Power Stability Control Strategy of the WPT System Based on Load Detection

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Abstract. The output power fluctuates when offset occurs between the receiving coil and the transmitting coil or load equivalent impedance changes in a wireless power transfer system (WPT). These two conditions will affect the safety of the system and the life of the battery load. Therefore, effective control methods are needed to ensure the stability of the load power. This paper analyzes the WPT system with LCC/S compensation topology and the secondary side containing DC/DC circuit. The relationship between mutual inductance and load voltage and current, mutual inductance and the system transmission efficiency, DC/DC circuit duty ratio and load voltage and current are deduced. The output power stability control strategy through load voltage and load current detection and control of DC/DC circuit is proposed. Finally, the WPT system with 1 kW output power is built through simulation and experiment, which verifies the effectiveness and correctness of theoretical analysis and control strategy in this paper.

1. Introduction
The WPT technology has been applied in implantable bioelectronics, portable electronic devices, unmanned aerial vehicles, electric vehicles and inspection robots in recent years [1-3]. The coupling coefficient and load impedance of WPT system are not fixed and may change during power supply, and these two parameters have a great influence on the output power. For example, when an electric vehicle drives to a wireless charge parking space, it cannot park in exactly the same place each time. There will be a certain deviation between the output power and the demand power if no measures are taken. This problem is more obvious in the application of dynamic wireless charging of electric vehicles. The output power fluctuates with the change of electric vehicle position in the process of dynamic wireless charging [4-5]. This situation may lead to the battery has been in charge and discharge switch state, which will have a greater impact on the battery life. In addition, the equivalent impedance of the battery load will also change during the charging process, which also can cause the output power fluctuation. Therefore, an effective output power stability control method needs to be proposed when there is deviation between the receiving coil and the transmitting coil or load equivalent impedance change.

There are many methods have been used to achieve the goal of stable output power. For example, the magnetic coupling mechanism is optimized to achieve more uniform distribution of magnetic field, the power source voltage is adjusted through primary and secondary real-time communication, and multiple transmitting coils are used for coordinated control to achieve stable output power [6-9]. An integrated control method of load estimation and power tracking is proposed in [10] to achieve constant power charging. In [11], a control strategy regarding two source voltages is investigated in
order to minimize output power fluctuation. [12] presents a detailed deduction process to acquire the optimal coupling coefficient, tuned at which the system can achieve minimum output voltage fluctuation. The authors of [13] proposed the three-coil structure WPT system to achieve stable CC and CV charging output characteristics for battery charging applications.

The paper is arranged as follows. Section 2 analysis the WPT system based on the compensation topology of LCC/S and the secondary side containing the DC/DC circuit. Section 3 proposes a power stability control strategy for load current and voltage detection. In section 4, the control strategy is verified by simulation and experiment. Finally, section 5 draws conclusions from the research.

2. Circuit analysis

![Figure 1. The WPT system with LCC/S compensation topology and secondary side containing DC/DC circuit.](image)

The WPT system based on the compensation topology of LCC/S and the secondary side containing the DC/DC circuit is shown in figure 1. The compensation topology of the primary side is LCC structure, and the capacitor of the secondary side forms a series compensation structure with the receiving coil. After the compensation topology of the secondary side is the rectifying circuit, and then supplies power to the load through the cascade DC/DC circuit. In this paper, Buck-Boost circuit is adopted for DC/DC circuit, and the equivalent impedance $Z_{eq}$ of rectifier filter circuit and Buck-Boost circuit is:

$$Z_{eq} = 8\pi^2 R_t (\alpha^{-1} - 1)^2$$

(1)

where $R_t$ is the load impedance, $\alpha$ is the duty ratio of the Buck-Boost circuit. In figure 1, $L_a$ and $L_t$ are the inductance of transmitting coil and receiving coil respectively. $R_t$ and $R_r$ are the internal resistance of transmitting coil and receiving coil, respectively. $C_t$ is connected in series with $L_t$, $C_1$ is in parallel with the series circuit of $L_t$ and $C_t$, and $L_1$ is in series with this circuit to form the LCC compensation topology. $C_r$ and $L_r$ are connected in series to form S compensation topology.

To ensure that the input impedance of the system is pure impedance, the configuration of parameters should be satisfied the relation 

$$\frac{L_a}{C_1} = \frac{L_t}{C_t}$$

(2)

in the resonance state. Then the input impedance $Z_{in}$ in figure 1 can be derived.

$$Z_{in} = \frac{\alpha^2 L_t^2 (Z_{eq} + R_t)^{-1}}{1 - \frac{j\omega L_t}{\omega C_t}}$$

(3)

From the input impedance, the input current $I_{in}$ is

$$I_{in} = U_{in} \left( Z_{eq} + R_t \right) \left( \frac{\alpha^2 L_t^2}{1 - \frac{j\omega L_t}{\omega C_t}} \right)^{-1}$$

(4)

Then, the current $I_t$ of the transmitter coil can be deduced to be

$$I_t = U_{in} \left( \frac{j\omega L_t}{\omega C_t} \right)^{-1}$$

(5)

The voltage $U_d$ in figure 1 can be obtained from $I_t$.

$$U_d = M U_{in} \left( \frac{L_t (R_t Z_{eq}^{-1} + 1)}{1 - \frac{j\omega L_t}{\omega C_t}} \right)^{-1}$$

(6)
Ignoring the internal resistance of the power source, the system transmission efficiency formula can be obtained as follows:

$$\eta = \left( \frac{R_R}{R_R + R_z} \right)^{-1} + R_z^{-1} \left( \frac{R_R}{R_R + R_z} \right)^{-1} + 2R_R \left( \frac{R_R}{R_R + R_z} \right)^{-1} + 1$$  \hspace{1cm} (6)

On the contrary, the expression of mutual inductance can be obtained from equation (6).

$$M = \sqrt{R^2_R + R_z^2} + 2R_R Z_{eq} \left( \frac{R_z \eta - R_z^2}{R_z \eta - R_z^2} \right)^{-1} \hspace{1cm} (7)$$

The relation curves of load equivalent resistance and system efficiency, mutual inductance and efficiency is drawn by equation (6), as shown in figure 2 and figure 3. The transmission efficiency increases first and then decreases with the increase of equivalent load. The greater the mutual inductance, the higher the transmission efficiency. And the higher the equivalent impedance is, the faster the transmission efficiency increases with mutual inductance.

When equivalent impedance meets $Z_{eq} = \sqrt{R^2 + \omega^2 M^2 R^{-1}}$ and mutual inductance is constant, the maximum value of transmission efficiency $\eta_m$ can be calculated.

$$\eta_m = \frac{\omega^2 M^2}{2R_R (\sqrt{R^2 + \omega^2 M^2 R^{-1}} + R_R) \omega^2 M^2} \hspace{1cm} (8)$$

When $R_R = Z_{eq}$, equation (5) can be simplified as:

$$U_d = M U_{in} \frac{\omega^2 M^2}{\pi} \hspace{1cm} (9)$$

Therefore, the WPT system under LCC/S compensation topology has constant voltage output characteristics. When the filter circuit is composed of capacitors as shown in figure 1, the relationship between output voltage and input voltage is $U_{dc} = \frac{\pi}{4} U_d \hspace{1cm} (U_d$ is the amplitude in equation (9)). Then, the expression of output voltage $U_{dc}$ can be deduced as:

$$U_{dc} = \pi MU_{in} \left( \sqrt{8} L_i \right)^{-1} \hspace{1cm} (10)$$

where $U_{in}$ is the effective value of high-frequency sine voltage in figure 1. Finally, the expression of the output voltage $U_L$ to the load is obtained.

$$U_L = \pi \alpha MU_{in} \left( \sqrt{8}(1-\alpha) L_i \right)^{-1} \hspace{1cm} (11)$$

From equation (11), we can get the expression of mutual inductance as:

$$M = \sqrt{8}(1-\alpha)L_i U_L \left( \pi \alpha U_{in} \right)^{-1} \hspace{1cm} (12)$$

Therefore, real-time mutual inductance values can be obtained from the values of input voltage, real-time load voltage and duty cycle. From equation (11), the output power can also be expressed as:
With the duty ratio $\alpha$ unchanged, the relation curve between output power and mutual inductance and load resistance is drawn by equation (13), as shown in figure 4. The output power decreases with the increase of load resistance and increases with the increase of mutual inductance. The output power fluctuates when the load equivalent impedance changes or the receiver coil is offset from the transmitter coil. For the battery load, the battery life will be reduced when the charging power fluctuates greatly.

**Figure 4.** Curve of output power with mutual inductance and load resistance.

The relationship between duty ratio $\alpha$ and demand power $P_d$ can be expressed as:

$$\alpha = \left( \frac{\pi^2 \alpha^2 M^2 U_{in}^2}{8(1-\alpha^2) L_s^2 R_L} \right)^{-1} + 1^{-1}$$

(14)

The load equivalent impedance can be obtained from the load voltage $U_{L-S}$ and current $I_{L-S}$ obtained by real-time sampling. Set the overall efficiency of DC/DC circuit and rectifier circuit is $\eta_d$. Considering $\eta_d$ and $\eta$, the equation (14) can be expressed as:

$$\alpha = \left( \frac{\pi^2 M U_{in}}{8 P_d L_s^2 / (\eta_d \eta I_{L-S})} \right)^{-1} + 1^{-1}$$

(15)

The output power of the system can be theoretically consistent with the load demand power by adjusting the value of $\alpha$ when the load resistance or mutual inductance changes, as shown in figure 5.

**Figure 5.** 3D diagram of output power with load resistance and mutual inductance.

3. **Power stability control strategy**

In this paper, the power stability control method only regulates in the secondary side and does not require real-time communication between the primary side and the secondary side. The goal of power
stability can be achieved by detecting the load voltage and current and then controlling the DC/DC circuit. The system can output relatively stable power even if the coil position has a large deviation. So the power stability control method is very suitable for applications with a wide deviation range.

It is assumed that the power source voltage $U_{in}$, the internal resistance $R_i$ of transmitting coil, the internal resistance $R_s$ of receiving coil, system working frequency $f_o$, the load demand power $P_d$, and the initial value of duty ratio $\alpha$ of DC/DC circuit are known. According to the load voltage $U_{L-S}$ and current $I_{L-S}$ detected in real time, the real-time mutual inductance value and the duty ratio of response load power demand can be obtained by equation (15). Therefore, this paper proposes a power stability control strategy by adjusting the duty ratio of DC/DC circuit based on load voltage and current monitoring. The control flow chart is shown in figure 6, and the specific process is as follows:

- **Step 1.** The value of $U_{in}$, $L_i$, $R_s$, $R_r$, $\eta_d$, $f_o$, $P_d$, initial duty ratio $\alpha(t)$ were determined, and stored to the controller.
- **Step 2.** Initialize the relevant constraints, including the minimum charge voltage $U_{L-min}$ and the maximum charging voltage $U_{L-max}$, adjustment range of duty ratio $(\alpha_{min} \leq \alpha \leq \alpha_{max})$, and the minimum transmission efficiency $\eta_{min}$.
- **Step 3.** According to equations (7) and (12), the maximum and minimum values of mutual inductance $M_{max}$ and $M_{min}$ can be obtained. These are the constraint conditions whether the proposed control strategy can be implemented or not.
- **Step 4.** Real-time voltage value $U_{L-S}$ and current value $I_{L-S}$ of the load were collected, and real-time mutual inductance value was obtained according to equation (12).
- **Step 5.** Determine whether the mutual inductance value calculated by Step 4 satisfies the relation of $M_{min} \leq M \leq M_{max}$. If meet constraint conditions, according to the equation (6) to get the transmission efficiency of the $\eta(t)$. If not, it indicates that stable power control cannot be achieved at this time, and the user is informed to turn off the system to stop charging.
- **Step 6.** According to the transmission efficiency $\eta(t)$ from step 5, the adjustment value of duty cycle $\alpha(t+1)$ can be obtained from equation (15).
- **Step 7.** Set $\alpha(t) = \alpha(t+1)$ according to the duty cycle adjustment value obtained by Step 6, and then output the value to switch $S_i$ of DC/DC circuit. Meanwhile, go to Step 4 to conduct the control process at the next moment.

![Figure 6. Flow chart of power stability control method.](image-url)
4. Experimental and simulation analysis

In order to prove the feasibility of the proposed control strategy, this paper designs an experimental platform of WPT system based on the compensation topology of LCC/S and the secondary side contains DC/DC circuit according to the system architecture in figure 1, as shown in figure 7.

Set the input voltage $U_{\text{in}} = 200V$, and the load demand power $P_d$ is 1 kW. The input of the experimental platform is a DC voltage source, which is converted into a high-frequency square wave through the full-bridge inverter circuit. Since the input voltage $U_{\text{in}}$ is sinusoidal wave, the voltage $U_{\text{DC}}$ of the DC source should satisfy the equation of $U_{\text{DC}} = \pi U_{\text{in}} (2\sqrt{2})^{-1}$ if the square wave is equivalent to it, so the DC source voltage $U_{\text{DC}} = 222V$. The full-bridge inverter circuit is composed of four SiC devices of IXFN70N120SK, and its working frequency is 85 kHz. The full-bridge rectifier circuit is composed of quick recovery diodes of DSEI2X101-12A and the Buck-Boost switch are IRFP460.

Figure 7. Experimental platform of WPT system.

The vertical distance between transmitter coil and receiver coil is 15 cm, and its dimensions are 46cm*46cm and 36cm*36cm respectively. The parameters of coils and the components in the LCC/S compensation topology are shown in table 1.

| Parameter | $L_1$(μH) | $C_1$(nF) | $L_t$(μH) | $R_t$(Ω) | $C_t$(nF) | $L_r$(μH) | $R_r$(Ω) | $C_r$(nF) |
|-----------|------------|------------|------------|-----------|------------|------------|-----------|------------|
| Value     | 28         | 125.2      | 224.6      | 0.475     | 17.83      | 129.6      | 0.23      | 27.05      |

In order to prove that the proposed control strategy can effectively solve the problem of unstable power of the coil in the case of offset, it is necessary to test the changing trend of output power when the receiving coil and transmitting coil are offset longitudinally. When the load resistance is 10 Ω, set $\eta_d = 0.97$. Through the method of simulation and experiment, output power data with longitudinal offset from -16 cm to 16 cm were recorded, and the curve was drawn as shown in figure 8.

Figure 8. Curve of output power and offset position.
As can be seen from figure 8, the output power fluctuates greatly without DC/DC circuit when the longitudinal offset is from -16 cm to 16 cm. When the power stability control strategy proposed in this paper is adopted, the minimum value and maximum value of the output power are 986 W and 1011 W respectively. The fluctuation rate is about ±2%, which proves the effectiveness of the proposed control strategy.

The equivalent impedance will change during the charging process for battery loads. It is necessary to verify whether the load with different resistance values can guarantee the stability of output power under the control strategy proposed in this paper. Keep the receiving coil and transmitting coil without deviation, record the output power data corresponding simulation and experiment when the load resistance from 4 Ω to 20 Ω changes, drawn into a curve as shown in figure 9.

![Curve of output power and load resistance.](image)

The figure 9 shows that output power fluctuation is very big if there is no DC/DC circuit in the system when the load resistance changes, and the value of output power is very high when the load resistance value is less than 8 Ω, so the black curve in figure 9 shows only the load resistance is greater than 8 Ω corresponding output power values. The minimum value and maximum value of the output power are 1005 W and 1031 W respectively when the power stability control strategy proposed in this paper is adopted. The small variation range proves that the proposed control strategy has strong power stabilization effect for the load whose equivalent impedance will change.

5. Conclusions

This paper analyzes the WPT system with LCC/S compensation topology and the secondary side containing DC/DC circuit. The relationship between mutual inductance and load voltage and current, the relationship between mutual inductance and transmission efficiency, and the relationship between DC/DC circuit duty ratio and load voltage and current are deduced. The output power stability control strategy by detecting the load voltage and current and then controlling the DC/DC circuit is proposed. Finally, the WPT system with 1 kW output power is built through simulation and experiment, and the stability of output power after coils deviation and load resistance change under the control strategy proposed in this paper is analyzed. The simulation and experimental results verify the correctness and effectiveness of the theoretical analysis and the proposed control strategy.

Acknowledgments

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References

[1] Mou X, Groling O and Sun H 2017 Energy-efficient and adaptive design for wireless power transfer in electric vehicles *IEEE Transactions on Industrial Electronics* **64** 7250–7260.

[2] Liu H, Huang X, Tan L, Guo J and Wang W 2018 Dynamic wireless charging for inspection robots based on decentralized energy pickup structure *IEEE Transactions on Industrial Informatics* **14** 1786-1797.

[3] Basar M, Ahmad M, Cho J and Ibrahim F 2017 Stable and high efficiency wireless power transfer system for robotic capsule using a modified Helmholtz coil *IEEE Transactions on Industrial Electronics* **64** 1113-1122.

[4] Zhu Q, Wang L, Guo Y and Liao C 2016 Applying LCC compensation network to dynamic wireless EV charging system *IEEE Transactions on Industrial Electronics* **63** 6557-6567.

[5] Li S, Liu Z, Zhao H, Zhu L, Shuai C and Chen Z 2016 Wireless power transfer by electric field resonance and its application in dynamic charging *IEEE Transactions on Industrial Electronics* **63** 6602–6612.

[6] Choi S, Huh J, Lee W and Rim C 2014 Asymmetric coil sets for wireless stationary EV chargers with large lateral tolerance by dominant field analysis *IEEE Transactions on Power Electronics* **29** 6406-6420.

[7] Kan T, Lu F, Nguyen T, Mercier P and Mi C 2018 Integrated coil design for EV wireless charging systems using LCC compensation topology *IEEE Transactions on Power Electronics* **33** 9231-9241.

[8] Tan L, Zhang M and Wang S 2019 The Design and optimization of a wireless power transfer system allowing random access for multiple loads *Energies* **12**.

[9] Liu F, Yang Y, Jiang D, Ruan X and Chen X 2017 Modeling and optimization of magnetically coupled resonant wireless power transfer system with varying spatial scales *IEEE Transactions on Power Electronics* **32** 3240-3250.

[10] Wang A, Liu J and Wang X 2019 The load estimation and power tracking integrated control strategy for dual-sides controlled LCC compensated wireless charging system *IEEE Access* **7** 75749-75761.

[11] Tan L, Guo J and Huang X 2018 Coordinated source control for output power stabilization and efficiency optimization in WPT systems *IEEE Transactions on Power Electronics* **33** 3613-3621.

[12] Yao Y, Wang Y, Liu X, Lu K and Xu D 2018 Analysis and design of an S/SP compensated IPT system to minimize output voltage fluctuation versus coupling coefficient and load variation *IEEE Transactions on Vehicular Technology* **67** 9262-9272.

[13] Yang L, Li X, Liu S, Xu Z, Cai C and Guo P 2019 Analysis and design of three-coil structure WPT system with constant output current and voltage for battery charging applications *IEEE Access* **7** 87334-87344.