Research on Frequency Tracking of Magnetic Coupled Resonant wireless Power Transmission System

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Abstract. In order to solve the problem that the magnetic coupling resonant WPT system with SS compensation structure causes a decrease in transmission efficiency when it is detuned, the resonant state of the system is tracked by detecting the output voltage of the transmitting coil inverter and the coil current of the receiving coil. Phase difference is converted into dc voltage signal with phase discriminator, ADC module is used to sample dc signal, PID algorithm is used to track resonance frequency of the system, 90° phase difference is taken as expected value of PID algorithm, and 90° phase shift is indirectly realized by digital method. The experiment shows that the resonant frequency tracking method is effective.

1. Introduction

With the progress of science and technology, human's life becomes more and more convenient. Wireless power transmission is a hotspot in recent research. There are also many mature applications of wireless transmission system in daily life, such as wireless charging of mobile phone and wireless charging of electric toothbrush. These mature applications are basically based on inductively coupled Wireless power transmission. Inductively coupled Wireless power transmission is suitable for small distance scenarios [1-3], usually no more than a few centimeters. In 2007, MIT proposed magnetically coupled Wireless power energy transmission technology, in which they lit a 60W light bulb at a distance of 2m, with transmission efficiency of 15%. Magnetic-coupled resonant radio energy transmission started late and is still a research hotspot, and many problems need to be solved urgently. The frequency tracking control problem of magnetically coupled resonant WPT (wireless transmission) system is one of the most urgent problems to be solved [4-6]. The transmission efficiency of the magnetically coupled resonant WPT system is greatly affected by the frequency. The system detuning will reduce the transmission efficiency. The frequency tracking control technology can ensure that the magnetically coupled resonant WPT system always works in resonance state. Literature [7-12] analyzed the detuning of WPT system and proposed the detuning control method. Based on the existing literature, this paper proposes a method to track the phase difference between the receiving coil current and the inverter output voltage to track the frequency. PID algorithm is adopted to set the...
expected value to 90° to avoid the phase shift error of 90° hardware and simplify the circuit. The feasibility of this method is verified by experiments.

2. wireless transmission model

The energy transfer principle of WPT system is the electromagnetic induction principle, which simplifies the magnetically coupled WPT system, and establishes the series-series equivalent circuit model as shown in figure 1 below. Where $R_1$ and $R_2$ are equivalent resistors of transmitting coil and receiving coil respectively, and the equivalent resistance is the sum of coil radiation resistance and loss resistance. $L_1$ and $L_2$ are the equivalent inductance of transmitting coil and receiving coil respectively. $C_1$ and $C_2$ are the equivalent capacitance of transmitting coil and receiving coil respectively, and the equivalent capacitance is the sum of distributed resistance and compensation capacitance of the coil. $R_L$ is the load resistor on the receiving coil side. $U_i$ is a high-frequency voltage source on the side of the transmitting coil. $M$ is the mutual inductance between two coils. $I_1$ and $I_2$ are the current of the transmitting coil and the receiving coil respectively.

![Figure 1. Magnetic coupling resonance equivalent circuit model](image)

According to Kirchhoff Voltage Law, the circuit equation of equivalent circuit in figure 1 is listed:

$$Z_1I_1 - j\omega MI_2 = \dot{U}_i$$  \hspace{1cm} (1)

$$Z_2I_2 - j\omega MI_1 = 0$$  \hspace{1cm} (2)

According to equations (1) and (2), it can be obtained:

$$\dot{I}_1 = \frac{\dot{U}_i}{Z_1 + \frac{j\omega M^2}{Z_2}}$$  \hspace{1cm} (3)

$$\dot{I}_2 = \frac{j\omega M U_i}{Z_2(Z_1 + \frac{j\omega M^2}{Z_2})}$$  \hspace{1cm} (4)

Where $Z_1$ and $Z_2$ are the self-impedance of the two coils respectively:

$$Z_1 = R_1 + j(\omega L_1 - \frac{1}{\omega C_1})$$  \hspace{1cm} (5)

$$Z_1 = R_2 + R_L + j(\omega L_2 - \frac{1}{\omega C_2})$$  \hspace{1cm} (6)

By type (3) it can be seen when both coils are resonance occurs, The phase difference between the transmitter coil current $I_1$ and high-frequency voltage source $U_i$ is 0°. By type (4) it can be seen when both coils are resonance occurs, The phase difference between receive coil current $I_2$ and high-frequency voltage source $U_i$ is 90°, so the magnetic coupling resonant WPT systems track by tracking the phase difference of $I_1$ and $U_i$, can also be used by tracking $I_2$ phase difference with the $U_i$. This paper adopts the method of tracking the phase difference between $I_2$ and $U_i$ to track the frequency.
3. Design and experiment of frequency tracking system

3.1 System circuit design

Figure 2 is the magnetically coupled resonant WPT system diagram. The DC power supply $U$ is transformed into the high-frequency power supply $U_i$ through the half-bridge inverter. The high-frequency power supply $U_i$ drives the transmitting coil to transfer energy to the receiving coil. The receiving coil converts the received high-frequency power supply through the rectified filter circuit into a DC power supply, which supplies the load $R_L$. The frequency tracking control system adjusts the driving signal frequency by detecting the phase difference between the receiving coil current and the transmitting voltage.

![Figure 2. Magnetic coupling resonance WPT system diagram](image)

Figure 3 is the frequency tracking control diagram of magnetically coupled resonant WPT. Figure 4 is the current sampling diagram of the receiving coil. Through the current transformer $I_2$ gets the $U_a$ of the same frequency and phase. Together with the sampling voltage $U_b$ at the output end of the transmitting coil inverter, it first goes through the preamplifier, and then generates the square wave signal through the high-speed comparison circuit. The phase difference of two square wave signals is treated as voltage signal by phase detector module. The amplitude of the voltage is proportional to the phase difference of the square wave signal. The voltage signal value is obtained by the ADC module. The MCU then controls the DDS module to adjust the driving signal frequency according to the voltage signal value. The high frequency driving square wave passes through the dead zone circuit to produce two square wave signals with certain dead zone time. Through the half-bridge drive circuit to increase the driving capacity of square wave signal.

![Figure 3. frequency tracking control diagram](image)
Figure 4 is the current sampling diagram. The receiving coil current $I_2$ is converted into a voltage signal with the same frequency and phase through the hall sensor. The voltage follower OP27 is used to isolate the front and rear stage circuit and increase the driving capacity of the voltage signal.

![Figure 4. current sampling diagram](image)

Figure 5 is the comparator circuit diagram. The reference voltage of the inverting input can be changed by adjusting the sliding rheostat $R_4$. Adjusting the reference voltage can cancel the offset voltage of the preamplifier and the comparator.

![Figure 5. Comparator circuit](image)

The half-bridge inverter circuit of this system is composed of two MOSFETs. In order to avoid the two MOSFETs turning on simultaneously, a dead zone time generator is required. The dead zone circuit is shown in figure 6. When the input is high, the capacitor is charged through the resistance, and the charging time is $t = RC$. As shown in the waveform figure (b) in figure 6, the rising edge of $U_2$ is higher than the delay time $t$ of $U_1$, and the waveforms behind the gate of $U_1$ and $U_2$ are still the same as $U_2$. $U_3$ and $U_4$ are inverted to $U_1$ and $U_2$ through inverters. The rising edge of $U_4$ also has a delay time of $t$ over $U_3$.

![Figure 6. Dead zone circuit](image)

(a) circuit diagram
3.2 Experiment

According to designing WPT frequency tracking system mentioned above, the design of the transmitter coil number of turns $N=10$, copper wire radius $a=1.6\text{mm}$, the coil radius $r=11.2\cm$, with digital bridge measured coil inductance $L=85.4\mu\text{H}$, ignore the radiation resistance of the coil, coil equivalent resistance $R=0.125\,\Omega$, take $C=6.8\text{nF}$ using mica capacitors. The parameters of the receiving coil and the transmitting coil are set to the same. $R_1=R_2=0.125\,\Omega$, $C_1=C_2=6.8\text{nF}$, $L_1=L_2=85.4\mu\text{H}$. Use the formula:

$$\omega = \sqrt{\frac{1}{LC}}$$

(7)

The resonant frequency is calculated to be $208.9\text{kHz}$. The calculation formula of mutual inductance $M$ is:

$$M \approx \frac{\pi}{2} \frac{\mu_0 r^4 N^2}{D^2}$$

(8)

Where, $D$ is the transmission distance, and $\mu_0 = 4\pi \times 10^{-7}\text{H/m}$ is the permeability of the vacuum.

This paper adopts the method of tracking the phase difference between the receiving coil current $I_2$ and the inverter output voltage $U_i$ to track the frequency. The current and voltage signals are amplified by the preamplifier and then converted into two square wave signals by a high-speed comparator. The chip AD8302 was used to process the phase difference of the two square wave signals into DC voltage signals. The amplitude of the DC voltage is proportional to the phase difference of the square wave signal. The ADC module of MCU is used for sampling to obtain the voltage signal value. The PID algorithm is used to adjust the frequency of the output drive signal. When the system resonates, the phase difference between $I_2$ and $U_i$ is $90^\circ$, so before the system works, input the standard signal with fixed $90^\circ$ phase difference at the voltage and current sampling end, and obtain the ADC sampling value $AD^*$ at this time. Take this sampling value as the expected value of PID algorithm, then the frequency adjustment formula of the driving signal is:

$$f_0 = f_1 + K_p \cdot (AD_0 - AD_1) + K_i \cdot AD_0$$

(9)

Where $f_1$ is the frequency of the last driving signal, $K_p$ and $K_i$ are the proportional coefficient and
differential coefficient respectively, $AD_0$ and $AD_1$ are the voltage signal values obtained by sampling this time and last time respectively, and $f_0$ is the frequency of the calculated driving signal. The MCU adjusts the driving signal frequency by controlling the DDS module.

The half bridge inverter circuit of this system chosen is IRF540. By formula $\tau = RC$, Take the $R_1$ and $R_2$ of 680 $\Omega$, $C_1$ and $C_2$ is 100 pF. As shown in figure 7, the two-channel inverse-phase square wave signals pass through the dead zone circuit. The high level time difference between the two square wave signals is about 50ns.

![Figure 7. dead time of control signal](image)

Load $R_L$ is set to 5 $\Omega$, under the transmission distance is 6 cm, set different frequency of the initial frequency, less frequency tracking and frequency tracking system transmission efficiency. As shown in figure 8, with different initial frequencies, the open-loop non-frequency tracking system has the highest working efficiency when the initial frequency is 207kHz. However, at the upper and lower frequencies of 207kHz, the transmission efficiency of the system decreases rapidly, proving that the transmission efficiency of the system is greatly affected by the frequency. The transmission efficiency of the system with frequency tracking is always unchanged, indicating that the frequency tracking is effective. When the system is disturbed by resonance parameters, the frequency tracking design in this paper can quickly find new resonance points to ensure the transmission efficiency of the system.

![Figure 8. comparison of system transmission efficiency](image)
4. Conclusion

This paper presents a method to track the phase difference between the current of the receiving coil and the output voltage of the inverter. PID algorithm is adopted to set the expected value to 90° to avoid the phase shift error of 90° hardware and simplify the circuit. Experiments show that the design of this paper can track the frequency of the system in real time and improve the anti-interference ability of the system effectively.

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