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RESEARCH ON FREQUENCY TRACKING CONTROL OF THE WIRELESS POWER TRANSFER SYSTEM BASED ON Wi-Fi

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The resonance detuning caused by the change of the magnetic conducting medium is one of the key reasons for the decrease of the transmission power and efficiency of the magnetically coupled resonant wireless power transmission system. Aiming at this problem, this paper theoretically analyzes the system resonance mechanism, and proposes the frequency tracking control based on WI-FI signal transmission phase-locked loop control technology. When the system works in over-coupling, the system will have frequency splitting, and the working frequency point may not be the coincidence point of maximum power and optimal efficiency. For the first time, this paper proposes and designs an innovative scheme to control the output voltage and frequency of the primary inverter circuit by the secondary current through the phase-locked loop control technology based on WI-FI wireless signal transmission. The experimental results verify the effectiveness of the frequency tracking scheme. The proposed scheme can further optimize the working state of the system and improve the efficiency of power transmission.

Keywords: Wireless power transfer; Resonance detuning; Frequency tracking; Phase-locked loop control; Wi-Fi signal transmission

1. Introduction

Wireless power transfer (WPT) technology has the advantages of convenience, safety, reliability and flexibility that traditional power transfer technology can't compare, so it has become a global research hotspot. Because the transfer distance of the magnetic coupling resonance (MCR) WPT can be in the range of tens of centimeters to several meters, the transfer power can be from tens of watts to several kilowatts, and the transfer efficiency can be more than 40% to 90%, all aspects have relatively balanced advantages. Therefore, it has become the hottest research direction in the field of WPT [1-3].

As an important index to measure the transfer performance of WPT system, power transfer efficiency and transfer power become the focus of the

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global research team. In order to realize the WPT system working under the maximum transfer power and optimal transfer efficiency, the frequency tracking scheme based on inverter output voltage and secondary current in literature [4] can always track the natural resonance frequency of the system under any mutual inductance and load conditions without the influence of frequency splitting phenomenon. This method needs to realize the communication between the primary and secondary systems to realize the frequency tracking control. The communication method is not described in this paper. In reference [5], aiming at the frequency splitting phenomenon when the system works in the over coupling state, a circuit with phase-locked function is proposed to track and control the resonance frequency of the opposite side. Simulation results show that the tracking of the resonance frequency point of the opposite side can achieve stable output power and transfer efficiency of the system. In order to solve the problem that the output power of the MCRWPT system is greatly reduced due to the detuning, a frequency tracking technology based on the sampling average value of the voltage commutation point and current at the transmitter is proposed in reference [6]. The experimental results show that this method can double the output power. In reference [7], a frequency tracking detuning control strategy based on differential phase-locked loop is adopted to realize the primary detuning and secondary resonance compensation, so as to ensure that the primary system works in the soft switch state, and the secondary resonance compensation can realize the transfer power fluctuation optimization under a certain transfer distance disturbance. In reference [8], a variable mode all digital PLL with adaptive PI control is proposed to track the current and frequency of the primary coil rapidly. FPGA is used as the controller of the frequency tracking system to make the system always work in resonance state. Through the experiment, when the resonance frequency changes from 125kHz natural resonance frequency to 113kHz, the adjustment of the working frequency is realized, which ensures that the system works in the resonance state. Reference [9] respectively detects the input power and output power of the system, takes the ratio of output power and input power of the system as the tracking object, and takes 70% of transfer efficiency as the regulating target. When the transfer efficiency is lower than the target value, frequency regulation is carried out with 10kHz as the step, until the transfer efficiency is not lower than 70%, and wireless communication is used between the primary side coil and the secondary side coil Signal transfer is realized by the way of signal. According to the analysis of reference [11], it is deduced that when the mutual inductance of transmitting and receiving coils is certain, the optimal load resistance value makes the transfer efficiency of the system optimal. An optimal load tracking system based on boost buck converter is proposed. The system efficiency is maintained at about 70% under different loads and relative positions of coils when the transfer efficiency is 40 W.

In this paper, the transfer characteristics of MCRWPT system are analyzed, and the causes of the detuning in the process of power transfer are summarized. Aiming at the frequency splitting phenomenon in the process of power transfer, in order to make the system always work under the natural resonance frequency without the influence of frequency splitting, a secondary current frequency tracking control strategy based on WI-FI wireless communication is proposed, and the feasibility of the system is verified by experiments.

2. Transfer principle of MCRWPT

MCRWPT system is based on the principle of power resonance coupling to realize the wireless transfer of electric power. In this paper, the series series (SS) circuit topology is used to analyze the transfer principle of the system, as shown in Fig. 1 is the equivalent circuit diagram of two coil MCRWPT system. The U_S and the R_S on behalf of the high frequency power supply and power resistance, R_1 and R_2 represent the emission circuit and receiving circuit equivalent resistance, R_L on behalf of the load resistance, L_1 and L_2 represent the primary coil and deputy coil inductance, C_1 and C_2 respectively represent the primary coil and secondary coil resonant capacitance, M represent the primary secondary coil mutual inductance .

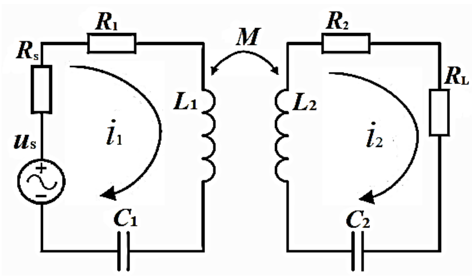

Fig.1 MCRWPT system equivalent circuit diagram

According to KVL and KCL, the system loop current can be obtained as follows:

$$\begin{bmatrix} i_1 \\ i_2 \end{bmatrix} = \begin{bmatrix} \dfrac{R_2' + \mathrm{j}X_2}{(R_1' + \mathrm{j}X_1)(R_2' + \mathrm{j}X_2) - (\mathrm{j}\omega M)^2} u_S \\ \dfrac{\mathrm{j}\omega M}{(R_1' + \mathrm{j}X_1)(R_2' + \mathrm{j}X_2) - (\mathrm{j}\omega M)^2} u_S \end{bmatrix} \tag{1}$$

In equation (1), $R_1^{'} = R_S + R_1$, $X_1 = \omega L_1 - \frac{1}{\omega C_1}$, $R_2^{'} = R_L + R_2$, $X_2 = \omega L_2 - \frac{1}{\omega C_2}$, $M = \frac{\pi\mu_0\sqrt{n_1 n_2}(r_1 r_2)^2}{2D^3}$, Among them, ω is the working angle frequency of the system, μ_0 is the vacuum permeability, n_1, n_2, r_1, r_2 are the turns and wire diameter of the primary side and secondary side coils respectively, D is the distance between the primary side and secondary side coils. The reflection impedance of primary side and secondary side can be expressed as follows:

$$\begin{cases} Z_1^{'} = \frac{(\omega M)^2}{Z_2} = \frac{(\omega M)^2}{R_2^{'} + \mathrm{j}X_2} = R_1^{''} + \mathrm{j}X_1^{'} \\ Z_2^{'} = \frac{(\omega M)^2}{Z_1} = \frac{(\omega M)^2}{R_1^{'} + \mathrm{j}X_1} = R_2^{''} + \mathrm{j}X_2^{'} \end{cases} \tag{2}$$

In equation (2),

$$\begin{cases} R_1^{''} = \frac{(\omega M)^2}{R_2^{'2} + X_2^2} R_2^{'} \\ X_1^{'} = -\frac{(\omega M)^2}{R_2^{'2} + X_2^2} X_2 \\ R_2^{''} = \frac{(\omega M)^2}{R_1^{'2} + X_1^2} R_1^{'} \\ X_2^{'} = -\frac{(\omega M)^2}{R_1^{'2} + X_1^2} X_1 \end{cases} \tag{3}$$

From equation (1), the transfer efficiency of the system can be calculated as follows:

$$\eta = \frac{(\omega M)^2 R_L}{(R_2^{'} + \mathrm{j}X_2)\left[(R_2^{'} + jX_2)(R_1^{'} + \mathrm{j}X_1 + R_S) + (\omega M)^2\right]} \tag{4}$$

When the MCRWPT system works in the over coupling state, frequency splitting will occur due to the impedance mismatch. At this time, the system will have multiple resonance frequencies, and the original resonance frequency is always a resonance frequency, but the system efficiency is very low at the original resonance frequency due to the small real part of the system input impedance [12].

In order to analyze the working characteristics of the system in the resonance state, the coupling coefficient $k = M\sqrt{L_1 L_2}$ is defined, Let $\omega_0 = 2\pi f_0$ be the resonance frequency of the system. For the convenience of analysis, let $L_1 = L_2 = L$, $C_1 = C_2 = C$, $R_1^{'} = R_2 = R$. The quality factors of primary and secondary coils can be obtained as follows:

$$\begin{cases} Q_1 = \dfrac{\omega_0 L}{R}, \\ Q_2 = \dfrac{\omega_0 L}{(1+\tau)R} \end{cases} \tag{5}$$

Where τ is the ratio coefficient between the equivalent load R_L of the receiving loop and the equivalent resistance R_2 of the receiving coil. In order to discuss the factors affecting the transfer of the system, the generalized detuning factors [13] of the primary and secondary coils are defined as:

$$\begin{cases} \xi_1 = Q_1(\dfrac{\omega}{\omega_0} - \dfrac{\omega_0}{\omega}) \\ \xi_2 = Q_2(\dfrac{\omega}{\omega_0} - \dfrac{\omega_0}{\omega}) \end{cases} \tag{6}$$

The expressions of the impedance angles of the primary and secondary circuits are obtained as follows:

$$\begin{cases} \varphi_1 = \arctan(\dfrac{X_1 + X_1^{'}}{R_1^{'} + R_1^{''}}) \\ \varphi_2 = \arctan(\dfrac{X_2 + X_2^{'}}{R_2^{'} + R_2^{''}}) \end{cases} \tag{7}$$

Substituting equations (3), (5) and (6) into equation (7), we can get the expression of the tangent of the primary and secondary circuit impedance angles as follows

$$\begin{cases} \tan\varphi_1 = \xi_1 \dfrac{(1+\tau)(1+\xi_2^2) - k^2 Q_1 Q_2}{(1+\xi_2^2) + k^2 Q_1 Q_2} \\ \tan\varphi_2 = \xi_2 \dfrac{(1+\tau)(1+\xi_1^2) - k^2 Q_1 Q_2}{(1+\xi_1^2) + k^2 Q_1 Q_2} \end{cases} \tag{8}$$

The normalized frequency f 'is defined as:

$$f^{'} = \frac{f}{f_0} \tag{9}$$

Taking Table 1 as an example, the quantitative relationship between the excitation frequency of the system and the impedance angle of the primary and secondary circuits is analyzed.

Table 1

Modeling parameter

Parameter	Value
***L*/μH**	100
***C*/pF**	6.33
***R*/Ω**	1
f_0/kHz	200

τ	24
k	0.25-0.35

The relationship between φ_1, φ_2 and normalized frequency f 'is shown in Fig.2.

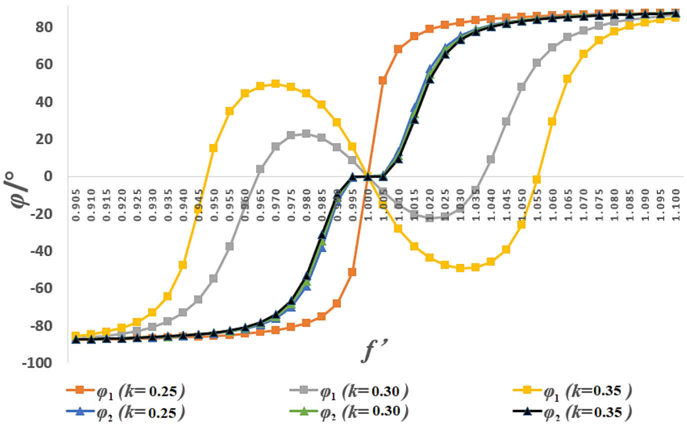

Fig.2 φ_1 and φ_2 - f 'change curve of primary side and secondary side circuit

It can be seen from the figure that when the coupling coefficient k is small, the impedance angle φ_1 of the primary circuit monotonically changes with the frequency, and there is only one point where the impedance angle is zero. When k is large, the system works in the state of over coupling. At this time, the impedance angle φ_1 will appear three zeros with the change of frequency, and the frequency splitting phenomenon will appear. However, the impedance angle of the secondary circuit φ_2 has no obvious change in the process of coupling coefficient change, and it always keeps monotonous change and has only one zero point. Therefore, by detecting the phase angle of the secondary circuit current, the resonance frequency can be tracked without the influence of frequency splitting.

3. Frequency tracking control strategy

The primary side and secondary side coil work in resonance state is the key for MCRWPT technology to carry out high-power and efficient power transfer. In this paper, based on Wi-Fi wireless signal transmission, real-time tracking detection of secondary side loop current is realized, and the excitation frequency of the system is controlled to realize frequency tracking control so as to ensure the system work in resonance state.

The principle of system frequency tracking control strategy is shown in Fig.3, The process of frequency tracking control is mainly realized by current detection circuit, phase shift circuit, phase compensation circuit, phase locked loop (PLL), ADC circuit, WI-FI signal transmission circuit, and PWM control circuit, in which PLL is realized by phase detection (PD), loop filtering (LF) and voltage controlled oscillator (VCO).

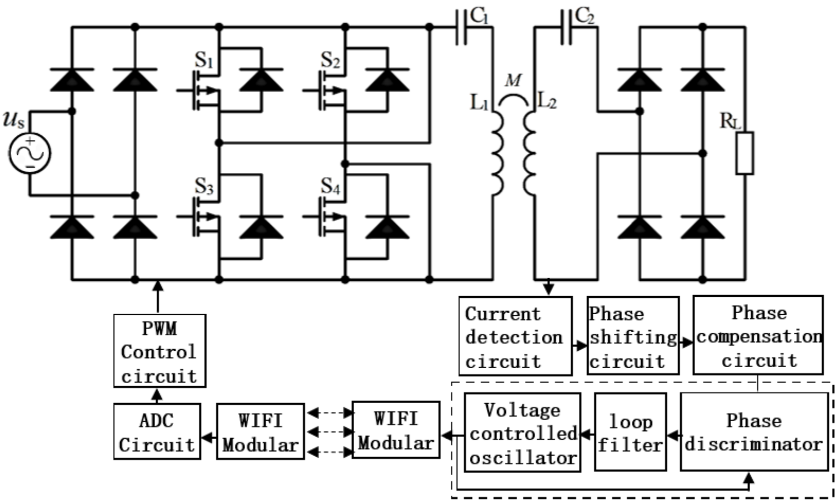

Fig.3 Schematic diagram of system frequency tracking control

The specific implementation steps of system frequency tracking control are as follows:

(1) The secondary circuit current signal i_2 is obtained by the real-time sampling of the secondary circuit current through the current detection circuit, and then a voltage signal u_i is obtained through the signal processing, and a voltage signal u_a with a phase difference of 90° between the phase and i_2 is obtained through the phase-shift circuit. u_a is a voltage signal with the same phase as the primary circuit voltage.

(2) After the phase compensation of u_a, the processed signal is used as the input signal of PLL circuit, which is firstly compared with the phase of PD and VCO signal, and the phase error voltage u_d between the two signals is output, then the error voltage is filtered by LF, and the filtered voltage signal u_c is sent to VCO as the control voltage to change the frequency of VCO to reduce the phase difference between the input signal and VCO Finally, VCO outputs voltage signal u_p.

(3) After the voltage signal u_p is processed by the ADC circuit, it is wirelessly transmitted to the PWM control circuit through the WI-FI module to control the inverter circuit of the primary circuit so that its output voltage excitation is the same as that of the u_p phase, thus completing the frequency tracking control process.

Working principle of PLL. The basic block diagram of PLL operation is shown in Fig. 4. The input signal phase is represented by φ_i, and the VCO output phase is represented by φ_o. Therefore, the voltage output by the phase detector is as follows:

$$u_d = K_d(\varphi_i - \varphi_o) \tag{10}$$

Where K_d is the gain factor of the phase detector.

In Fig. 4, *F (s)* is used to represent the transfer function of LF. LF outputs a control voltage to control the frequency of VCO. In the Laplace transform domain, VCO functions as follows:

$$U_c(s) = F(s)U_d(s) \tag{11}$$

In the equation, $U_c(s)=L\{u_c(t)\}$ denotes Laplace transformation.

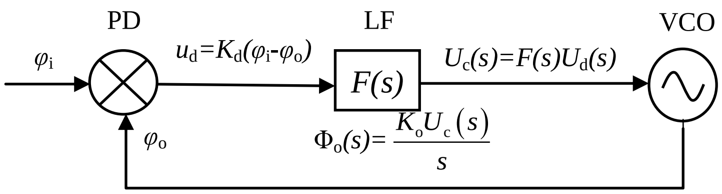

Fig. 4 Basic block diagram of PLL

The deviation from the center frequency of VCO is $\Delta\omega = K_o u_c$, in which K_o is the gain factor of VCO. As the frequency is the derivative of phase, it can be calculated $d\varphi_o / dt = K_o u_c(t)$, and obtained by Laplace transform $L\{ d\varphi_o / dt \} = s\Phi_o(s) = K_o U_c(s)$, so it can be obtained as follows:

$$\Phi_o(s) = \frac{K_o U_c(s)}{s} \tag{12}$$

Where $s = \sigma + j\omega$ is the independent variable of Laplace transform.

PLL is a closed-loop feedback control process, in which PD circuit is used to detect the phase difference between two input signals and convert the phase difference into voltage signal. The main function of LP circuit is to establish the dynamic characteristics of the feedback loop, and to filter out the high frequency components in the output voltage of the phase detector, to play a filtering and smoothing role, to ensure the loop stability, improve the loop tracking performance and noise signals, as well as to provide appropriate control signals to VCO. VCO circuit plays the role of converting voltage into phase, its oscillation frequency phase is controlled by LP output voltage, and its output signal changes with the phase change of loop input signal, so as to realize phase tracking.

Wi-Fi communication process. The process of system WI-FI communication is the key to ensure the implementation of frequency tracking control strategy. WI-FI communication mainly realizes the following functions: The transmitting end of the WI-FI module collects the secondary side frequency tracking output signal, and then transmits it to the receiving end of the Wi-Fi module in the Wi-Fi wireless communication mode. Because PLL outputs analog signal, it needs to send the result to MCU after ADC conversion processing, so as to realize wireless transmission of signal through Wi-Fi interface module. The task flow of system Wi-Fi communication is shown in Fig.5.

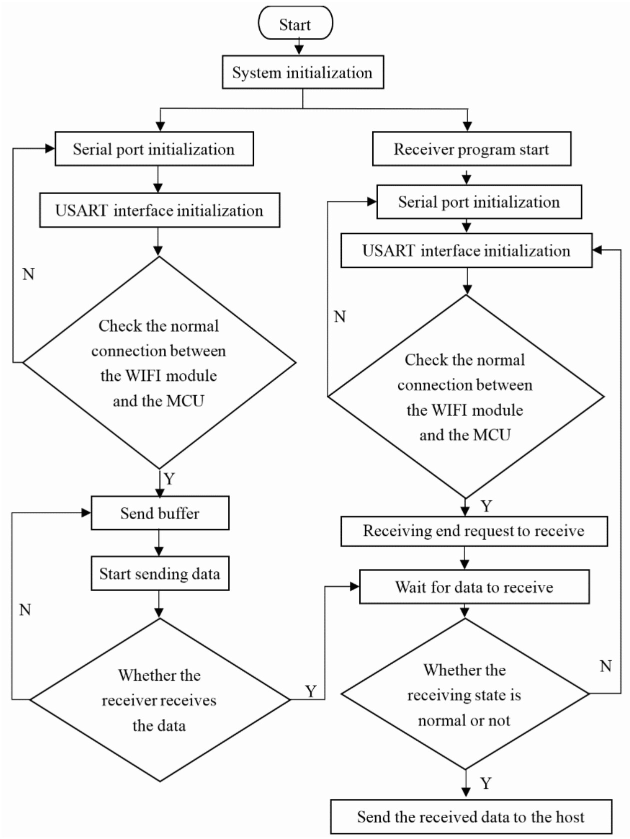

Fig. 5 WI-FI communication task flow chart

The speed and precision of wireless signal transmission determine the speed and precision of system frequency tracking and control. The selection of Wi-Fi module requires not only less power consumption, but also higher transmission speed and precision. At present, there are two kinds of widely used low-power Wi-Fi modules: serial port Wi-Fi module and SDIO-Wi-Fi module. The serial Wi-Fi module conforms to the embedded module of WI-FI wireless network standard, which can realize the conversion between serial data and wireless network. This paper adopts the serial Wi-Fi module with people networking, which has the advantages of small power consumption, small volume, supporting AP, STA, AP+STA multiple working modes, and multiple serial port rates to choose. The functional structure of Wi-Fi communication transparent transmission mode is shown in Fig. 6.

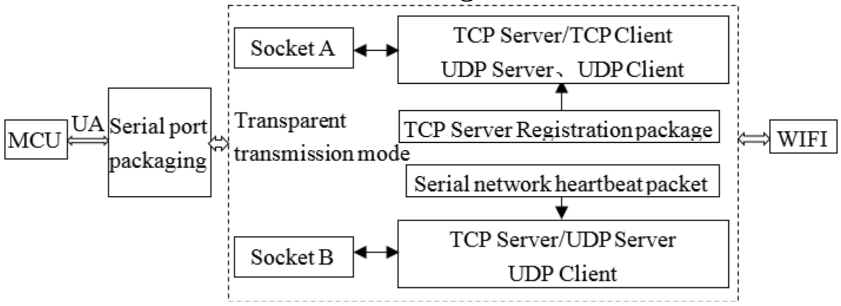

Fig. 6 Function structure diagram of transparent transmission mode

4. Experimental verification and result analysis

Based on the above theoretical analysis and frequency tracking control strategy, a frequency tracking control experimental platform based on Wi-Fi wireless power transfer system is built. Simultaneous interpreting experiments are carried out at different transfer distances and transfer channels with magnetic medium. The circuit parameters of the system experimental design are shown in Table 2.

Table 2

Circuit parameters

Parameter	Value
L/μH	100
C/pF	6.33
R/Ω	1
f_0/kHz	200
D/cm	5-20
n_1、n_2	15
r_1、r_2/cm	15

In the case of no ferromagnetic medium in the transmission channel, the experimental platform of WPT system is shown in Fig. 7.

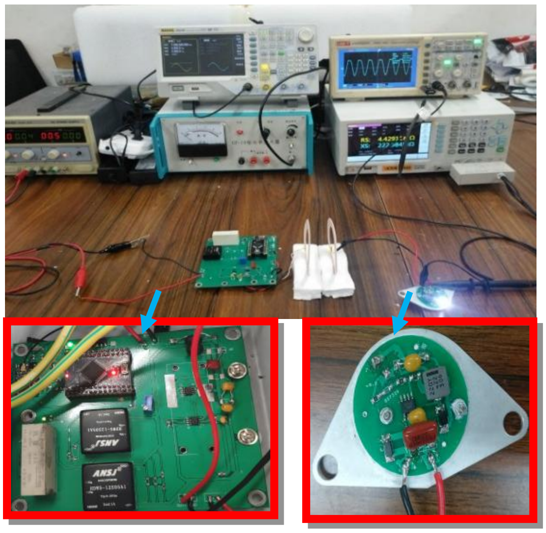

Fig.7 Experimental platform of WPT system with double coil structure

The simultaneous interpreting of the radio transfer experiments with different transfer distance is carried out before and after the frequency tracking control strategy is adopted. The transfer efficiency of the corresponding distance is η_1 and η_2, respectively, and the experimental results are shown in Fig. 8.

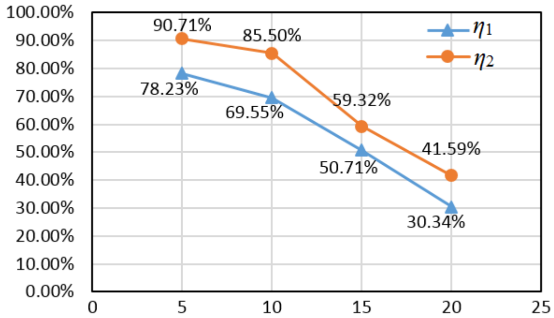

Fig.8 Experimental results of transfer efficiency without ferromagnetic media

From the results of Fig. 8, it can be seen that when the WPT system does not have frequency tracking control strategy, the transfer efficiency can reach 78.23% when the primary and secondary side spacing is 5cm. When the system adopts frequency tracking control strategy, the transfer efficiency of simultaneous interpreting is improved at the first and the two sides of different transfer distances, and when the primary side and the secondary side spacing are 10cm, the efficiency is the highest. Transfer efficiency increased by 15.95%.

The experimental platform of WPT system is shown in Fig. 9 when magnetic medium is added to the transfer channel.

Fig.9 Experimental results of transfer efficiency without ferromagnetic media

The simultaneous interpreting of the radio transfer experiments with different transfer distances is carried out before and after the frequency tracking control strategy is adopted. The corresponding transfer efficiency of each distance is η_1' and η_2', respectively, and the experimental results are shown in Fig. 10.

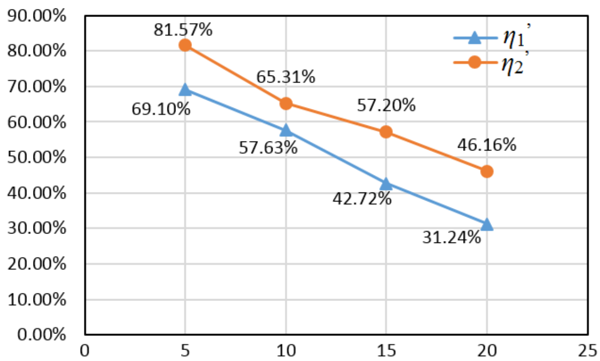

Fig.10 Experimental results of transfer efficiency in ferromagnetic media

According to the analysis of the experimental results in Fig. 10, when the primary side and secondary side coils pass through the ferromagnetic metal medium, the efficiency of the system is significantly reduced. Compared with the frequency tracking control strategy, it can be seen that the transfer efficiency of WPT system is significantly improved, and when the transfer distance is 20cm, the efficiency is the highest, and the transfer efficiency is increased by 14.92%.

Based on the experimental results of two working conditions, it can be seen that the transfer efficiency of WPT system with double coil structure will change obviously when ferromagnetic medium passes through, and the reason for the change has been explained and analyzed in reference [14], which will not be introduced in detail in this paper. From the analysis of the experimental results, it can be seen that when the frequency tracking control strategy is adopted in the system, the transfer efficiency of the system has an obvious improvement effect regardless of whether there is ferromagnetic medium passing through the transfer channel of the coil, and the improvement range of the transfer efficiency of the system is about 12%.

5. Conclusions

In this paper, through the analysis of the resonance mechanism of the magnetic coupling resonance wireless power transfer system, the key factors affecting the resonance of the system are obtained, and a PLL frequency tracking control strategy based on WI-FI wireless signal transfer is proposed. By tracking the phase of the secondary side current, the frequency control of the primary side inverter output voltage excitation is realized, so that the system always works at the natural resonance frequency point, so as to ensure the optimal transfer efficiency of the system. Through the experimental verification, when the system adopts the frequency tracking control strategy, when there is no ferromagnetic medium in the transfer channel, the transfer efficiency of the system can be effectively increased by about 12.07%; when there is ferromagnetic medium in the transfer channel, the transfer efficiency of the system can be effectively increased by about 12.39%.

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