S$ of the required litz wire | 50mm² |
| | number $n$ of litz wire is calculated by equation (9) | 6400 |
DC resistivity $\rho_{dl}$ of corresponding single line 2.176Ω/m
DC resistivity $\rho_{d}$ of the multi-strand litz wire 0.34mΩ/m
AC resistivity $\rho_{ac}$ of the multi-strand litz wire 0.76mΩ/m
maximum winding length $L_1$ 364.47m
maximum winding length $L_2$ 151.488m
coil design indexes ① maximum winding length $L$ 151.488m
actual primary coil resistance 0.077Ω
actual secondary coil resistance 0.038Ω
coil design indexes ② minimum mutual inductance $M$ 8.33μH

Step 4: Coil scheme design
The coil design scheme is formed in Fig. 2

| Deviation | Coil space | $L_1$(μH) | $L_2$(μH) | $M$(μH) |
|-----------|------------|-----------|-----------|----------|
| 0mm       | 190mm      | 452.95    | 113.01    | 25.39    |
| X axis 150mm | 190mm | 455.80    | 113.92    | 23.95    |
| Y axis 150mm | 190mm | 444.47    | 112.72    | 17.05    |
| XY axis 150mm | 190mm | 449.19    | 113.91    | 16.07    |

According to the constraints: 1. Size constraint $V$. 2. Maximum winding length $L$. 3. Mutual inductance $M$ requirements, as well as the specified coil type and distribution mode, the coil design scheme is established as shown in Fig. 2 to verify the correctness of the design method.

![Coil design scheme structure chart](image)

**Figure 2.** Coil design scheme structure chart.

The simulation results are shown in Table 3 below. As can be seen from the table, from 0mm deviation to the maximum 150mm deviation, the overall mutual inductance is greater than the corresponding minimum mutual inductance requirement of 8.33μH, and the efficiency meets the requirement at this time.

| Deviation | Coil space | $L_1$(μH) | $L_2$(μH) | $M$(μH) |
|-----------|------------|-----------|-----------|----------|
| 0mm       | 190mm      | 452.95    | 113.01    | 25.39    |
| X axis 150mm | 190mm | 455.80    | 113.92    | 23.95    |
| Y axis 150mm | 190mm | 444.47    | 112.72    | 17.05    |
| XY axis 150mm | 190mm | 449.19    | 113.91    | 16.07    |

Power validation and efficiency optimization work are carried out with circuit simulation in the Simulink. The circuit parameters adopt the parameters in Table 2, and the simulation results of system efficiency and power are shown in Table 4.
Table 4. Simulation verification of the system performance.

| Name               | Value      | Name            | Value  |
|--------------------|------------|-----------------|--------|
| primary coil resistance | 0.077Ω     | input voltage   | 653V   |
| secondary coil resistance | 0.038Ω    | output resistance | 12Ω    |
| transmission power  | 27.145kW   | transmission efficiency | 97.99% |

The chart shows that when the load is 12Ω and the input voltage is 653V, the efficiency has reached 97.99% and meet 95% efficiency index, but the transmission power didn't reach 30 kW power. The scheme needs to be optimized. The transmission power could be increased by increasing the input voltage. We make a curve of the output power changing with the input voltage as Fig.3. According to the curve, when the input voltage reaches 687V, the output power reaches 30kW, and the efficiency remains unchanged. Finally, the coil that meets the requirements in step 1 is designed.

4. Conclusion

In this paper, based on the actual charging environment of electric vehicle, the proposed power level and efficiency index, as well as the deviation and distance requirements, we propose a coil design method. In this paper, the loss constrained condition is first calculated according to the limit index. Then, all possible losses of the coil except the coil internal resistance loss in the series string topology are analyzed and calculated, and the maximum internal resistance of the coil is obtained. The internal resistance of the primary and secondary coils are calculated by comparing the maximum length of the coil L1 under the limit size and the maximum length of the coil L1 corresponding to the internal resistance. Finally, the mutual inductance design requirement is obtained.

According to the mutual inductance design requirements, combined with the limited coil size and coil type, the coil scheme is designed. Through the voltage adjustment method, the power, efficiency and deviations are satisfied, and the feasibility of the proposed method is verified.

With the help of the method of this paper, the coil design of the electric vehicle wireless charging system can be better designed with the actual environment. Therefore, the proposed method can facilitate the design of complex WPT systems and lay the foundation for its wider application.

![Figure 3](image-url) The curve of the output power changing with the input voltage.

Acknowledgments

This work was supported by National key R&D project (NO.2018YFB0106300).
References

[1] P. Andea, D. Mnerie, D. Cristian, and O. Pop, “Conventional vs. alternative energy sources overview. Part I. Energy and environment.” *International Joint Conference on Computational Cybernetics and Technical Informatics*, 2010, pp.595-600.

[2] Z. Zhang, H. Pang, A. Georgiadis and C. Cecati, “Wireless power transfer - an overview.” *IEEE Transactions on Industrial Electronics*, pp.99.

[3] Lee Seung Beop, Lee Changwoo and Jang In Gwun. “Precise determination of the optimal coil for wireless power transfer systems through post processing in the smooth boundary representation.” *IEEE Transactions on Magnetics*, 1-1, 2016, pp. 99.

[4] H. Moon, S. Kim, H. H. Park and S. Ahn, “Design of a resonant reactive shield with double coils and a phase shifter for wireless charging of electric vehicles.” *IEEE Transactions on Magnetics*, 2015, pp. 51(3): 1-4.

[5] T. Yilmaz, N. Hasan, R. Zane and Z. Pantic, “Multi-objective optimization of circular magnetic couplers for wireless power transfer applications.” *IEEE Transactions on Magnetics*, 2017, pp. 53(8): 1-12.

[6] Z. Zhang, B. Jia, H. Pang and C. Liu, “Comparative analysis and optimization of dynamic charging coils for roadway-powered electric vehicles.” *IEEE Magnetics Conference*, 2017.

[7] X. Zhang, Z. Yuan, Q. Yang, Y. Li, J. Zhu and Y. Li, “Coil design and efficiency analysis for dynamic wireless charging system for electric vehicles.” *IEEE Transactions on Magnetics*, 2016, pp. 52(7): 1-4.

[8] SAE J2954. Wireless Power Transfer for Light-Duty Plug-In/Electric Vehicles and Alignment Methodology SAE international [S]. Revised: July, 2017.