Modeling and Analysis of a 3kW Wireless Charging System for Electric Vehicle

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***Abstract*—This paper designs a 3kW magnetic resonance wireless charging system for electric vehicles (EVs), and an explicit solution is derived. The maximum power transmission efficiency (PTE) is above 90% in this system. By the way of adjusting the duty ratio, this system adapts the dynamic change of the battery load and balances current of the transmitting coil and receiving coil. At the same time, the charging power and PTE are also greatly increased.**

Keywords*—*WPT; EVs; Duty Ratio; 3kW

I. INTRODUCTION

With the energy and environment issues becoming more prominent, it is necessary to develop the electric vehicles (EVs) so that we can save energy and reduce air pollution emissions as well as dependence on fossil fuels. The existing EVs use charging cables and plugs for charging in the form of direct contact. The charging process needs artificial operations on outlet and will greatly lower the flexibility of EVs charging. Exposure of charging cable and plug also has a potential danger of electric leakage and electric shocks, producing spark and forming the electric erosion wear. So, it's remained to improve security [1-2]. Wireless charging for EVs not only solves the above problems like charging cable exposure, but also brings many advantages such as convenience, safety, reliability, and so on [3-4]. EVs wireless charging technology is currently a research focus.

Both colleges and enterprises at home and abroad have invested a lot of manpower and material resources to carry out the research in the wireless charging of EVs, including the charging topology, modeling, simulation and hardware experiment etc. [5-6]. At present, the well-known automobile manufacturers such as BMW, Toyota has developed some of the prototype [7-8]. In general, the EVs wireless charging technology is still in infancy, which has many problems to solve such as charging efficiency, electromagnetic coupling mechanism, power control and other issues. Traditional cable charging can reach above 97% efficiency [9-10], while wireless charging just meets 90% efficiency [11]. It is restricting the promotion of the technology severely.

In addition, electromagnetic environment issues of EVs wireless charging system remain to be concerned. A magnetic resonance wireless charging scheme for EVs is designed. Meanwhile power electronic transformation technology is used to balance current of the transmitting coil and receiving coil, solve the problem of dynamic access battery load and improve the power transmission efficiency (PTE).

II. EVS WIRELESS CHARGING SYSTEM MODELING

A. System Topology Design

EVs wireless charging system schematic diagram is shown in Fig.1. This system includes alternating current (50Hz), rectifier filter, high-frequency inverter, transmitter, receiver, rectifier control circuit and battery. Produced by AC 220V or 380V is rectified by AC-DC converter, the DC source is connected to high frequency inverter. High frequency inverter produces alternating current. Its frequency is the same as resonance frequency of transmitter and receiver. The transmitter and receiver both are composed of an inductor and a compensation capacitor in series. Rectifier control circuit consists of rectifier and buck converter, changing power from receiver into DC for charging battery. Sometimes, it will be added that DC voltage regulator after rectifier in order to further stabilize the charging voltage.

According to different transmission distance, power level and PTE, the resonant frequency of EVs wireless charging system can be setting from tens of kHz to thousands of kHz. So the power electronic device can fully meet demand, and high-frequency inverter topology designed to full bridge inverter topology is shown in Fig.2.

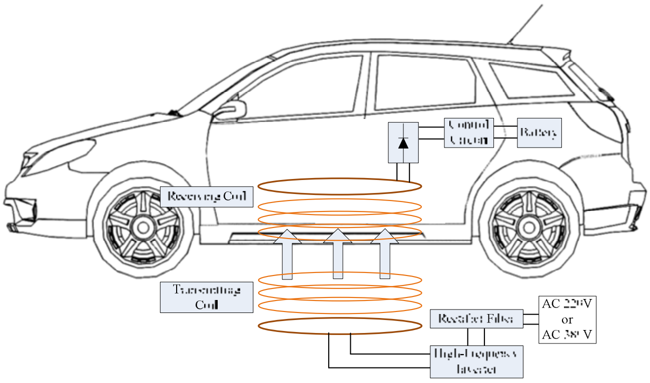

Fig.1. Electric vehicles charging system schematic diagram

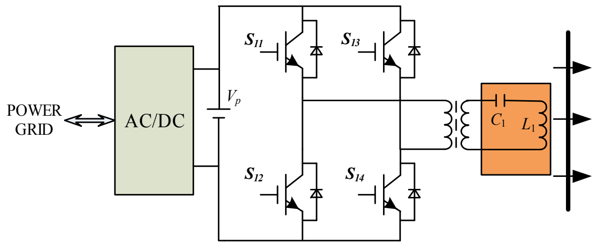

Fig.2. Full bridge inverter power supply topology

Transmitting coil and receiving coils have space spiral coil, flat spiral coil, and so on. In consideration of reducing the size of axial space as much as possible and convenient installation, EVs wireless charging system usually uses a flat spiral coil. So, this paper designs a flat spiral coil shown in Fig.3. The turn spacing of flat spiral coil is constant. For a given shape, a flat spiral coil is completely specified by the number of turns N, the outer diameter D_{max}, and the inner diameter D_{min}. For a flat spiral coil, the calculation of equivalent self-inductance can be given in (1).

$$\begin{cases} d_{\text{avg}} = 0.5\left(\text{D}_{\max} + \text{D}_{\min}\right) \\ L = \dfrac{\mu_0 N^2 d_{\text{avg}} m_1}{2}\left(\ln\left(\dfrac{m_2}{\beta}\right) + m_3\beta + m_4\beta^2\right) \\ \beta = \left(\text{D}_{\max} - \text{D}_{\min}\right)/\left(\text{D}_{\max} + \text{D}_{\min}\right) \end{cases} \tag{1}$$

Where m_1, m_2, m_3 and m_4 are fitting parameters. For the hollow flat spiral coil shown in Fig.3, there are m_1=1.0, m_2=2.46, m_3=0 and m_4=0.2. μ_0 represents the permeability of vacuum. N represents coil turns.

For designed flat spiral coil, the resonance frequency of transmitter and receiver is decided by the L and C. Frequency f is given by

$$f = \frac{1}{2\pi\sqrt{LC}} \tag{2}$$

Through a series of control and transformation, power is transmitted to receiver and changed into the charging voltage of battery. So, the PTE is given by

$$\eta = 1 - \frac{P_1 + P_2 + P_c}{P_{\text{i}}} \tag{3}$$

P_i is the total input power. P_1 is the loss power of transmitter. P_2 is the loss power of receiver. P_c is the loss power of radiation. In fact, P_c is very small, much smaller than P_1 and P_2[12]. So P_c can be ignored.

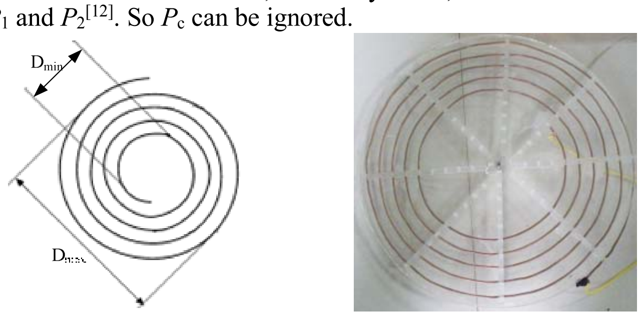

Fig.3. Flat spiral coil

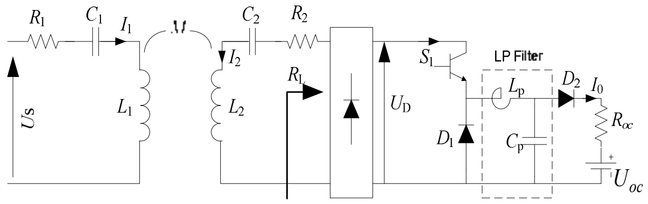

Fig.4. Equivalent circuit of electric vehicle wireless charging system

B. System circuit Modeling

In the process of modeling, the battery model is very complex. This paper uses the model of voltage source and equivalent resistance in series for facilitating the analysis. And power supply is equivalent to a constant voltage source U_s with ignoring the internal resistance. Buck chopper is used as DC-DC converter in the end of battery charging. In conclusion, the equivalent circuit of Fig.1 is shown in Fig.4. According to the circuit, the equation can is obtained

$$\begin{cases} R_1\dot{I}_1 + j\omega M\dot{I}_2 = \dot{U}_s \\ j\omega M\dot{I}_1 + \dot{I}_2(R_2 + R_L) = 0 \\ \dfrac{8}{\pi^2} I_2 R_L = U_D \\ DU_D = U_0 = I_0 R_{oc} + U_{oc} \\ DI_0 = I_2 \end{cases} \tag{4}$$

R_1 and R_2 are the equivalent series resistance (ESR) of coils in high frequency. M is the mutual inductance between transmitting coil and receiving coil. I_1 is the RMS of the transmitting coil current. I_2 is the RMS of the receiving coil current. I_0 is the charging current of battery. U_D is the RMS of the equivalent voltage after rectifier. R_{oc} is the equivalent resistance of battery. U_{oc} is the equivalent voltage of battery. D is the duty ratio of Buck chopper.

When the load is a battery, the equivalent external characteristic is one of the main factors affecting the system performance by (4). Further, the equivalent resistance of containing the receiver and battery can be obtained by

$$R_L = \frac{\pi^2\left[\omega M U_S R_{oc} + DU_{oc}\left(R_1 R_2 + \omega^2 M^2\right)\right]}{8D^2\omega M U_S - \pi^2 DU_{oc} R_1} \tag{5}$$

If U_s is too small, it will lead that U_d is too low in receiver so that not to provide enough charging voltage for battery by (5). It will cause the calculation result is not applicable in (5). When using (5), it must be meet that $U_S > \pi^2 R_1 U_{oc} / (8D\omega M)$. In addition, in order to reduce battery charging voltage fluctuation, the system adds LC filter unit. For guaranteeing the continuous charging current, L_p should meet following condition.

$$L_p = \frac{T_s U_0}{2I_{Lb}}(1 - D) = \frac{U_0}{2I_0 f_s}(1 - D) = \frac{U_0^2}{2P_{omin} f_s}(1 - D_{\min}) \tag{6}$$

I_{Lb} is the average current of inductance. f_s is the frequency of switch transistor. P_{omin} is the minimum output power. Filter capacitance value is obtained by

$$C_p = \frac{U_0}{8L_p \Delta U_0 f_s^2}(1-D) \tag{7}$$

ΔU_0 is the output voltage ripple. As for the design of filter inductance, critical current and output current ripple requirement should be taken into consideration. The required value should be less than 30%-50% of I_{omax}. So the output filter inductance L_p needs to satisfy

$$L_p \geq \frac{(V_{in} - V_0)T_{on}}{(0.3-0.5)I_{omax}} \tag{8}$$

III. Characteristic Analysis

A. Experimental Design

From the previous section analysis, for a EVs wireless charging system whose resonance parameters are given, we know that battery equivalent Characteristic will be changed with the charging process. Reasonable and effective impedance matching is one of the key ways to solve the problem that the PTE of system is low. So, it is important to calculate and monitor the equivalent impedance of the battery load in the process of charging.

According to the proposed scheme, system parameters are chosen and shown in Table I. The experimental system is shown in Fig 5. The parameters of the lithium battery are that charging voltage is 72V and capacity is 200AH.

TABLE I System Parameters

Parameters	Value
L_1 / μH	121.927
L_2 / μH	121.927
f / kHz	113
R_1, R_2 / Ω	0.45
N_1, N_2	10
M / μH	17.6
U_{oc} / V	72
R_{oc}/ Ω	0.035
f_s / kHz	20

B. Battery Equivalent Resistance Analysis

The ESR of the battery load accessed system is not only related to parameters of battery itself, but also operating frequency, coil parameters, input voltage and the duty ratio of the DC-DC converter. In this paper, when the system parameters are like as Table 1, the ESR will vary with the duty ratio and the variation curve is shown in Fig.6. When D=0.55, It can be found that the ESR is 1 to 2 times than when D=0.85, which will have a great influence on the impedance matching design and control for the system.

If the system impedance is designed when D=0.55, when D=0.85 that will cause difficulties of frequency tracking and the system starts. At the same time, it can be found that the ESR of battery decreases gradually with the increase of the U_s, especially in the low voltage part.

Fig.7 shows the curve of charging power and PTE under different duty ratio. From curves shown in Fig. 7, it can achieve higher PTE when the duty ratio is high and the charging power of system is small. But the variation rate of the system charging power with U_s is lower than low duty ratio.

When the charging power increases, the efficiency will decrease with the increase of the duty ratio. When charging power increases to a certain extent, for the same U_s, the PTE and charging power under high duty ratio lower than low duty ratio. Therefore, the regulation of charging power can be achieved by adjusting the duty ratio, and the choice of duty ratio can be determined by according to practical demand.

C. Transmitter and Receiver coil Current Analysis

Further research found that the change of duty ratio has less effect on the current of receiving coil, which mainly affecting the current of transmitter coil. It is shown that the smaller of duty ratio, the greater of transmitter coil current, as shown in Fig.8.

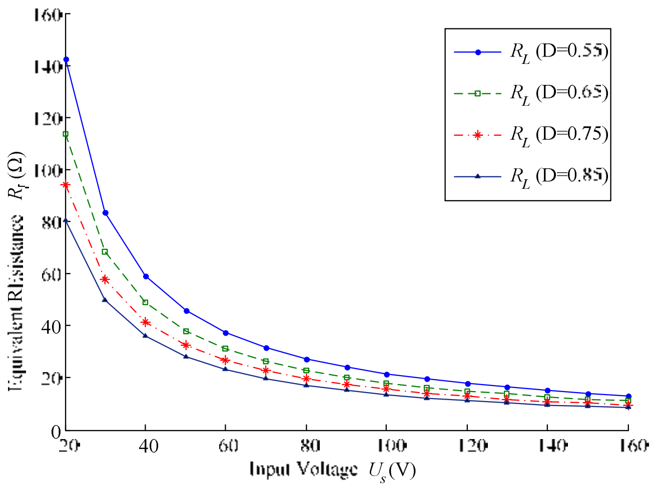

Fig.6. The change curves of equivalent resistance of battery

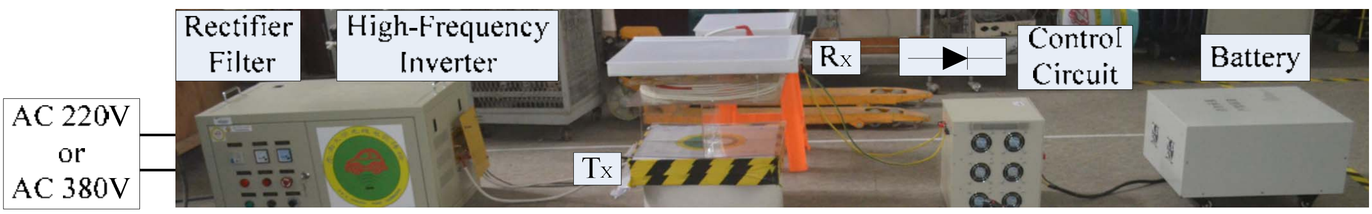

Fig.5. Experiment system of electric vehicle wireless charging

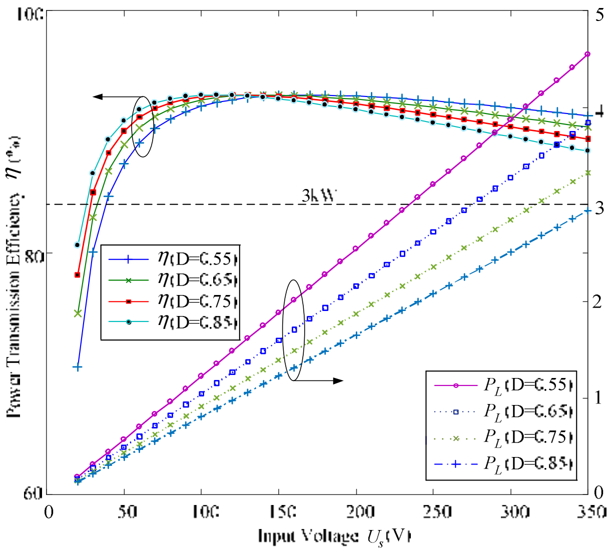

Fig.7. The change curves of power and PTE

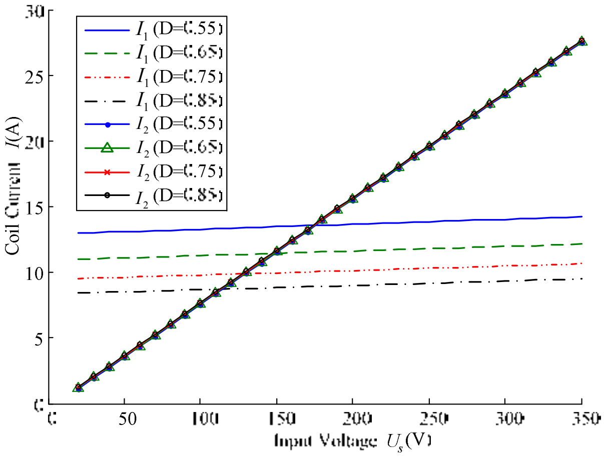

Fig.8. The change curves of transmitter and receiver

To realize the 3kW power transfer in the system, when D=0.85, the input voltage is AC 380V, the current of transmitting coil is 9.49A and receiving coil is 27.67A. When D=0.55, the input voltage is AC 240V, the current of transmitting coil is 13.81A and receiving coil is 18.71A. Moreover, when D=0.85 and U_s=350V, the system can reach 3kW power transfer and the PTE is about 90%.

Therefore, reasonable adjusting the duty ratio can realize high PTE and power transmission under the different power levels. At the same time, it also can reduce the current of receiver, balancing the current of transmitter and receiver. In this way, the electromagnetic field of system is also regulated and optimized.

IV. CONCLUSIONS

Based on the magnetic resonance technology, this paper proposes a design of wireless charging system for EVs with theoretical analysis and modeling. With analysis on the characteristic of ESR of battery load, this paper presents a solution based on adjusting the duty ratio. When D=0.85 and U_s=350V, the system has realized 3kW power transfer with the PTE about of 90%. Moreover, by adjusting the duty ratio, the current of resonator can be balanced, which provides a method for improving the electromagnetic environment around the system.

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