Research on efficiency optimization control strategy of WPT system based on optimal load matching

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Abstract. Aiming at the problem that the transmission efficiency of SS-compensated MCR-WPT (Magnetic resonance wireless power transmission) is affected by load changes, this paper uses mutual inductance theory to analyze the equivalent circuit model, obtains the relationship between load and transmission efficiency, and proposes a controllable rectifier bridge for load matching, the front-end cascaded buck converter makes the output voltage regulation control scheme. Finally, modeling and simulation are used to verify the correctness of the load matching theory and control strategy.

1. Introduction

For SS-compensated MCR-WPT, there is an optimal load to maximize the transmission efficiency of the system [1]. In reality, the size of the system load is often different or variable. Generally, it is necessary to modulate the load resistance of the receiving end to improve the transmission efficiency, which is called load impedance matching[2-3].

Literature [4] adds a matching feed coil after the secondary coil to form a new impedance transformation structure. The matching feed coil adjusts its own inherent parameters to match different loads, but the inherent parameter value of the matching feed coil itself requires manual adjustment and cannot dynamically track changes in load. Literature [5] achieves equivalent load matching by adjusting the duty cycle D of the downstream DC-DC converter, and adjusts the output voltage by changing the phase shift angle of the primary side inverter. However, the switching loss caused by the primary inverter during high-frequency operation cannot be ignored. Literature [6] proposed a new impedance transformation method based on pulse density full cycle modulation on the basis of a controllable rectifier bridge structure at the receiving end. However, the matching accuracy of this method is affected by the on-off ratio.

Based on the existing research, this paper analyzes the circuit equivalent model by using mutual inductance theory, obtains the relationship between load and transmission efficiency and the optimal load value corresponding to the maximum transmission efficiency, in addition, proposes a load matching structure based on controllable rectifier bridge. Since there are often requirements for output voltage stabilization in actual situations. In order to reduce the switching loss of the inverter[7], the voltage stabilizing control scheme of front-end cascaded buck converter is adopted. The correctness of load matching theory and control strategy is verified by modeling and simulation.
2. Structure of rectifier bridge load matching system

![Figure 1. Structure of rectifier bridge load matching system.](image)

The overall circuit model of the system is shown in figure 1. In figure 1, Vin is a DC voltage source, Qin is a MOS tube, Din is a diode, Lin, and Cin form a buck converter to adjust the output voltage; the primary side inverter bridge composed of MOS transistors Q1, Q2, Q3 and Q4 transforms DC into AC, v1 and i1 are the output port voltage and current, respectively; Li, Ci and Ri (i = 1,2) are the coil inductance, resonant capacitance and internal resistance of the primary and secondary sides respectively; the electromagnetic energy is exchanged through the primary and secondary coils, and the resonant capacitance is used to compensate reactive power; the diodes VD1, VD2 and MOS transistors Q5 and Q6 form a secondary controllable rectifier bridge, v2 and i2 are input voltage and current; Rc is input equivalent resistance; Co is output filter capacitor and RL is load resistance.

The four tubes of the primary side inverter conduct complementary conduction, and the output voltage of the inverter is mainly adjusted by the buck converter connected in the previous stage. Q5 and Q6 on the controllable rectifier are switched on and off at the same time, and the rectifier bridge output port voltage v2 and current i2 are in phase, as shown in figure 2.

![Figure 2. Secondary side control strategy.](image)

The input impedance of the rectifier bridge can be equivalent to a pure resistance Rc, Rc is a function of the load resistance RL and the pulse width of the controllable rectifier bridge [8].

\[ R_c = \frac{8}{\pi^2} R_L \sin^2 \frac{\beta}{2} \]  

3. System equivalent model and efficiency analysis

Since the system works in resonance \( \omega = \frac{1}{L_1C_1} = \frac{1}{L_2C_2} \), the resonance network has sufficient filtering effect on high-order harmonics. There is almost only the fundamental wave component in the harmonic network. The mutual inductance theory is used to establish the system fundamental wave equivalent circuit model as shown in figure 3.
Among them, the four tubes of the primary inverter conduct complementary conduction, V₁ is the fundamental wave component of the inverter output voltage, V₂ is the fundamental wave component of the rectifier bridge input voltage, and \( R_c \) is the equivalent resistance of the rectifier bridge input. The loop voltage equations at resonance are as shown in equation (2).

\[
\begin{align*}
&\dot{R}_1 I_1 - j\omega M I_2 = V_1 \\
j\omega M I_1 - (R_c + R_2) I_2 = 0
\end{align*}
\]

By solving equation (2), the loop current expression equation (3) can be obtained.

\[
\begin{align*}
I_1 &= \frac{R_2 + R_c}{R_c(R_2 + R_c) + (\omega M)^2} V_1 \approx \frac{R_2 + R_c}{(\omega M)^2} V_1 \\
I_2 &= \frac{j\omega M R_c}{R_c(R_2 + R_c) + (\omega M)^2} V_1 \approx -\frac{1}{j\omega M} V_1
\end{align*}
\]

In the above formula, \( \omega M \gg \max (R_1, R_2) \), the expressions of transmission power and transmission efficiency are further derived as equations 4 and 5, respectively.

\[
P_{\text{co}} = \left( \frac{\omega M U_1}{R_1(R_2 + R_c) + (\omega M)^2} \right)^2 R_c \approx \left( \frac{U_1}{\omega M} \right)^2 R_c
\]

\[
\eta = \frac{(\omega M)^2 R_c}{(R_2 + R_c) \left[ R_c(R_2 + R_c) + (\omega M)^2 \right]}
\]

Differentiate equation 5 to the equivalent resistance, there is a unique extreme point.

\[
R_{c-opt} = \sqrt{\frac{R_2^2 + \frac{R_c^2}{R_1^2} (\omega M)^2}{\frac{R_c}{R_1}}}
\]

Substituting equation 6 into equation 5, the maximum efficiency can be obtained.

\[
\eta_{\text{max}} = \frac{1}{1 + \frac{2R_2 R_c}{(\omega M)^2} + \frac{2R_c^2}{(\omega M)^2} \sqrt{\frac{R_2^2 + \frac{R_c^2}{R_1^2} (\omega M)^2}}}
\]

According to equation (1), \( R_c \) can be modulated to \( R_{c-opt} \) by changing the conduction angle of the rectifier bridge to maximize transmission efficiency.

4. Simulation analysis
Use MATLAB Simlink to simulate and verify this control strategy. The simulation data is shown in Table 1.
| Lin/uH | 20  | Cin/nF | 600 |
|-------|-----|--------|-----|
| L1、L2/uH | 183 | C1、C2/nF | 60 |
| R1、R2/Ω | 0.1 | M12/uH | 40 |
| Co/nF | 600 | f/kHz | 48 |

The output voltage regulation reference value to 40v. According to equation (6), \( R_c - opt = \omega M = 12.057\Omega \) at this time.

Figure 4 is a graph of the rectifier bridge input resistance value \( R_c \) varying with the load RL. The load variation range is between 20~90\( \Omega \), it can be seen that the matching error is within 0.2\( \Omega \), and the matching accuracy is high.

![Figure 4](image)

Figure 4. The rectifier bridge input resistance value \( R_c \) varies with the load RL.

Figure 5 is a graph of the system transmission efficiency \( \eta \) varying with the load RL. The load variation range is between 20 and 90\( \Omega \), \( \eta_1 \) is the transmission efficiency without load matching, and \( \eta_2 \) is the transmission efficiency after load matching. It can be seen that the larger the load RL, the more obvious the efficiency optimization effect.

![Figure 5](image)

Figure 5. System transmission efficiency \( \eta \) varies with load RL.

Figure 6 shows the output voltage waveform when the load resistance is suddenly changed. When \( t=5s \), the resistance value is suddenly reduced from 40\( \Omega \) to 20\( \Omega \), and it only takes 0.01s to stabilize at about 40v, and the output steady-state and dynamic characteristics are excellent.
Figure 6. The output voltage waveform when the load resistance changes suddenly.

5. conclusion
Aiming at the problem that the transmission efficiency of MCR-WPT is affected by load changes, this paper proposes a control scheme based on a controllable rectifier bridge for load matching and a front-end cascaded buck converter output voltage regulation control scheme. Finally, modeling and simulation are used to verify the correctness of the load matching theory and control strategy. Theoretical analysis and simulation results show that the proposed control scheme can maintain a stable output even when the load changes.

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