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Design and Optimization of Ground-Side Power Transmitting Coil Parameters for EV Dynamic Wireless Charging System

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ABSTRACT This paper proposes a ground-side power transmitting coil parameter design method that takes the length of the transmitting coil as an optimization target, which takes into account the driving speed of EV (Electrical Vehicle), the EV's power consumption per kilometer, the coil energy loss and the system charging efficiency. The system uses a long-track transmitting coil, rectangular receiving coil, and LCC-S resonance compensation topology. First, the charging power and energy transmission efficiency are calculated. Based on the condition that the dynamic wireless charging power within 1km is not less than the EV's power consumption per kilometer, the lower limit of the charging power is determined. Secondly, the minimum value of transmitting coil current is inferred from the peak value of the charging power, the corresponding compensation inductance and transmitting coil wire diameter are further obtained, then the relationship between the system efficiency, the load resistance and the transmitting coil length is calculated. Under the condition that the charging efficiency is not less than 80%, the selection range of the transmitting coil's length and the load resistance value is initially determined, which further refined by combining the curve of the charging power with the load resistance value and ''2 second principle''. Finally, aiming at segmenting a road section of 1 km in integers with the least number of transmitting coil segments, the number of transmitting coil segments and coil length that simultaneously meet the economic requirements for coil laying and system efficiency are determined. Finally, the feasibility of the above transmitting coil parameter design method is verified through experiment. The parameter design and optimization method of ground-side power transmitting coil of EV DWPT charging system proposed in this paper provides a reference for the design of the power transmitting coil length of EV DWPT charging system in the high-speed driving scene.

INDEX TERMS Dynamic wireless power transmission (DWPT), on-road charging, speed variation, coil parameters optimization.

I. INTRODUCTION

Compared with traditional fuel vehicles, electric vehicles are becoming an important choice for solving today's energy and environmental problems. At the same time, compared with the traditional wired charging method of electric vehicles, WPT (Wireless Power Transmission) technology has significant advantages such as its flexibility and simple operation. Therefore, the WPT technology of EVs has attracted the attention of automobile industries around the world. WPT technology for EV is divided into static wireless power transmission (SWPT) and dynamic wireless power transmission (DWPT). Developed from SWPT, DWPT can effectively reduce the volume of on-board battery packs, increase cruising range, reduce mileage anxiety, improve the flexibility of the charging process, and realize ''charging while driving'' [1]–[9].

At present, the optimization of DWPT system is mainly focused on the optimization of charging power and coil distribution. The author of [10] proposed an optimal power

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allocation scheme for a multi-target WPT system without a communication network. Reference [11] proposed a charging area determination method for a dual-excitation unit DEU-WPT system for EV dynamic charging, and based on this, a switching control method for switching the working mode of the system is proposed when an electric vehicle enters the charging area, which is beneficial to increase the power capacity of the system without increasing the voltage and current stress. Reference [12] proposed a method based on mathematical optimization for simultaneously designing EV speed curves and allocating WPT systems in lane sections. Reference [13] analyzed DWPT system with S-S resonance compensation topology, the vehicle-side charging power is optimized by employing impedance matching network according to the urgency of the charging demand. However, in the process of modeling the transmitting side of DWPT system, only the safe braking distance between vehicles is considered, the laying cost and energy loss of transmitting coil are not taken into consideration. Reference [14] mainly focused on the driving characteristics of EVs and supercapacitors, and aimed to optimize the layout of energy storage equipment and discontinuously laid short power transmitting track layout costs by particle swarm genetic algorithm to limit the investment cost of EV DWPT system. However, on the one hand, the charging efficiency of the system and energy loss of transmitting coil are not taken into consideration. On the other hand, discrete and different specifications of the coils are not conducive to the unified maintenance and management of the system. In many researches, the modeling of DWPT systems mostly use short coil array structure at the transmitting side, and use S-S topology for resonance compensation [15]–[17]. Although this compensation topology has the advantage that the value of primary capacitance does not depend on the variation of coupling coefficient, but the transmitting-side current varies with the fluctuation of the charging state, the loss at transmitting side is uncontrollable when applied to DWPT system [3]. In the case of EVs driving at high speed in the charging area for dynamic wireless charging, there is a problem that the response speed of the ground-side short-segmented energy transmitting coils is not fast enough which will further cause the problem of receiving power fluctuations. Therefore, the transmission coil structure of the long-track DWPT system is more suitable for EVs to perform dynamic wireless charging at high driving speed, a more suitable resonance compensation network for DWPT system needs to be further studied.

Although the long-track EV-DWPT system has the advantages of simple control and stable charging power, the energy loss caused by the continuous conduction of the transmitting coil during charging cannot be ignored, excessive coil length will also lead to low charging efficiency. Since standardisation is necessary in all areas concerning WPT systems, most important is the need to standardise the road-based transmitter design [18]. At present, there is no clear method and standard for how to determine the length of the long-track power transmitting coil. Therefore, it is necessary to study a reasonable length design method of power transmitting coil in EV-DWPT system adapted to the high-speed driving situation.

In order to optimize the ground-side transmitting coil parameters of EV DWPT charging system, the following work is carried out in this paper: 1. Based on the EV driving speed, transmitting coil energy loss, and system charging efficiency, a method for selecting the transmitting coil length and resonance compensation network parameters of a long-track EV DWPT charging system is proposed. 2. Based on the vehicle's power consumption per kilometer and the system's charging efficiency, the selecting range of the vehicle-side equivalent load resistance is proposed. 3. Combined with the laying cost of transmitting coil in the charging area, the selecting criteria of the transmitting coil length in the actual engineering construction scenario is discussed. In section II of this paper, a model of long-track EV-DWPT system is established, and the expressions of the transmitting coil current, the receiving power, and the transmitting efficiency of the system are derived. In section III, combined with the driving speed, the lower limit of the EV charging power is determined on the condition that the DWPT charging power within one kilometer is not less than the EV's power consumption per unit kilometer; Secondly, based on the peak value of the charging power, the minimum value of the transmitting coil current is inferred, and the corresponding compensation inductance and the wire diameter of the transmitting coil are further obtained. The relationship between the charging efficiency, the load resistance and the length of the transmitting coil is calculated. Under the condition that the charging efficiency is not less than 80%, the selection range of the transmitting coil's length and the load resistance is initially determined, then further refined by combining the changing curve of the charging power with the load resistance value and the "two-second principle"; Finally, aiming at segmenting a road section of 1 km in integers with the least number of transmitting coil segments and the shortest winding length, that is, the lowest coil laying cost, the number of transmitting coil segments and coil length that simultaneously meet the economic requirements for coil laying and system efficiency are determined. In section IV, an experimental model using the above-mentioned design method of transmitting coil parameters is established, and the theoretical analysis is verified.

II. SYSTEM DESCRIPTION

A. SYSTEM MODELING

The long-track EV-DWPT system is composed of a ground-side terminal and a vehicle-side terminal. The ground-side terminal is composed of a rectifier inverter device, resonance compensation inductor, resonance compensation capacitor, and a long power transmitting coil. The vehicle-side terminal includes a rectangular power receiving coil, resonance compensation capacitor, rectifier, impedance matching network (IMN) and EV battery. Many studies have

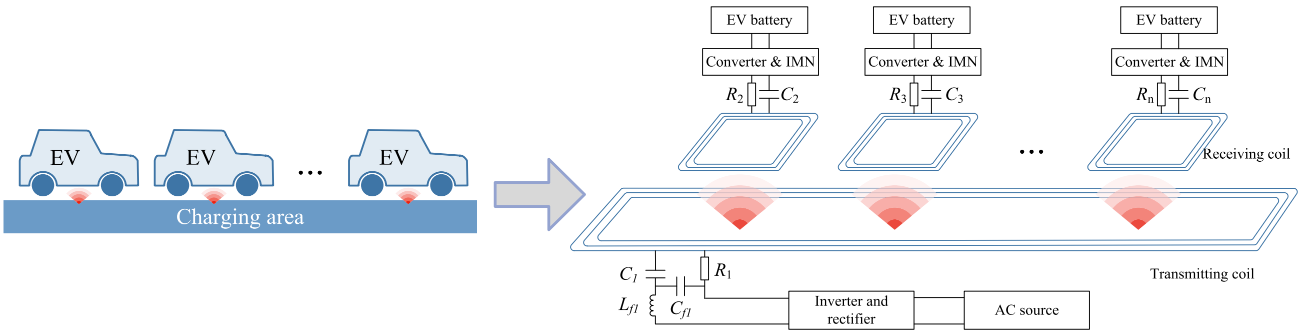

FIGURE 1. Schematic of long-track EV-DWPT system.

shown that load resistance significantly affect the charging performance of WPT systems. [19]–[21] Therefore, IMN is used to obtain a constant reflected load resistance to achieve timely and accurate control of the received power of each EV, and this resistance can be set to a standard value. Specifically, IMN can be implemented with different topologies such as DC/DC converters [22], [23] or variable inductors and capacitors [24], [25]. The power frequency AC power is converted into high frequency AC power by the ground-side rectifier and inverter device, and is transmitted by the long-track power transmitting coil to the vehicle-side power receiving coil through magnetic coupling resonance. The high-frequency AC power received by the receiving coil is converted by the rectifying device into DC power for EV battery. The structure and working principle of the system are shown in Fig.1.

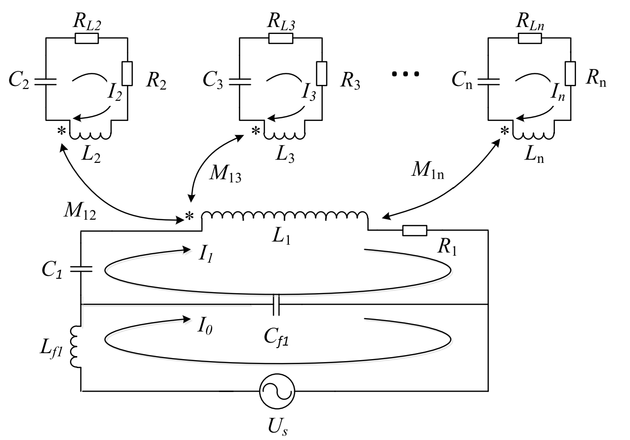

FIGURE 2. Equivalent circuit diagram of long-track EV-DWPT system using LCC-S resonance compensation topology.

Based on the principle shown in Fig.1, the system circuit model shown in Fig.2 can be established. In Fig.2, U_S represents the output voltage after rectification and inversion, L_{f1}, C_{f1} and C_1 are the resonance compensation inductor and capacitors at the transmitting-side; L_1 and R_1 are the self-inductance and internal resistance of power transmitting coil. Let the number of EVs in the charging area be n-1, L_2-L_n and R_2-R_n represent the self-inductance and internal resistance of the vehicle-side power receiving coil respectively, C_2-C_n are the resonance compensation capacitors at the receiving-side, and R_{L2}-R_{Ln} are the equivalent load impedance of the receiving side of EVs, which can be adjusted through an impedance matching network (IMN).

From the model shown in Fig.2, the vehicle-side loop equivalent impedance can be expressed as

$$Z_{si} = j\omega L_{f1} + \frac{1}{j\omega C_{f1}} + R_i + R_{Li} \quad (i = 2, \ldots, n). \tag{1}$$

Let M_{12}-M_{1n} be the mutual inductance between the receiving coil and the transmitting coil, I_0 be the output current after inversion at the transmitting-side, I_1 be the current through the transmitting coil, I_i be the load current, and the system resonant frequency is f. Z_{p0} is the equivalent impedance of the loop which I_0 flowing throw, Z_{p1} is the equivalent impedance of the loop which I_1 flowing throw. Ignoring the internal resistance of U_S, then

$$Z_{p0} = j\omega L_{f1} + \frac{1}{j\omega C_{f1}}, \quad Z_{p1} = j\omega L_1 + \frac{1}{j\omega C_1} + \frac{1}{j\omega C_{f1}} + R_1.$$

According to the circuit theorem, the system equivalent circuit equation can be obtained as:

$$\begin{bmatrix} Z_{p0} & -\frac{1}{j\omega C_{f1}} & 0 & 0 & \cdots & 0 \\ -\frac{1}{j\omega C_{f1}} & Z_{p1} & -j\omega M_2 & -j\omega M_3 & \cdots & -j\omega M_n \\ 0 & -j\omega M_2 & Z_{s2} & -j\omega M_{23} & \cdots & -j\omega M_{2n} \\ 0 & -j\omega M_3 & -j\omega M_{32} & Z_{s3} & \cdots & -j\omega M_{3n} \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & -j\omega M_n & -j\omega M_{2n} & -j\omega M_{3n} & \cdots & Z_{sn} \end{bmatrix} \times \begin{bmatrix} I_0 \\ I_1 \\ I_2 \\ I_3 \\ \vdots \\ I_n \end{bmatrix} = \begin{bmatrix} U_s \\ 0 \\ 0 \\ 0 \\ \vdots \\ 0 \end{bmatrix} \tag{2}$$

According to the resonance condition of the LCC-S topology: $j\omega L_{f1} + \frac{1}{j\omega C_{f1}} = 0$, $j\omega(L_1 - L_{f1}) + \frac{1}{j\omega C_1} = 0$, the following equation can be further obtained.

$$\begin{bmatrix} 0 & j\omega L_{f1} & 0 & 0 & \cdots & 0 \\ j\omega L_{f1} & R_1 & -j\omega M_2 & -j\omega M_3 & \cdots & -j\omega M_n \\ 0 & -j\omega M_2 & R_2 & 0 & \cdots & 0 \\ 0 & -j\omega M_3 & 0 & R_3 & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & -j\omega M_n & 0 & 0 & \cdots & R_n \end{bmatrix} \times \begin{bmatrix} I_0 \\ I_1 \\ I_2 \\ I_3 \\ \vdots \\ I_n \end{bmatrix} = \begin{bmatrix} U_s \\ 0 \\ 0 \\ 0 \\ \vdots \\ 0 \end{bmatrix} \tag{3}$$

The current through the transmitting coil is

$$I_1 = \frac{Us}{\omega L_{f1}}. \tag{4}$$

Obtained from $R_i I_i = j\omega M_i \cdot I_1$, the current of the receiving-side is

$$I_i = \frac{M_i U_s}{R_i L_{f1}}, \quad (i = 2, \ldots, n). \tag{5}$$

Thus the power loss at the transmitting end and the received power of a single load are

$$P_{loss} = I_1^2 R_1 = \frac{Us^2}{\omega^2 L_{f1}^2} R_1, \tag{6}$$

$$P_{ri} = I_i^2 R_{Li} = \frac{M_i^2 U_s^2 R_{Li}}{(R_{si} + R_{Li})^2 L_{f1}^2}. \tag{7}$$

It can be further deduced that the system efficiency is

$$\eta = \frac{\sum_{i=1}^{n} P_{ri}}{\sum_{i=1}^{n} P_{si} + P_{loss}} = \frac{\sum_{i=1}^{n} \frac{M_i^2 R_{Li}}{(R_{si}+R_{Li})^2}}{\sum_{i=1}^{n} \frac{M_i^2}{(R_{si}+R_{Li})} + \frac{R_1}{\omega^2}}, \tag{8}$$

where P_{si} is the receiving power of the ith load.

It can be seen from (7) and (8) that the charging power and charging efficiency of the long-track EV-DWPT system are related to U_s, M, R_1, and R_L.

B. ANALYSIS OF INTERNAL RESISTANCE AND COUPLING CHARACTERISTICS OF ENERGY TRANSMITTING COIL

Mutual inductance is an important parameter index of magnetical coupling resonant wireless power transmitting system, which can be calculated by Nieman formula

$$M = \frac{\mu_0 N_1 N_2}{4\pi} \int_{l_1} \int_{l_2} \frac{dl_1 dl_2}{r} \tag{9}$$

where μ_0 is the vacuum permeability, N_1 and N_2 represent the number of turns of the transmitting coil and receiving coil, l_1 and l_2 represent the length of the single-turn transmitting coil and the single-turn receiving coil, and r represents the distance between the transmitting coil microelement and the receiving coil microelement. Because the height of the EV chassis is fixed, so the vertical distance between the power transmitting and receiving coils is fixed during dynamic wireless charging. In order to study the effect of the transmitting coil's length on the mutual inductance between power transmitting coil and receiving coil, the mutual inductance value when the transmitting coil length was taken at different lengths within 1000m was plotted by Matlab, while the width of the transmitting coil and the size of the receiving coil were fixed. The simulation parameters are shown in Table.1.

TABLE 1. Simulation parameters of transmitting coil and receiving coil.

Size of transmitting coil /（m*m）	Size of receiving coil /（m*m）	Transmitting coil turns / receiving coil turns	Vertical distance between the transmitting coil and the receiving coil /m
1000*1.5	1.5*1.5	7/6	0.2
500*1.5	1.5*1.5	7/6	0.2
333.33*1.5	1.5*1.5	7/6	0.2
142.86*1.5	1.5*1.5	7/6	0.2
76.92*1.5	1.5*1.5	7/6	0.2
38.46*1.5	1.5*1.5	7/6	0.2

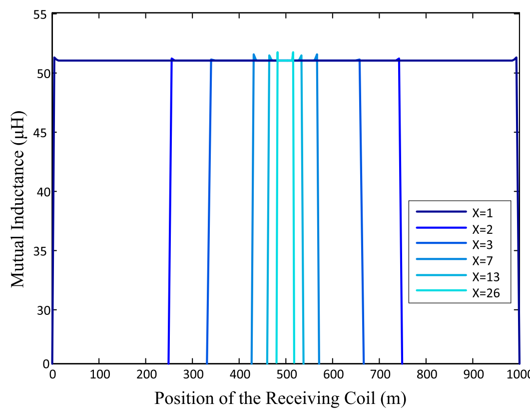

FIGURE 3. Mutual inductance between transmitting coil and receiving coil while the length of transmitting coil changes.

It can be seen from Fig.3 that when the width and turns of transmitting coil, the vertical distance between the transmitting coil and receiving coil are fixed, and the length of the transmitting coil is much longer than the length of the receiving coil, the mutual inductance between the long-track transmitting coil and the receiving coil is hardly affected by the length of transmitting coil. Therefore, it can be known that the charging power of EV and charging efficiency of the system are mainly related to U_s, R_1 and R_L.

III. DESIGN AND OPTIMIZATION METHOD OF TRANSMITTING COIL PARAMETERS OF EV DYNAMIC WIRELESS CHARGING SYSTEM

A. DETERMINATION OF THE RESONANCE COMPENSATION INDUCTANCE AT THE TRANSMITTING END

The specific parameters of the long-track EV-DWPT system are shown in Table.2.

TABLE 2. Parameters of the long-track EV-DWPT system.

Parameters	value
Source voltage (DC)	750V
Working frequency	85kHz
Width of transmitting coil	1.5m
Size of receiving coil	1.5m*1.5m
Mutual inductance	51μH
Transmission distance	20cm
Power consumption	0.15kWh
Load resistance	0Ω~30Ω

Because the resonator also functions as a filter, the harmonic component is ignored, only the fundamental component of the high-frequency power supply is considered. Fourier expansion is performed on the output voltage of the high-frequency inverter to obtain the fundamental wave amplitude $\frac{4U_{in}}{\pi}$, where U_{in} is the AC square wave voltage amplitude. Taking 750V DC / DC as example, the voltage fundamental wave amplitude is 954.93V.

In this paper, the power consumption per unit kilometer of an EV Q is used to determine the charging power of each EV that the system needs to provide. According to Joule's law $Q = P \cdot t$, where t is the time required for the EV to travel 1 km, and P is the power consumed by the EV per unit time. As the mileage of the charging area is fixed and the charging time is inversely proportional to the driving speed, if it is hoped that the power provided by the EV-DWPT system can offset the power consumption of EV during driving, it must be ensured that when the vehicle is driving at maximum speed limit, the charging power can also meet the power consumption requirement per kilometer, that is, the charging power is not less than $P_0 = \frac{Q \cdot v_{\max}}{L}$, $(L = 1km)$.

Taking BYD e5 as an example, the power consumption per kilometer Q is 0.15kWh, and the corresponding lower limit of the charging power at the speed of 60km / h is $P_0 = 9$kW.

Since the charging power is a function of load resistance, let $\frac{\partial P_{ri}}{\partial R_{Li}} = 0$ we can derive $R_{Li} = R_{si}$, that is, the peak value of the EV receiving power is $P_{rm} = P_r|_{R_{Li}=R_{si}} = \frac{M_i^2 U_s^2}{4R_{si}L_{f1}^2}$, and R_{Li} corresponding to P_{rm} the peak value of the received power is only a few tenths. In order to widen the adjustment range of the load resistance, let $P_{rm} > 4P_0$ and take P_{rm} as about 40kW. The peak value of the receiving power corresponds to the minimum transmitting coil current I_1 and the maximum value of the resonant compensation inductance L_{f1} at the transmitting side. Considering that the LCC-S topology is a source-side constant current structure, the smaller I_1 is, the smaller the transmitting coil loss is when the overall structure is determined. Therefore, the smallest L_{f1} corresponding to I_1 is taken as the compensation inductance value at the transmitting end, $L_{f1} = \sqrt{\frac{M_i^2 U_s^2}{4R_{si}P_{rm}}}$.

B. ANALYSIS OF THE ENERGY LOSS OF THE TRANSMITTING COIL

In order to reduce the skin effect, DWPT systems often use Litz wire for coil winding. The current carrying capacity of the Litz wire is 4A / mm^2, and the single-strand wire radius is 0.1mm. According to (4), the current through the transmitting coil is about 6.6A, so the cross section of the Litz wire used for winding the transmitting coil is not less than 2 mm^2, and the number of strands is not less than 64.

The high frequency equivalent resistance of Litz wire consists of a DC resistance and a high frequency AC resistance. The expressions of DC resistance and high-frequency AC resistance of Litz wire are $R_{dc} = \frac{4\rho l}{\pi N_S D_S^2}$ and $R_{ac} = R_{dc}(H + 2(\frac{N_s D_s}{D_w})^2(\frac{D_s\sqrt{f}}{32\times 10.44})^4)$, where ρ is the resistivity of Litz wire, l is the length of Litz wire, and H d is the ratio of AC resistance to the DC resistance of a single-stranded solid core wire. D_W can be calculated from the empirical formula $D_w = 1.155\sqrt{N_s} \times D_s + 0.0508$. f is the frequency of the current through the Litz wire. Therefore, the high-frequency equivalent resistance of the Litz wire is:

$$R_{ESR} = R_{dc} + R_{ac} = \frac{8\rho l}{\pi N_s D_s^2}(1+(\frac{N_s D_s}{D_w})^2(\frac{D_s\sqrt{f}}{32 \times 10.44})^4) \tag{10}$$

Let the length and width of the transmitting coil be a and b, the number of turns is N_1, then the length of Litz wire used is $l = 2N_1(a + b)$, so the high-frequency equivalent resistance of the transmitting coil is $R_1 = \frac{16\rho N_1(a+b)}{\pi N_s D_s^2}(1 + (\frac{N_s D_s}{D_w})^2(\frac{D_s\sqrt{f}}{32\times 10.44})^4)$, and the energy loss of the transmitting coil is $P_{loss} = I_1^2 R_1 = \frac{Us^2}{\omega^2 L_{f1}^2} R_1$, which is proportional to the coil length b.

The radiation resistance is calculated as $R_{rad} = 320\pi^4 N^2 \frac{A^2}{\lambda^4}$, where N is the number of turns of the coil, A is the loop area of the coil (m^2), and λ is the wavelength of the electromagnetic wave. It can be calculated that when the resonance frequency is 85kHz and the maximum transmitting coil length is 1000m, the radiation resistance is 0.0163Ω, which is much smaller than the internal resistance of the transmitting coil. Therefore, the radiation resistance is ignored in this analysis.

According to the analysis in II.A, after the system topology is determined, the receiving power and transmission efficiency are mainly affected by U_S, M, R_1 and R_L. However, according to the above analysis, R_1 is positively related to the transmitting coil length b, so the charging power is only affected by U_S and R_L, the efficiency is only affected by U_S, b and R_L. In order to ensure the stability of the current through transmitting coil, this study makes U_S a fixed value, and focuses on the influence of b and R_L on the system performance parameters.

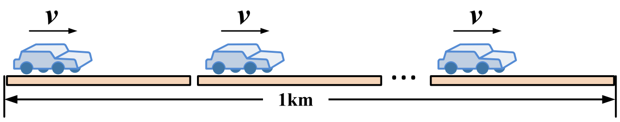

FIGURE 4. Schematic diagram of laying method of transmitting coils of long-track EV-DWPT system.

C. DETERMINATION OF SEGMENT LENGTH AND THE RANGE OF EQUIVALENT LOAD RESISTANCE

For the selection of the length of power transmitting coil of long-track EV DWPT system, the length can be infinitely long in theory, but it is obviously unrealistic. Therefore, this article takes the 1-km long section as a boundary. Assuming that multiple sections of long-track power transmitting coils are laid continuously within 1 km, the length design of a single coil must meet the "2 seconds principle" to ensure effective braking between adjacent EVs.

According to the "2 seconds principle", the safe braking distance of adjacent vehicles is $d = v_{\max} \cdot t_0$, where $v_{\max}$ is the maximum speed limit of the vehicle, its unit is m/s, t_0 is 2 seconds, assuming that a single segment of transmitting coil charges N EVs at the same time, the length of transmitting coil should not be less than $l = N(d + L_{EV})$, where L_{EV} is the length of EV. Taking BYD e5 as an example, whose size is. If the maximum speed limit during EV-DWPT charging process is 60km / h, the shortest length of transmitting coil when must not be less than 38.01m.

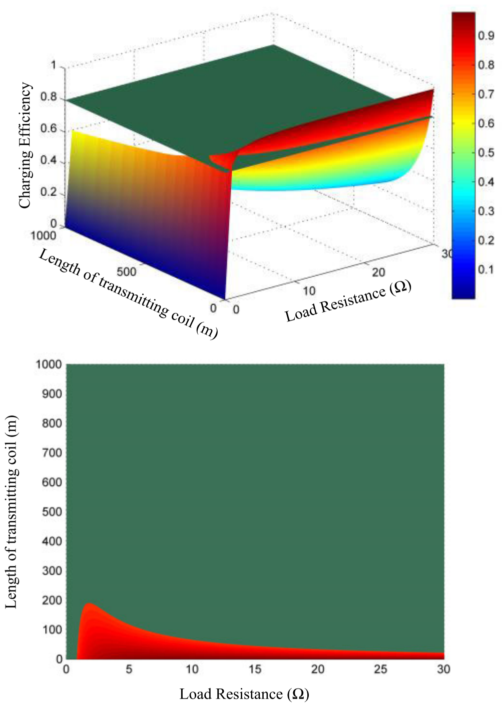

FIGURE 5. Relationship between the system charging efficiency and the EV equivalent load resistance and the length of transmitting coil b.

According to (8), the change of the system charging efficiency with EV equivalent load resistance and the length of transmitting coil b is shown in Fig.5.

When the system charging efficiency is not less than 80%, the range of the transmitting coil length and EV equivalent load resistance is shown in Fig.5. It can be seen from the figure that the charging efficiency of the system decreases rapidly with the increase of the transmitting coil length, the range of b that satisfies the charging power requirement is greatly reduced while the range of the equivalent load resistance value R_L is basically not reduced.

It can be seen from the figure that the range of R_L which meets the requirement that the charging power is not lower than P_0 is much narrower than the range of R_L which meets the system charging efficiency requirements. Therefore, it is necessary to take the overlapping part of the range of R_L that meets both the charging efficiency requirements and the charging power requirements to serves as an effective adjustment range of the EV equivalent load resistance value.

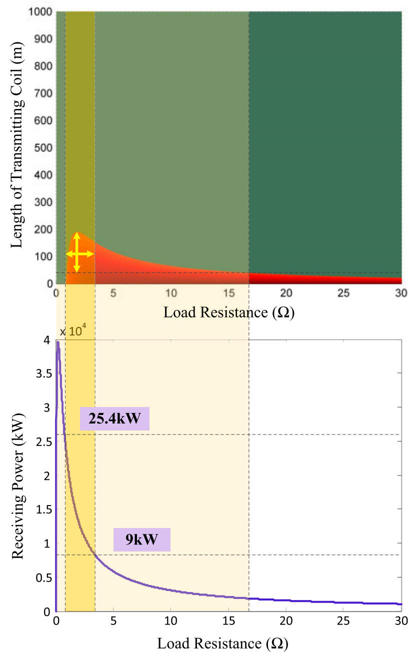

FIGURE 6. Determination of the value range of and b.

It can be seen from Fig. 6 that the load equivalent resistance value R_L and the range of the length of long-track transmitting coil which satisfy the three conditions of the charging efficiency of not less than 80%, the "two-second principle" and the charging power being able to compensate for the power consumption per kilometer are superimposed, the three have a common coincident area, so there exists a set of values of R_L and b that meet the three conditions mentioned above.

D. DETERMINATION OF SEGMENT LENGTH IN ACTUAL ENGINEERING SCENARIOS

Because the value set of R_L and b obtained in III.C is a continuous interval, it is necessary to further accurately determine the length of the segmented transmitting coil and reduce the optional range of b during actual project laying. If the

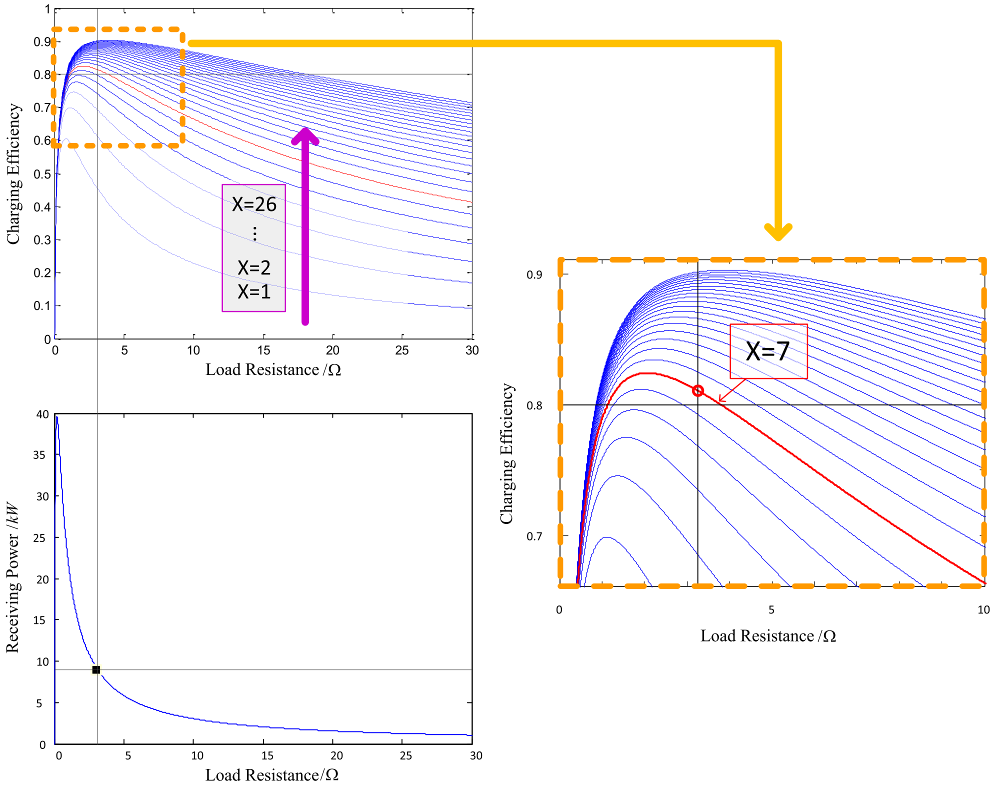

FIGURE 7. The trend of load receiving power and system efficiency with.

number of transmitting coils laid within 1 km is an integer, the optional length range of the transmitting coils is a set of discrete values.

Combined with the requirements for the shortest length of transmitting coil in section III.A, if the maximum speed limit of the vehicle during DWPT charging is 60 km/h, the shortest length of transmitting coil when $N = 1$ must not be less than 38.01 m, that is, the number of transmitting coil segments X within 1 km is not more than 26.

Fig. 7 shows the relationship between the system charging efficiency and the equivalent load resistance of the vehicle when the number of transmitting coil is different within 1 km. As can be seen from the figure, to meet the requirements of both the EV charging power and the system charging efficiency, when $v_{\max} = 60$km/h, $N = 1$, the range of X is among 7 to 26 segments.

Since the cost of power transmitting coils is directly proportional to its winding length, from the perspective of the coil laying cost, the more the number of power transmitting coils is, the longer the winding length of power transmitting coils will be, and the higher the cost will be. Therefore, the minimum number of power transmitting coils that satisfies the charging efficiency and charging power range is selected for laying the 1 km charging area. That is, when $v_{\max} = 60$km/h and $N = 1$, laying the transmitting coil in 7 sections within 1km can meet the economical and system efficiency requirements.

IV. EXPERIMENTAL VERIFICATION

This article demonstrates the above research content by building an experimental model. Assuming that long-track type wireless power transmitting coils are continuously laid in integer segments within a length of 1000 cm, the length of a single coil is 1000/X cm (X = 1,2, …, 10). In this experiment, the width of the transmitting coil is 15cm, the size of the receiving coil is 15cm*15cm, the number of turns of the transmitting coil and the receiving coil are 4 turns and 7 turns respectively, the distance between the transmitting and receiving coils is 5cm, and the mutual inductance between transmitting coil and receiving coil is 1.96μH.

This experiment simulates the driving speed by assuming the load power demand P_0 corresponding to the upper limit of driving speed, and using the power demand corresponding to the upper limit of the driving speed as the lower limit of the charging power. In this experiment, we set $P_0 = 10$W and $P_{rm} = 55$ W, and calculate $L_{f1} = 5\mu$H from $L_{f1} = \sqrt{\frac{M_i^2 U_s^2}{4R_{si}P_{rm}}}$. According to (7), the changing curve of charging power with load resistance is obtained. In this experiment, it is stipulated that the receiving efficiency is not less than 85%, and the charging efficiency curves of a single coil after 1000cm divided into X segments are separately made. According to the load charging power curve, it can be seen that only when the number of segments X ≥5 can the load receiving

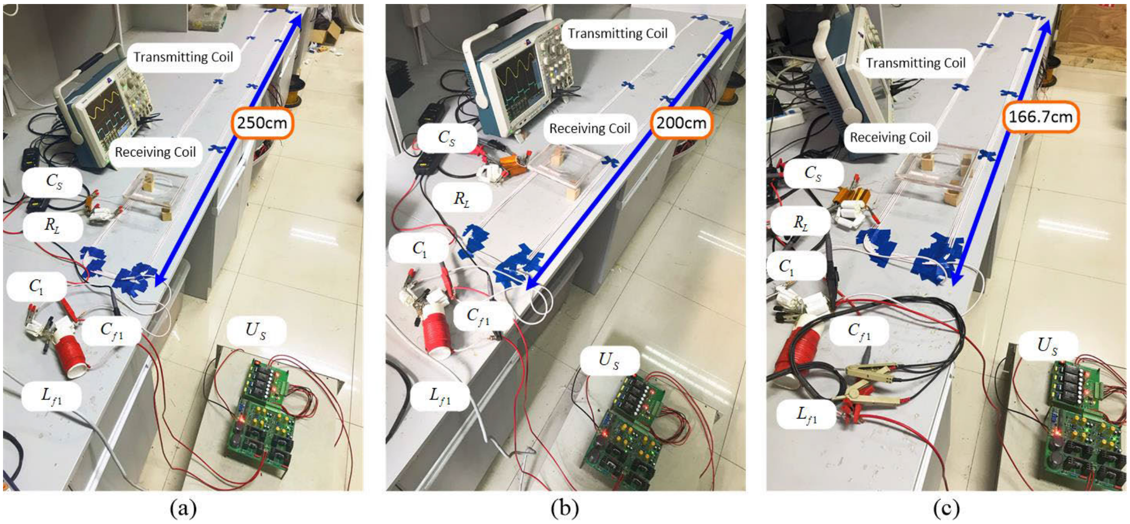

FIGURE 8. **The experimental scaled-down prototype of the long-track DWPT system. (a) b = 250cm; (b) b = 200cm; (c) b = 166.67cm.**

power greater than 10W and the charging efficiency greater than 85%.

Because the length of the Litz wire used is directly proportional to the number of coil segments in the coil laying range, the optimal number of segments for long-track power transmitting coils in the range of 1000 cm is 5 segments. This experiment verifies the receiving power and system efficiency of the load in the charging area under the conditions of X = 4, 5, 6 respectively, that is, the length of a single power transmitting coil is 250cm, 200cm, and 166.67cm. The experimental platform is shown in Figure 8. The power supply is a full-bridge inverter, and the system resonance frequency is 85 kHz. The specific experimental parameters are shown in Table.3.

TABLE 3. **Parameters of the experimental prototype.**

(A) FIXED PARAMETERS

Parameters	Value
Source voltage	10 V
Compensation inductance of the transmitting-side L_{f1}	5μH
Compensation capacitor of the transmitting-side C_{f1}	687.4nF
Resistance of the receiving coil	0.066 Ω
Inductance of the receiving coil	20.74 μH
Compensation capacitor of the receiving-side	169.03 nF

(B) CHANGING PARAMETERS

Parameters	b=250cm	b=200cm	b=166.67cm
Resistance of the transmitting coil	0.108Ω	0.080Ω	0.068Ω
Inductance of the transmitting coil	63.46μH	51.18μH	44.13μH
Compensation capacitor of the transmitting-side C_1	60.07nF	76.08nF	89.83nF

Fig.9 shows the mutual inductance between the transmitting coil and the receiving coil when the transmitting coils' width is 15cm, lengths are 250 cm, 200 cm, and

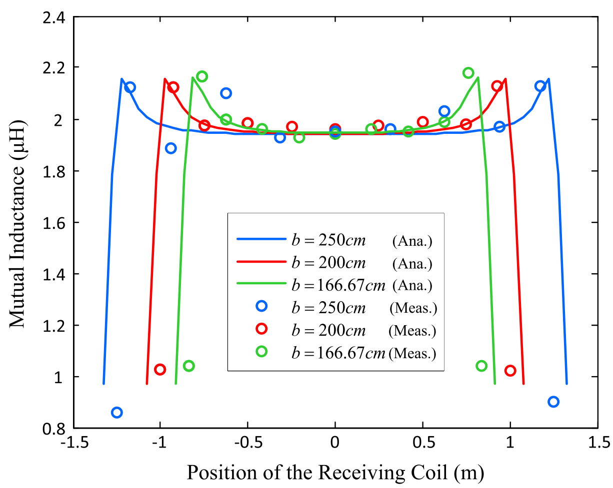

FIGURE 9. **Mutual inductance change between transmitting coil and receiving coil with different transmitting coil lengths.**

166.67 cm, respectively. As can be seen from the figure, when the length of the transmitting coil is different, if the mutual inductance mutation at the edge of the transmitting coil is ignored, the mutual inductance between the transmitting coil and the receiving coil is almost unchanged. It can be seen that the mutual inductance is hardly affected by the length of the transmitting coil, which is consistent with the previous analysis results. The experiment results shows that when the width and turns of transmitting coil, the vertical distance between the transmitting coil and receiving coil are fixed, and the length of the transmitting coil is much longer than the length of the receiving coil, the mutual inductance between the long-track transmitting coil and the receiving coil can hardly be affected by the length of transmitting coil.

The trend of the load receiving power and system efficiency with load resistance is shown in Fig.10. It can be seen

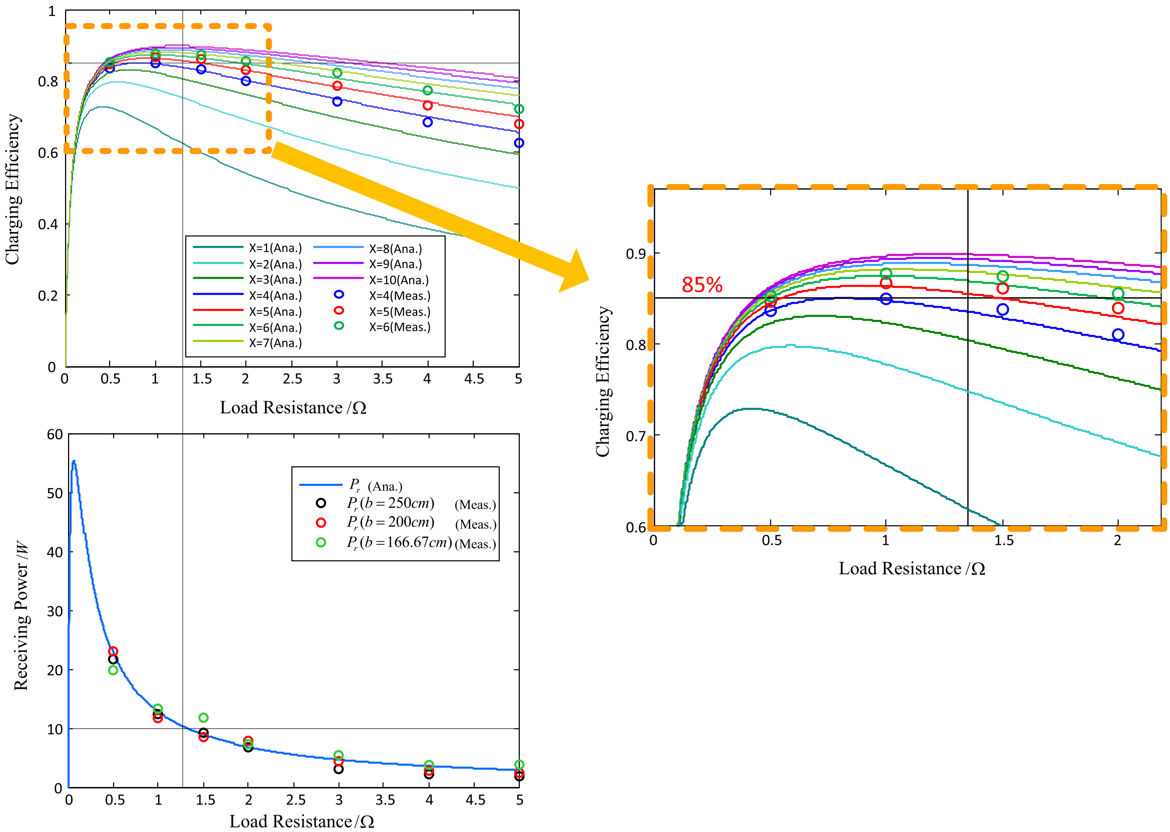

FIGURE 10. The trend of load receiving power and system efficiency with R_L.

from Fig.10 that as the load resistance value continues to increase, the system efficiency shows a trend of increasing first and then decreasing, and at the same time, the system efficiency becomes larger as the length of the transmitting coil decreases. Under the condition of load receiving power equals to 10W, when X = 4, the charging efficiency is lower than 85%; when X = 5 and X = 6, the charging efficiency is higher than 85%. When the length of the transmitting coil is 200cm, the system can simultaneously meet the conditions that the charging efficiency is not less than 85%, the charging power is not less than 10W, and the number of coil segments is the smallest. The experimental results are consistent with the calculation results.

V. CONCLUSION

This paper proposes a method for selecting the length of the transmission coil in a long-track EV-DWPT system that combines the vehicle speed limit and the energy loss of the power transmitting coil. This paper focuses on the maximum speed limit of the vehicle during dynamic wireless charging, which mainly affects the selection of the length of power transmitting coil and the determination of the lower limit of vehicle's charging power. The EV-DWPT system studied in this paper is based on the LCC-S source-side constant current topology. First, the parameters b and R_L that affect the transmitting power and efficiency of the system are determined. By combining the requirements of system charging efficiency, the EV's power consumption per kilometer and the speed limit, the range of the transmitting coil length and the load resistance were determined; Finally, based on the premise of continuous laying multiple long-power transmitting coils in a 1-km area, the length of a single power transmitting coil was further screened and determined in conjunction with the laying cost of the ground-side power transmitting coils. The feasibility of the above method is verified by experiment, which meets the requirement of load's charging power whereas the system charging efficiency is not less than 85%. The parameter design and optimization method of ground-side power transmitting coil of EV dynamic wireless charging system proposed in this paper provides a reference for the construction of EV-DWPT system in high-speed driving scenarios from the perspective of system efficiency and construction cost.

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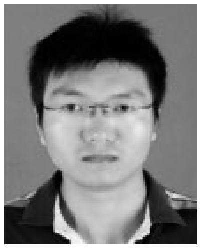

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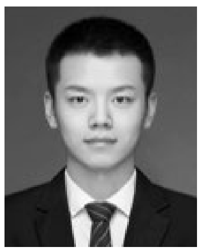

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