Output power stabilization control strategy of WPT systems based on secondary side circuit

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Abstract. In the wireless power transfer (WPT) system, the output power is sensitive to the change of mutual inductance and load resistance. It is necessary to keep the output power stable quickly through effective control methods when the receiving coil and transmitting coil are offset or the load equivalent impedance changes. Based on the analysis of the WPT system with DC/DC converter on the secondary side, the relationship between mutual inductance and load voltage and load current, as well as the relationship between duty cycle of DC/DC converter and load demand power are given. A mutual inductance identification method based on load voltage and load current detection is proposed to monitor mutual inductance changes in real time. The output power stability control strategy based on DC/DC converter is also proposed. Finally, the effectiveness and correctness of the theoretical analysis and control strategy in this paper were verified by simulation and experiment.

1. Introduction

WPT technology has been applied in portable electronic devices, smart homes, inspection robots and electric vehicles [1-4]. The coupling coefficient and load impedance in WPT system are uncertain and may change in application. These two parameters have significant influence on the output power. For example, the receiving coil and transmitting coil of the electric vehicles static wireless charging system cannot be aligned every time. When the offset between transmitting coil and receiving coil is large, the deviation between output power and charging power demand will also be big. More seriously, the mutual inductance of electric vehicles will always change during dynamic wireless charging, and the output power will fluctuate greatly. What's more, the mutual inductance of the dynamic wireless charging system of electric vehicles will always change. Therefore, the output power will fluctuate greatly in this case. In addition, the equivalent impedance of the battery will also change during the charging process. It also leads to changes in the output power, which will have a greater impact on the battery life. Therefore, it is necessary to put forward effective control methods to ensure stable output power of the WPT system [5-8].

At present, there are many methods to achieve stable output power. For example, optimization of magnetic coupling mechanism, voltage control of power supply, adoption of multi-receiver coil, etc. [9-12]. In [13], a control strategy regarding two source voltages is investigated in order to minimize output power fluctuation. Ref. [14] presents the methods to improve output stability over large
misalignment from the perspective of compensation topology and magnetic coupler. Ref. [15] presents a detailed deduction process to acquire the optimal coupling coefficient, tuned at which the system can achieve minimum output voltage fluctuation. Based on the analysis of the WPT system with DC/DC converter on the secondary side, an output power stability control strategy based on the detection of the current and voltage on the secondary side is proposed. The stable output power can be obtained by this control method. Another advantage of this implementation is that the power regulation is performed on the receiving side so that the control does not rely on wireless communication links. In other words, the response speed is fast.

2. Circuit Analysis

The WPT system containing DC/DC converter on the secondary side is shown in Figure 1. S-S compensation topology is adopted, and the buck-boost circuit is used in the DC/DC converter. The full bridge rectifier filter circuit as shown in Figure 1 is often used in the WPT system. The equivalent impedance \( Z_{eq} \) is shown in Equation (1).

\[
Z_{eq} = \frac{8}{\pi^2} R_c \left( \frac{1}{\alpha} - 1 \right)^2
\]

According to the mutual inductance theory, the current \( I_t \) of the receiving coil can be obtained as

\[
I_t = \frac{j \omega M U_m}{R_t + \omega^2 M^2 / \left( R_t + Z_{eq} \right)}
\]

Set \( \gamma = \frac{2\sqrt{2}}{\pi} \left( \frac{1}{\alpha} - 1 \right) \), then the load voltage \( U_L \) and load current \( I_L \) are respectively

\[
U_L = \frac{\gamma \omega M U_m R_t}{R_t (R_t + \gamma^2 R_t) + \omega^2 M^2}
\]

\[
I_L = \frac{\gamma \omega M U_m}{R_t (R_t + \gamma^2 R_t) + \omega^2 M^2}
\]

If \( \beta = R_t / \omega^2 M^2 \), the load power can be expressed as

\[
P_L = \frac{U_{in}^2}{\gamma^2 \beta R_t R_t / R_t + R_t R_t (1 / \beta + 2) / \gamma^2 R_t + 2 R_t (1 + \beta)}
\]

Therefore, \( P_L \) can get the maximum value when \( \gamma^2 \beta R_t R_t / R_t = R_t R_t (1 / \beta + 2) / \gamma^2 R_t \). The maximum power \( P_{max} \) and the corresponding optimal load \( R_{Lo} \) are respectively.
\[ P_{\text{max}} = \frac{U_{\text{in}}^2}{4R_{\text{in}}(1+\beta)} \]  \hspace{1cm} (7)
\[ R_{\text{Lo}} = \frac{R_{\text{in}}(1+1/\beta)}{\gamma^2} \]  \hspace{1cm} (8)

(a) The curve of output power relative to load resistance.  \hspace{1cm} (b) The curve of output power relative to mutual inductance.

**Figure 2.** The curve of output power.

According to Equation (7), the maximum output power \( P_{\text{max}} < U_{\text{in}}^2 / 4R_{\text{in}} \) since \( \beta \) is greater than 0. Keep the value of \( \alpha \) unchanged, the characteristic curve of output power with respect to load resistance can be drawn if \( M_1 < M_2 \), and the characteristic curve of output power with respect to mutual inductance can be drawn if \( R_{\text{Lo,1}} < R_{\text{Lo,2}} \), as shown in Figure 2.

According to Equation (8), the requirement of \( \alpha_{\text{in}} \) which can make the system operate at the maximum power can be met

\[ \alpha_{\text{in}} = \frac{1}{\pi \sqrt{R_{\text{in}}(1+1/\beta)/8R_{\text{in}} + 1}} \]  \hspace{1cm} (9)

The maximum output power can be kept unchanged theoretically by adjusting the value of \( \alpha \) after the change of load impedance. When the mutual inductance increases, the output power theoretically increases by a smaller range by adjusting the value of \( \alpha \), as shown in Figure 3.

**Figure 3.** Three-dimensional diagram of output power with load resistance and mutual inductance.

3. **Proposed output power stabilization method**

At present, the research on power stability control strategy of wireless charging system is mainly regulated under the condition of real-time and reliable communication between the primary and secondary sides, but its response speed is slow. The power stability control method proposed in this paper is only regulated on the secondary side and does not require real-time communication between the primary and secondary sides. The system can output relatively stable power even if the receiving coil position is offset. The power stability control method is very suitable for the application of wide offset range.

The power supply voltage \( U_{\text{in}} \), transmitting coil internal resistance \( R_{\text{t}} \), receiving coil internal resistance \( R_{\text{r}} \), system operating frequency \( f_0 \), load demand power \( P_d \), initial values of duty cycle \( \alpha \) are given. Suppose the total efficiency of rectifying filter circuit and DC/DC converter is \( \eta_0 \), then \( P_L = P_d / \eta_0 \). According to the load current \( I_L \) and load voltage \( U_L \) detected in real time, the value of real-time
mutual inductance $M$ and the duty cycle $\alpha$ in response to load power demand can be obtained from Equation (4) - (6), which are respectively

\begin{equation}
M_{1,2} = \frac{\gamma U_m \pm \sqrt{\gamma^2(U_m^2-\pi^2 I_r^2 R R_t/2) - 4I_r^2 R R_t}}{2\omega I_r}
\end{equation}

(10)

\begin{equation}
\alpha_{1,2} = \frac{1}{\pi} \left( \frac{\eta U_m^2}{P_0} - 2R(1+\beta) \pm \sqrt{\left(\frac{\eta U_m^2}{P_0} - 2R(1+\beta)\right)^2 - 4\frac{U_m^2}{P_0} R R_t} \right)
\end{equation}

(11)

From Equation (10), it can be seen that theoretically each value of $\alpha$ has two mutual inductance corresponding to it, but actually only one is correct. In order to identify the mutual inductance of the WPT system, this paper presents a mutual inductance identification method based on load voltage and load current detection. According to Equation (11), theoretically each $P_d$ has two $\alpha$ values corresponding to it, and the better one should be selected as the output of the control.

There are four situations when control is not added to the system. For the case in the region (1), it is necessary to increase the equivalent impedance by controlling the DC/DC converter so that the load power increases to the required power. In the case of region (2), the equivalent impedance needs to be reduced or increased to reduce the load power to the required power. For the situation in the region (3), it is necessary to increase or decrease the equivalent impedance to reduce the load power to the required power. For the region in the case of (4), need to reduce the equivalent impedance so that the load power increased to the demand power. To achieve the above control, the specific process is as follows:

Step 1. The values of $U_m$, $R$, $R$, $f_0$, $P_d$ were determined, and the initial value of $\alpha(t)$ was set as $\alpha_0=0.5$.

Step 2. Collect the values of $U_1(t)$ and $I_1(t)$ corresponding to $\alpha(t)$. According to Equation (10), two mutual-inductance values corresponding to $\alpha(t)$, $M_{11}$ and $M_{21}$, are calculated.

Step 3. Set the $\alpha(t+1)$ type of $\alpha(t+1) = \alpha(t) + \Delta \alpha$ and outputs the value by changing. $U_1(t+1)$ and $I_1(t+1)$ were collected, and the two mutual-inductance values($M_{12}$ and $M_{22}$) corresponding to $\alpha(t+1)$ were calculated according to Equation (10).

Step 4. Judge whether the $M_{11}$ and $M_{12}$ calculated by Step 2 and Step 3 satisfy $|M_{11} - M_{12}| / M_{11} \leq 0.5$ ($\delta$ is a small value). If so, it is considered that $M = (M_{11} + M_{12}) / 2$. If not, it is considered that $M = (M_{21} + M_{22}) / 2$.

Step 5: According to the mutual inductance value $M$ obtained by Step 4, the values of two duty cycle $\alpha_1(t+2)$ and $\alpha_2(t+2)$ were calculated by Equation (11).

Step 6: Judgment of $\alpha_1(t+2)$ and $\alpha_2(t+2)$ whether meet $|\alpha_1(t+2) - \alpha(t+1)| \leq |\alpha_2(t+2) - \alpha(t+1)|$. If so, let $\alpha(t+2) = \alpha_1(t+2)$ and output to the controller. If not, let $\alpha(t+2) = \alpha_2(t+2)$ and output to the controller. At the same time, the value of the $\alpha(t+2)$ is transferred to Step 2 for calculation and power stability control at the next moment.
Figure 4. Flow chart of power stability control method

4. Experiment Results
In order to prove the feasibility of the proposed control strategy, an experimental platform of WPT system with DC/DC converter on the secondary side was designed, as shown in Figure 5.

Figure 5. Experimental platform for WPT system.

The input voltage is 30V DC and remains unchanged. The operating frequency of the system is 85 kHz. The vertical distance between transmitting coil and receiving coil is 6cm, and the size is 24cm*33cm. The parameters of the transmitting coil and receiving coil and the corresponding compensation capacitance are tested, as shown in Table 1. The secondary side is first converted to DC through the full bridge rectifier circuit, and then the load is connected after passing through the buck-boost circuit.

Table 1. Parameters of the coils and compensation capacitor

| Parameter | $L_t$(μH) | $R_t$(mΩ) | $C_t$(nF) | $L_r$(μH) | $R_r$(mΩ) | $C_r$(nF) |
|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| Value     | 40.4      | 35.1      | 87.7      | 40.1      | 39.2      | 87.1      |

When the load resistance is 5 Ω, assuming the total efficiency $\eta_d$ of the rectifier filter circuit and the DC/DC converter is 0.9. Test the variation trend of load power when the longitudinal offset (Y direction) occurs between the receiving coil and the transmitting coil. When the longitudinal offset is -12.5 cm, -10 cm, -7.5 cm, -5 cm, -2.5 cm, 0 cm, 2.5 cm, 5 cm, 7.5 cm, 10 cm, 12.5 cm, respectively, the simulation value and the experimental value curve of load power can be obtained, as shown in Figure 6.

Figure 6. Output power curves at different offsets between the receiving coil and the transmitting coil.

As can be seen from Figure 6, when the longitudinal deviation rate of the receiving coil and transmitting coil is from 0 to more than 50%, the receiving power of the load will fluctuate greatly when there is no control over the DC/DC converter. When the power stability control strategy based on DC/DC converter proposed in this paper is adopted, the received power of the load fluctuates from the minimum 197.4 W to the maximum 210.3 W. The fluctuation rate of ±5% proves the effectiveness of the proposed control strategy.

The equivalent impedance will change during charging for the battery load. It is necessary to verify whether the load with different resistance values can guarantee the power stability under the control strategy proposed in this paper. Keep no deviation between the receiving coil and the transmitting coil.
and test the variation trend of the load power when the load changes. When the load resistance from 1 Ω to 10 Ω changes, the curve of load power as shown in Figure 7.

![Figure 7. Output power curves at different resistance values.](image)

The output power increases linearly with the load resistance when there is no control over the DC/DC converter as can be seen from Figure 7. When the power stability control strategy proposed in this paper is adopted, the minimum and maximum values of the output power are respectively 195.9 W and 200.6 W. The small variation range of output power proves that the proposed control strategy has a strong power stability effect for the load whose equivalent impedance will change.

5. Conclusions

This paper analyzes the WPT system with DC/DC converter. The relationship between mutual inductance and load voltage and load current is deduced. The relation between duty cycle of DC/DC converter and load demand power is given. The output power stabilization control strategy of adjusting duty cycle of DC/DC converter by detecting load voltage and load current is proposed. Finally, the stability of the output power after the deviation of the receiving coil and transmitting coil and the change of the load resistance value under the control strategy proposed in this paper is analyzed through simulation and experiments. And the results verify the correctness and effectiveness of the theoretical analysis and control strategy in this paper.

6. References

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