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# Rectifier Load Analysis for Electric Vehicle Wireless Charging System

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**ABSTRACT**: This paper presents the analysis of rectifier load used for electric vehicle (EV) wireless charging system, as well as its applications on compensation network design and system load estimation. Firstly, a rectifier load model is established to get its equivalent input impedance, which contains both resistance and inductance components, and can be independently calculated through the parameters of the rectifier circuit. Then, a compensation network design method is proposed, based on the rectifier load analysis. Furthermore, a secondary side load estimation method and a primary side load estimation method are put forward, which adopt only measured voltages and consider the influence of the rectifier load. Finally, an EV wireless charging prototype is developed, and experimental results have proved that the rectifier equivalent load can be correctly calculated on conditions of different system load resistances, rectifier input inductances, DC voltages, and mutual-inductances. The experiments also show that rectifier load equivalent inductance will impact system performances, and the proposed methods have good accuracy and robustness in the cases of system parameter variati

## I. INTRODUCTION

ELECTRIC vehicle (EV) wireless charging system (WCS) has the advantages of convenience, space-saving, etc. So, it has attracted much attention. In recent years, working principle, operation characteristics, system design, and control method of both stationary and dynamic wireless EV charging systems have been studied and applied to some demonstrations [1,2].

In applications of EV wireless charging, rectifier and output filter capacitor are needed to convert the high frequency AC to DC, in order to charge the power battery. Rectifier and the circuit after it are usually equivalent to a pure resistance load to design the system or control strategy [3,4]. A conventional way is using the coefficient $8/\pi^2$ to make an equivalent relationship between the rectifier input impedance and the system load resistance [5,6]. However, stray parameters and non-ideal behaviors of the devices will become obvious at the high frequency range [7]. Also, rectifier input impedance can be affected by the input inductance and other parameters. So, it will bring some deviations, if only considering WCS rectifier input impedance as a pure resistance.

Actually, rectifier input impedance of EV wireless charging system contains both resistance part and inductance part [7-9]. It can be expressed as a series of an equivalent resistance and an equivalent inductance [8,9]. Although there has not been an effective method to get the equivalent load impedance of WCS rectifier, some existing researches could be helpful. Based on the on and off states [10], the rectifier and its related inductance and capacitance circuits can be described by the state space model [11], considering the stray resistances and diode forward voltage drop [12]. Then, the expressions of the related voltages and currents have been obtained in the time domain, frequency domain, or complex frequency domain [13,14], which can be used for the analysis of WCS rectifier equivalent load impedance. Besides, non-linear switching functions and circuit simulations could also be adopted to study this issue [15].

The non-linear process of rectifier load will bring some difficulties to system compensation network design. As we know, compensation networks are very important to system performances [16], and can be designed to achieve maximum efficiency, maximum power, or conjugate matching [17,18]. In most cases, a pure resistance is used to express the rectifier load [19-21]. But the operation modes of WCS rectifier load will affect the working states of compensation network [22]. So, actual equivalent input impedance of WCS rectifier load should be considered, while designing the compensation networks.

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Load estimation of WCS has faced the same problem. Effects of the rectifier load could complicate the equations used for load estimation [23], and lead to the increasing of calculation and control complexity. Hence, a pure resistance load is approximately used for most of the load estimation, detection, or optimal load tracking [24-26]. Another situation is that the voltages and currents are usually both measured for load estimation, in order to calculate the impedances in the primary side [24,27]. Since the voltage and current sensors or probes have different phase delays at the high frequency range, some deviations may be introduced into the estimation process. Also, the robustness of the estimation method is very important.

It can be analyzed through parameter derivation, root locus, Nyquist curve, Bode graph, or directly calculating the results on conditions of parameter variations [28-30].

Based on the previous researches, an effective method to quantitatively analyze the equivalent load of WCS rectifier is put forward in the paper firstly. The equivalent load can be independently calculated through the parameters of the rectifier circuit, and the results are basically not affected by other WCS parts. Secondly, a compensation network design method is proposed considering the equivalent impedance of the rectifier load, especially the equivalent inductance. This method will further decouple the primary and secondary side design, to achieve four system performance indicators at the same time. Thirdly, the effects of the rectifier non-linear process are taken into count to estimate the system load resistance

## **II.**II. RECTIFIER LOAD ANALYSIS AND CALCULATION

Full-bridge diode rectifier is the most commonly used topology in EV wireless charging system. Also, dual-side *LCC* compensation networks can provide several appropriate design degrees of freedom to achieve several system performance indicators at the same time. Moreover, it can be designed to make the system resonant frequency independent of the load condition [16,22]. So we discuss the rectifier load on the basis of this kind of topology.

Avoid too large current peaks in the diodes. Hence, only CCM states are shown in Fig.2, and discussed in this paper. Besides, the steady state waveforms of $u_{rec}$ and $i_{rec}$ are presented in Fig.2, when only a few fluctuations exist on the voltage of the output capacitor $C_o$ and the voltage drop on $R_{Co}$ is very small. So, $u_{rec}$ can be approximately described as a square wave.

Fig.2 suggests that the waveform of rectifier input current $i_{rec}$ has some distortion, because of the effect of the rectifier input inductance. This makes the fundamental wave of $i_{rec}$ lags behind the one of $u_{rec}$. So, the rectifier input impedance does not just include resistance component, but also contains a certain inductance component. Moreover, Fig.2 shows that the positive and negative half-cycles are symmetric for all the voltage and current waveforms. Hence, we just need to consider the positive half-cycle, and the negative half-cycle can be obtained from the symmetry. Fig.3 shows the equivalent circuit of the rectifier circuit in the positive half cycle, considering the stray parameters and the diode forward voltage drop; where, $u_{dio}$ represents the diode forward voltage drop; $R_{dio}$ is diode conduction resistance; $R_{Ls}$ and $R_{Co}$ are stray resistances of $L_s$ and $C_o$, respectively; $u_d$ and $i_d$ are load voltage and current.

Then, the input variables and the initial values of the state variables are given by (2), according to the schematic waveforms in Fig.2; where, $\omega$ is system angle frequency; the diode forward voltage drop is treated as a constant value $V_{dio}$. Since only a few fluctuations exist on the voltage of $C_o$ and the voltage drop on $R_{Co}$ is very small, their influences can be ignored, and the initial value of $x_2$ can be approximately equivalent to a DC voltage variable $V_d$. Also, amplitude of $u_s$ is defined as $V_s$, and it will be affected by WCS parameters, such 0278-0046 (c) .

To sum up, the above analysis suggests that the rectifier load equivalent impedance contains both resistance and inductance components. Also, the series equivalent resistance and inductance can be independently calculated through parameters of rectifier circuit, and the results are basically not affected by other WCS parameters. So, the rectifier load can be decoupled with other parts of WCS, and make system design easier.

III. COMPENSATION NETWORK DESIGN Since the rectifier load has been decoupled with other parts of WCS, we are going to propose a compensation network design method, based on the rectifier load analysis and some existing researches [16-18]. Moreover, the proposed method will further decouple the primary and secondary side design, and make the WCS compensation network design simpler. As same as the rectifier load analysis, the dual-side *LCC* compensation networks are used here. The rectifier input inductance $L_s$ should be big enough to keep the rectifier working in CCM state as mentioned above, so we will confirm it before the compensation network design. Also, the primary side compensation inductance $L_p$ is assumed to be known, and only the four compensation capacitors are used in the design method in this section.

Because $I_d = V_d / R_L$, another relationship between $V_d$ and $\theta_b$ can be got and given by (6).

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$V_d = V_s (2 \sin \theta_b + \pi \cos \theta_b) / (\pi (\omega L_s / R_L + \pi / 2))$. (6) Based on the two relationships between $V_d$ and $\theta b$, they can be obtained from (4) and (6). The expression of $\theta_b$ is given by (7), and the expression of $V_d$ can also be got according to their relationships. Equation (7) indicates that the phase difference between $u_s$ and *urec* (or *irec*) is mainly decided by *Ls* and *RL*, and approximately independent of other WCS parameters. Since amplitudes of $u_{rec}$ and *irec* are basically proportional to the one of $u_s$ as mentioned above, we can say that the other parts of WCS have little effect on the rectifier circuit, and the rectifier load can be decoupled to analyze its equivalent input impedance. It is should be noticed that the rectifier circuit seems to be equivalent to a pure resistance $R_L$, according to (7). However, this equivalent relationship is only suitable for (7) when calculating the phase angle $\theta_b$, and cannot be used for any other part in the rectifier load analysis.

$\theta_b = \arctan(\omega L_s / R_L)$. (7) After getting $V_d$ and $\theta b$, full response of the rectifier circuit in the positive half cycle can be calculated by (8); where, $\Phi(t)$ is the characteristic matrix of rectifier circuit; the part before the plus sign is used for solving zero-input response, and the other part is used for solving zero-state response. On the basis of (8), time domain expressions of $u_{rec}$ and *irec* can be obtained, according to the symmetry of their waveforms.

$im\,(Z_p\ 1)/\omega + L_p = L_{soft}$. (16) Through simultaneously solving (15) and (16), values of the primary side compensation capacitors $C_{1s}$ and *C1p* can be obtained, which is not affected by the secondary side design process. Also, it should be noticed that sometimes there is no analytical solution for these equations. Numerical solution methods need to be used on this condition.

Finally, the primary and secondary side compensation networks have been decoupled for design. Also, four compensation capacitors with four degrees of freedom are designed by considering four system performance indicators, including achieving maximum efficiency, optimal load resistance, making WCS output rated power, and realizing the soft switching of the inverter. Besides, calculated values of the designed compensation capacitors require fine tuning in practice to get better results.

## III. SYSTEM DESCRIPTION

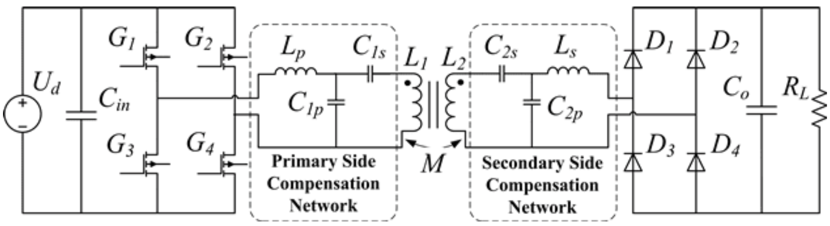


Fig. 1. EV wireless charging system with full-bridge diode rectifier and dual-side *LCC* compensation networks.

Fig.1 shows the EV wireless charging system with full-bridge diode rectifier and dual-side *LCC* compensation networks; where, $U_d$is DC voltage source; the high frequency inverter is composed of $G_1$-$G_4$, and the full-bridge rectifier is composed of $D_1$-$D_4$; the primary side compensation network consists of $L_p$, $C_{1s}$, and $C_{1p}$; the secondary side compensation network consists of $L_s$, $C_{2s}$, and $C_{2p}$; $L_1$and $L_2$are self-inductances of the transmit coil and receive coil; $M$ is mutual-inductance between them; $C_{in}$and $C_o$are system input and output filter capacitors; $R_L$is system load resistor. It should be noticed that the WCS load is an EV power battery in the practical case, which behaves as a voltage source series with its parasitic resistance. But the power battery could be equivalent to a load resistance $R_L$[1,19]; the value of this equivalent resistance can be calculated by the voltage on the power battery divided by the current flowing through it. Moreover, the full-bridge rectifier, its input inductor, output filter capacitor, and the load resistor are together defined as the rectifier circuit. Although the following analysis is conducted based on the specific system, it can be extended to applications on other rectifier and compensation network topologies, avoid too large current peaks in the diodes. Hence, only CCM states are shown in Fig.2, and discussed in this paper. Besides, the steady state waveforms of $u_{rec}$and $i_{rec}$are presented in Fig.2, when only a few fluctuations exist on the voltage of the output capacitor $C_o$and the voltage drop on $R_{Co}$is very small. So, $u_{rec}$can be approximately described as a square wave.

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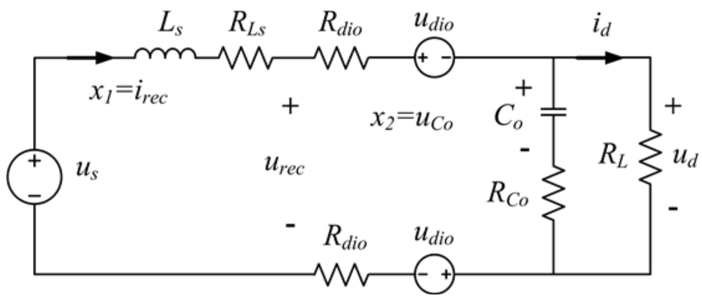
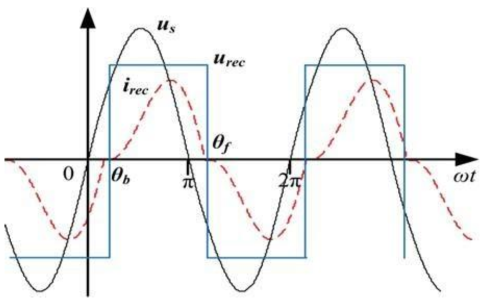



Fig. 3. Equivalent circuit of the rectifier circuit in the positive half cycle.

Based on the equivalent circuit, $i_{rec}$is defined as state variable $x_1$, and the voltage on $C_o$is defined as state variable $x_2$. $u_s$and $u_{dio}$are treated as the input variables, and $u_d$is treated as the output variable. So, state space equation of the rectifier circuit in the positive half cycle is given by (1a).



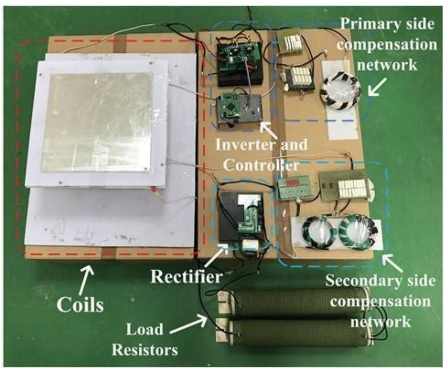




Fig. 7. Photograph of the developed EV wireless charging prototype.

The prototype is designed with rated output power 3.3 kW on the input DC voltage 400 V. System operation frequency is 85 kHz. Load resistance $R_L$is 42.9 Ω, which is selected according to an EV power battery with about 325 V - 340 V open-circuit voltage and 8 A charging current. System impedance parameter values are measured by a LCR meter, and the results are given as follows. Self-inductances values of the transmit coil and receive coil are 232.9 uH and 219.7 uH. Mutual-inductance value is 25.4 uH, when the receive coil is aligned with the transmit coil.

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Compensation inductors $L_p$ and $L_s$ are selected to be 79.9 uH and 83.3 uH. Based on the design method in Section III, the compensation capacitors can be obtained as follows: $C_{1s}$=19.7 nF, $C_{1p}$=82.8 nF, $C_{2s}$=23.6 nF, $C_{2p}$=69.6 nF. The

above parameter values are defined as the standard parameter values, which can make the system achieve good performances, such as rated output power, high efficiency, inverter soft switching, etc. In the following sections, some of these parameters will be changed to different values for further verifications and discussions.

The type of MOSFET is IPW65R037C6. Also, the values of $V_{dio}$ and $R_{dio}$ will vary with the junction temperature $T_j$ (in degrees Celsius), as shown in the datasheet of the diode C3D16060D, which is used in the developed prototype. So, their values can be obtained from the measured temperature by a thermal imager and the following equations in the datasheet: $V_{dio}$= 0.93+((-9.3×$10^{-4}$)×$T_j$); $R_{dio}$= 0.058+((5.7×$10^{-4}$)×$T_j$).

## IV.CONCLUSION

This paper presents a systematic analysis of the rectifier load used for EV wireless charging system. The rectifier load model has been established to calculate its equivalent input impedance, which contains both resistance and inductance components,and can be independently calculated through the parameters ofthe rectifier circuit. Based on the rectifier load analysis, a compensation network design method is proposed to achieve the decoupling design of the primary and secondary side compensation capacitors. Furthermore, a secondary side load estimation method and a primary side load estimation method are put forward, considering the influence of the rectifier load. They adopt only measured voltages to avoid the deviations introduced by different phase delays between measured voltage and current. Finally, the established model, the proposed rectifier load calculation method, compensation network design method, secondary and primary side load estimation methods have been verified, based on the developed EV wireless charging prototype. The experimental results have shown the following conclusions: the equivalent input impedance of rectifier load is mainly affected by system load resistance and rectifier input inductance; rectifier load equivalent inductance will impact system performances, and should be considered for compensation network design; the proposed load estimation methods have good accuracy, but still need to be improved in further research; the proposed rectifier load calculation method and system load estimation methods all have good robustness, on conditions of WCS parameter variations. Although the works in this paper are conducted based on the specific system, they can be extended to more applications, such as wireless charging systems with other rectifier or compensation network topologies etc. They will be helpful for system design and control to make EV wireless charging systems achieve stable operation and high performance.

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