Control Strategy of Amplitude Regulation and Frequency Tracking for Wireless Charging Considering Load Characteristics

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Abstract. When charging wirelessly, the load will change and the resonance state of the system will change accordingly. Especially when the load is not purely resistive, the efficiency and power will decrease. In order to improve the transmission efficiency and output power of the system, a control strategy control strategy of phase shift control and frequency tracking for wireless charging considering load characteristics is proposed. The control strategy adopts the frequency tracking control mode to realize the frequency tracking control through the phase of the voltage and current output of the primary side high frequency inverter of the acquisition system. The system always maintains the resonance state under the condition of variable load, and realizes efficient energy transmission. The loop control principle adjusts the phase of the voltage and current in real time. The simulative and experimental results verify the feasibility of the proposed control strategy.

1. Introduction

New progress in medium-range wireless power transmission was made by Marin Soljacic in 2007, successfully achieving 60W power transmission at 2m distance, and the efficiency reached 40% [1]. This technology makes up for the shortcomings of the previous transmission distance, and achieves high power and high efficiency power transmission. Subsequently, researchers around the world have carried out more and more research on wireless power transmission. According to the different transmission mechanism, wireless power transmission can be divided into electromagnetic radiation, electric field coupling and magnetic field coupling. Electromagnetic radiation transmission has long distance and high power, but it needs high efficiency rectifier antenna and high directional antenna when transmitting over a long distance. At present, the technology is not mature. In the electric field coupling for wireless power transmission, the electric field of the capacitor is used to transmit the energy. Since the electric field is more harmful to the human body than the magnetic field, it is currently less studied [2, 3].

The magnetically coupled wireless power transmission can be divided into an inductive and a resonant type depending on whether resonance occurs and the transmission distance is relative to the diameter of the transmission coil. The disadvantage of magnetically coupled inductive wireless power transmission is its short transmission distance, low efficiency and need to be compensated. The
magnetically coupled resonant wireless power transmission has the advantages of long transmission distance, high system efficiency and large transmission power, and has been widely concerned by researchers and successfully applied in many fields. But in the practice of magnetically coupled resonant wireless power transmission, the load mostly presents capacitance or induction. When the load will changes, the equivalent impedance of the system will changes. This change affects the resonance frequency of the system and reduces the energy transmission efficiency of the system under the inherent resonance frequency. Literature [4] compares two frequency tuning methods, zero phase angle and minimum reflection coefficient amplitude, in order to improve power transmission efficiency and output. Literature [5] proposes an automatic adaptive frequency tracking system for medium-distance radio power transmission system. The system frequency is fed back to the front section through wireless communication, so that the frequency of the system can always be maintained at more than 70%. Literature [6] proposes a method to actively modify the equivalent secondary side load impedance by controlling the phase shift of the active rectifier and its output voltage level, so as to improve the transmission efficiency of the system. But they are all based on the realization of separate frequency tracking control and phase shift control.

In order to improve the transmission efficiency and output power of the system, this paper proposes a control strategy of amplitude regulation and frequency tracking for wireless charging considering load characteristics. The control strategy combines frequency tracking with phase-shifting control. Frequency tracking control is realized by collecting the phase of voltage and current on the output side of high frequency inverters, and keeps the system in resonant state under variable load to achieve efficient energy transmission. The magnitude of voltage and current is realized by controlling the phase shift angle of trigger pulse of high frequency inversion.

2. System model and load characteristics analysis
The system of magnetically coupled resonant wireless power transmission mainly includes high frequency power supply, transmitting coil, receiving coil, tuning capacitor and load[7]. The high-frequency power supply is connected with the transmitting coil. After electrification, an alternating magnetic field is formed around the transmitting coil. The receiving coil is placed in the magnetic field generated by the transmitting coil. The transmitting circuit and the receiving circuit have the same resonance frequency through the tuning capacitance. The receiving coil is coupled to the energy in the magnetic field generated by the transmitting coil and resonates. The energy can flow from the transmitting coil to the receiving coil and then be supplied to the load for use, thus realizing the wireless power transmission. The equivalent circuit model of the system is shown in Figure 1.

![Figure 1. Equivalent circuit model of the system.](image)

\[
\begin{align*}
U_S &= I_1 \left( R_S + j\omega L_1 + \frac{1}{j\omega C_1} \right) - j\omega M I_2 \\
M I_1 &= I_2 \left( j\omega L_2 + \frac{1}{j\omega C_2} + R_R + Z_L \right)
\end{align*}
\]

Where \( U_S \) is the excitation source, \( R_S \) is the sum of the power equivalent internal resistance and the transmitting coil, \( R_R \) is the equivalent internal resistance of the receiving coil, \( L_1 \) and \( L_2 \) are the equivalent inductances of the coils on both sides of the transmitting and receiving ends of the system, respectively. \( Z_L \) is the equivalent impedance. \( C_1 \) and \( C_2 \) are the series resonant capacitors at the
receiving and transmitting ends of the system, respectively. \( I_1 \) and \( I_2 \) are the currents flowing through the resonant circuit of the transmitting end and the receiving end, respectively. \( M \) is the resonant frequency of the system. \( \omega \) is the mutual inductance value of the coil.

According to the condition of series resonance

\[
\omega L = \frac{1}{\omega C}
\]

(2)

The primary and secondary compensation capacitance values of the system can be obtained

\[
\begin{align*}
C_1 &= \frac{1}{\omega^2 L_1} \\
C_2 &= \frac{1}{\omega^2 L_2}
\end{align*}
\]

(3)

The impedance expression of the wireless power transmission system is

\[
Z_L = R_L + jX_L
\]

(4)

Ultimately, we can get the following equation

\[
\begin{align*}
\dot{I}_1 &= \frac{U_S}{R_S + \left(\omega M\right)^2} \\
\dot{I}_2 &= \frac{j\omega M U_S}{R_S \left(R_R + jX_L\right) + \left(\omega M\right)^2}
\end{align*}
\]

(5)

It can be seen from the equation (5) that when the load is purely resistive, the change of the load does not affect the resonant frequency of the transmitting end, and the voltage and current are in phase. But when the load is capacitive or inductive, the change of the load will affect the phase of the primary and secondary side voltage and current, and make it not in resonance state. The traditional phase-shifting control method can adjust the output voltage well, but the output frequency of the high-frequency inverter is fixed. Therefore, frequency tracking control is adopted in wireless charging system considering load characteristics, which can solve the problem of resonant frequency change caused by load impedance change.

3. Control strategy and simulation verification

The common control modes of high frequency inverter (HFI) in the primary side of the radio power transmission system are PWM control, phase shift control and frequency tracking control. Since the working frequency of the system is 85 kHz, if the traditional PWM control is adopted, the switching frequency of the high frequency inverter switching device will reach several times of the working frequency. Under the hard switching working condition, the switching device will lose a lot, and it is easy to produce high electromagnetic interference, which will affect the reliability of the system. Therefore, the phase shift control theory and frequency tracking control theory are adopted in the control of transmitter.

3.1. Phase shift control

The principle of phase-shifting control is to set the duty ratio of the driving signal of the switching device to 50%. The two switches on the same bridge arm are mutually complementary and conducting. The output voltage is adjusted by changing the phase-shifting angle \(^8\), as shown in Figure 2.

The range of phase shifting angle is \(0^\circ \sim 180^\circ\). The function expression of phase shifting angle and output voltage in the range of phase shifting can be obtained as follows:
By performing Fourier decomposition on Equation 6, the following equation can be obtained:

$$V(\alpha) = -\sum_{n=1}^{\infty} \frac{4}{n\pi} V \sin \frac{n\alpha}{2} \sin \frac{n\pi}{2} \sin(n\omega t)$$  \hspace{1cm} (7)

It can be seen from Equation 7 that the fundamental amplitude of the output voltage is:

$$V_1 = \frac{4}{\pi} V_{dc} \sin \frac{\alpha}{2}$$  \hspace{1cm} (8)

Therefore, changing the phase shift angle within the phase shift range can change the magnitude of the output voltage. The principle of phase shift control has good stability under constant load or pure resistive load changes. The phase shift control itself has the advantage of being able to adjust the magnitude of the output voltage.

Figure 2. Schematic diagram of phase shifting.

Figure 3. Principle diagram of phase-shifting control for wireless charging.

Figure 3 is a schematic diagram of the phase shift control adopted in this paper. The closed-loop control principle is adopted in transmitting end of the system the primary side of the system. The output voltage of the primary side is sampled as the feedback voltage. According to the relationship between the output voltage and the phase shift angle, the difference of the output voltage is converted into the difference of the phase shift angle, and the PI is adjusted to keep the output voltage of the primary side high frequency inverters constant. Figure 4 shows the waveform of the primary side current following the linear change of the load when the pure resistive load changes. It can be seen from Figure 4 that the secondary voltage of the system has a linear relationship with the primary current measurement. When the secondary voltage changes linearly with the load, the system can work in a constant current state.

As can be seen from Figure 5, the secondary side of the system can maintain constant current charging when the pure resistive load changes. Because of the closed-loop control of the original side, the output voltage of the system remains unchanged when the load changes. However, due to the constant frequency of the output driving signal, the system cannot track the change of frequency when the capacitive or inductive load changes, and cannot continue to maintain the resonance state, which results in the decrease of transmission efficiency.
3.2. Frequency tracking control

Phase locked loop (PLL) is used in frequency tracking control. Its essence is feedback control circuit. By controlling the phase of output signal and input signal to keep synchronization, the output frequency of the system is consistent with the input frequency. The basic principle is shown in Figure 6. PD is a phase discriminator in Figure 6, LF is a loop filter and VCO is a voltage controlled oscillator.

In order to maximize the transmission efficiency and power of the system, the system should always be in a resonant state when the load changes. In this paper, the output voltage and current of the primary side of the system are in the same phase to judge whether the system is in the resonant state. When the voltage and current are in the same phase, the system is in the resonant state and the transmission efficiency is the highest. Therefore, based on the principle of phase-locked loop, this paper collects the output phase of the voltage and current on the primary side of the wireless power transmission system, and uses feedback control to keep the voltage and current in phase when the load changes. Figure 7 is the schematic diagram of the control system. AC-DC is the uncontrolled rectifier, HIF is the high frequency inverter, $U_1$ is the output voltage of the high frequency inverter of the primary side, and I1 is the output current of the high-frequency inverter of the primary side.

The phase of the output voltage and current of the primary side high frequency inverters is measured. The phase difference between them is calculated. The phase difference is converted to frequency. The output frequency of the high frequency inverters is changed by PI regulation and feedback control principle, so that the voltage and current are always in the same phase, that is, the system is always in the resonant state.
In order to verify the frequency tracking control, firstly, the frequency tracking control is not added, and the system operating frequency is 85 kHz, and the load property changes from pure resistance to inductive. As can be seen from Figure 8, when the system is purely resistive, the voltage and current are in phase. After the load is changed, the phase is shifted, that is, the system is not in a resonant state. In Figure 8, (a) is a waveform diagram of a purely resistive load, and (b) is an inductive load waveform after a load change.

When frequency tracking control is added to the system, when the system operating frequency is 85 kHz, it can be seen from Figure 9 that the system can be stabilized in the resonant state after the load changes through the transient process. In Figure 9, (a) is a pure resistive load before the load changes, (b) is a transient process of change, (c) is an inductive load, and finally reaches the resonant state after frequency tracking control.

4. Experimental verification of control strategy
The control strategy is validated. The frequency tracking and amplitude adjustment are combined in the control system, and the frequency and voltage regulation are realized by controlling the high frequency inverters. The experimental results is shown in Figure 10.

The simulation results are divided into four stages, in which the first stage (a1) and (b1) are the voltage-current relationship between the primary and secondary sides of the system when the resistive load is pure. It can be seen from the figure that the primary side and the secondary side are resonant when the resistance is pure. In the second stage, (a2) and (b2) loads mutate into sensibility. It can be seen from the figure that the primary side and the secondary side are not resonant when the load changes, and the secondary side load current decreases, the transmission power of the system
decreases, and the efficiency decreases. The third stage (a3) and (b3) are frequency control. Through frequency tracking control, the trigger pulse frequency of high frequency inverters is adjusted to make the primary side voltage and current resonate. In the fourth stage, (a4) and (b4) are controlled by phase-shifting voltage regulation. By changing the phase-shifting angle of trigger pulse of high frequency inversion, the original voltage is increased, so that the system maintains constant current charging. The experimental results verify the correctness of the control strategy. The voltage and current control can be realized through the high frequency inverters, and the frequency tracking control can also be realized.

5. Conclusion
The system equivalent circuit model is built in this paper. Through theoretical analysis, the relationship between the resonant state and the load of the magnetically coupled resonant system in the string compensation mode is obtained. After comparing the phase shift control and the frequency tracking control mode, it is found that the frequency tracking control can always maintain the system resonance, and the phase shift control can well control the output power of the system. Therefore, this paper combines the phase shift control and the frequency tracking control. Through the control of the high-frequency inverter, the power-modulation frequency modulation control of the wireless energy transmission system is realized, and the feasibility of the proposed control strategy is verified by experiments.

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