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Design of Magnetically Coupled Resonant Wireless Power and Signal Synchronous Transmission System Based on Digital Frequency Modulation

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***Abstract*—A magnetically coupled resonant wireless power transmission system which can realize synchronous transmission of energy and information is porposed in this paper. The digital frequency modulation signal is used to control the working frequency of the inverter circuit and change the resonant working state of the transmission system. The voltage at both of transmitting and receiving coil changes regularly, and the signal to be transmitted is restored after signal processing,including:detection, filtering, comparison. The simulation results of the proposed circuit show that the scheme is feasible and a communication mode for this system is proposed, which can send the signal correctly.Furthermore, the transmission of the signal has little influence on the power transmission efficiency.**

Keywords-wireless power transmission; FSK control; ASK modulation；synchronous transmission; resonance

I. INTRODUCTION

Wireless power transmission(WPT) technology, is a research hotspot in recent yearsand the near field WPT can be classified into two types: electromagnetic induction and magnetic coupling resonance.

The magnetic coupling resonance system has many advantages, such as long transmission distance and strong anti-interference ability,so the magnetic coupling resonance mode is adopted as the main transmission system in this paper.

With the vigorous development of WPT technology, it is widely used in various fields, such as medical equipment, mobile phones, electric vehicles and household appliances.If information can transferred synchronously while power transmission, the application field of WPT will be further expanded.

In the research of synchronous transmission of shared channel signals in WPT systems, many feasible methods are proposed the common methods are to add the signal control switch on the primary side, to control the switching period of the resonant converter [2], and to load the data signal into the power transmission system through the coupling coil [3]. At present, the methods commonly used to transmit signals in power transmission systems are energy modulation (energy envelope formed by baseband signal) and carrier modulation [3].The main ways of signal transmission based on energy modulation technology are as follows: in references [4] and [5], the variable capacitance method is used to realize the synchronous transmission of electric energy and signal, which can realize the reverse transmission of the signal, the principle is simple and the maneuverability is strong. The reference [6] adds a function switch at the transmitter to realize the reverse transmission of the signal, and the reference [7] amplifies the modulated signal as energy wave transmission. The common way of carrier modulation is to add the modulated and carrier signal to the energy transmission system through the coupling coil.

In this paper, on the basis of magnetically coupled resonant WPT with traditional double-coil structure, a synchronous transmission scheme of both electric energy and signal is proposed. And a signal modulation and demodulation circuit is designed. Frequency modulation is used to change the output frequency of the inverter circuit to realize signal transmission. The feasibility of the proposed scheme is verified by simulation analysis.

II. 1. ANALYSIS OF THE PRINCIPLE OF SYNCHRONOUS TRANSMISSION OF ENERGY AND SIGNAL.

A. 1.1 Modeling and Analysis of overall system structure based on Magnetic Coupling Resonance system

The diagram of the proposed double-coil magnetically coupled resonant wireless power and signal synchronous transmission system is shown in Figure 1. The energy transmitting part consists of an excitation source, an inverter, transmission coils, a rectifier bridge, and a load. The transmitter will convert the DC power into high-frequency AC through the inverter circuit, and transmit the high-frequency power to the load through the transmitting coil to realize the power transmission. When the working frequency is at the natural resonate frequency of transmitter and receiver circuit, the total impedance of the circuit is the smallest resulting the maximum output voltage.

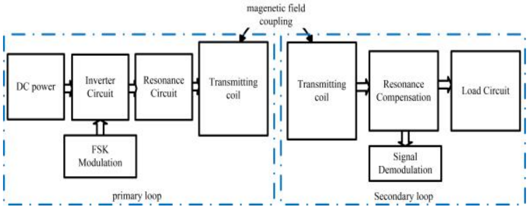

Figure. 1 structure of inductively coupled power system

The signal modulation circuit is added to the primary side loop to control the inverter circuithe signal demodulating circuit is added to the secondary side circuit.

The detail circuit is shown in figure 2: Uin is the power supply voltage, RL is the load resistance, C1 and C2 are the compensation capacitors of the primary and secondary coils,respectively.

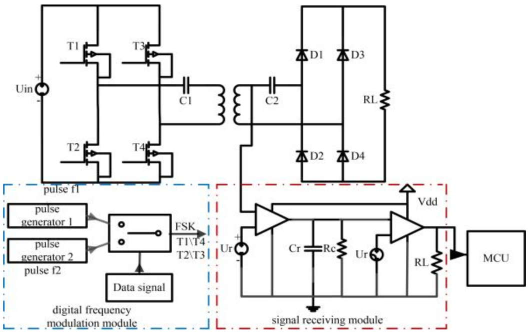

Figure. 2 circuit structure diagram of the system

Because the modulation and demodulation circuit is added on the basis of the original transmission system and its topology is not changed, the modulation signal controls the inverter circuit switch, while the demodulation circuit demodulates and restores the digital signal by collecting the voltage of the receiver, which realizes the signal transmission with little affecting the power transmission of the WPT system.

B. principle of synchronous signal transmission

In this paper, different output voltages and currents are obtained by controlling the output frequency of the full inverter circuit to control the resonant state of the whole system. According to different working frequencies, different power or voltage change information is picked up at the receiver for calculation and analysis to determine the threshold value of the voltage so as to recover the transmitted signal. In the data transmission system, the digital signal is modulated by binary frequency shift keying (2FSK). It is easy to control the frequency of the inverter circuit output high frequency AC.Figure 3 shows the equivalent circuit of a magnetically coupled resonant WPT. In order to simplify the derivation process, the coefficient of mutual inductance between the two coils in figure 3 is M,and the internal resistance of the compensation capacitance and inductance of the primary and secondary side circuit is equivalent to C1,C2,L1 and L2, respectively.

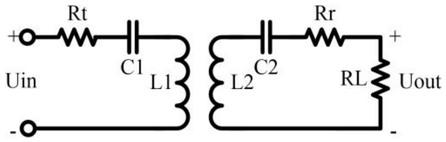

Figure. 3 equivalent circuit diagram of MCR-WPT system

According to the circuit theory, the self-impedance of the transceiver coil is

$$Z_t = R_\mathrm{t} + j\omega L + \frac{1}{j\omega C} \qquad （1）$$

$$Z_r = R_\mathrm{r} + j\omega L + \frac{1}{j\omega C} + R_L \qquad （2）$$

According to Kirchhoff theorem (KVL) , the loop equation can be writtten as

$$\begin{bmatrix} \dot{U}_{in} \\ 0 \end{bmatrix} = \begin{bmatrix} Z_\mathrm{t} & j\omega M \\ j\omega M & Z_\mathrm{r} \end{bmatrix} \begin{bmatrix} \dot{I}_t \\ \dot{I}_\mathrm{r} \end{bmatrix} \qquad （3）$$

When the system is in a resonant state

$$Z_t = R_{\mathrm{t}} \tag{4}$$

$$Z_r = R_{\mathrm{r}} + R_L \tag{5}$$

In this case, the impedance is the lowest, and the maximum loop current is obtained on the primary and secondary sides, respectively.

$$\dot{I}_t = \frac{(R_{\mathrm{r}} + R_L)\dot{U}_{in}}{R_{\mathrm{t}}(R_{\mathrm{r}} + R_L) + \omega^2 M^2} \tag{6}$$

$$\dot{I}_{\mathrm{r}} = \frac{-j\omega M\dot{U}_{in}}{R_{\mathrm{t}}(R_{\mathrm{r}} + R_L) + \omega^2 M^2} \tag{7}$$

The maximum output power of the load resistance RL is obtained

$$\begin{aligned} P_o &= I_r^2 R_L \\ &= \left(\frac{\omega M U_{in}}{R_{\mathrm{t}}(R_t + R_L) + \omega^2 M^2} \right)^2 R_L \end{aligned} \tag{8}$$

In the resonant state, if the impedance and load of the system are kept constant, the output power mainly depends on the input DC source and high frequency AC frequency. At the same time, the output voltage of the system is

$$\begin{aligned} U_O &= I_r R_L \\ &= \frac{\omega M R_L}{R_{\mathrm{t}}(R_{\mathrm{r}} + R_L) + \omega^2 M^2} U_{in} \end{aligned} \tag{9}$$

It can be obtained that the output voltage can be controlled only by changing the resonant frequency of the system, and the frequency change of the system can be adjusted by the digital signals 0 and 1, and then the digital signals 0 and 1 can be distinguished by detecting different output voltages.

III. PERFORMANCE ANALYSIS OF SYNCHRONOUS TRANSMISSION OF ENERGY AND SIGNAL.

The synchronous transmission mode of power and signal sharing channel proposed in this paper is to display the digital signal on the voltage waveform of the system transmission energy by changing the output frequency of the inverter circuit. Because the resonant network is the common channel of information flow and power transmission, the impedance characteristics of the resonant network will affect the power transmission characteristics and signal transmission characteristics.

A. *A.Analysis of system transmission efficiency*

In the magnetically coupled resonant radio energy and signal synchronous transmission system, the energy wave carries the digital signal transmission, and the power Po received by the secondary coil can be obtained from the formula [9]. In the same way, the output power of the original coil can be deduced.

$$\begin{aligned} P_{o1} &= I_{\mathrm{t}}^2 R_t \\ &= \left(\frac{(R_{\mathrm{r}} + R_L)U_{in}}{R_{\mathrm{t}}(R_{\mathrm{r}} + R_L) + \omega^2 M^2} \right)^2 R_t \end{aligned} \tag{10}$$

The output efficiency of the transmission system

$$\begin{aligned} \eta &= \frac{P_o}{P_{o1}} \\ &= \frac{\omega^2 M^2 R_L}{(R_{\mathrm{r}} + R_L)^2 R_{\mathrm{t}}} \end{aligned} \tag{11}$$

The transmission efficiency of the above system is positively related to the working frequency, that is, the transmission efficiency η increases with the increase of the frequency ω ,but in the process of synchronous transmission of energy and signal, while ensuring high efficiency transmission, it is also necessary to take into account whether the output power of the system meets the practical application requirements.It can also be concluded that when the signal and energy are transmitted synchronously,the power transmission efficiency will not be greatly affected when the working frequency of the system is changed in a small range. Therefore, the resonant frequency point of the system and its adjacent frequency point can be selected as the working frequency of the system.

B. *signal acquisition and demodulation*

The digital signal is loaded into the power transmission structure by frequency shift keying. When the signal is extracted at the receiver, a reasonable demodulation structure needs to be designed in order to obtain the output voltage waveform containing the signal characteristics to recover the digital signal. Figure 4 shows the topology of the signal demodulation circuit. The digital signal is loaded into the power transmission structure by frequency shift keying. When the signal is extracted at the receiver, a reasonable demodulation circuit needs to be designed in order to obtain the output voltage waveform containing the signal characteristics to recover the digital signal. Figure 4 shows the topology of the signal demodulation circuit.The secondary side coil receives the energy of the carrying signal through the envelope detector to obtain the voltage envelope, and then connect the voltage envelope to the next topology for demodulation and recovery.

After obtaining the signal to be transmitted, it is sent to the MCU to determine whether to start receiving the digital signal.

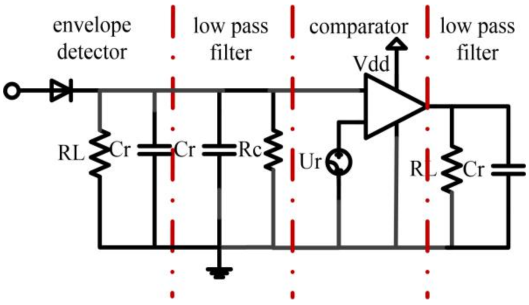

Figure. 4 Topology of signal recovery circuit

When the digital signal is 1, the FSK modulation circuit outputs the pulse with frequency f1; when the digital signal is 0, it outputs the pulse with frequency f2. The output frequency of the full-bridge inverter circuit is controlled to make the primary coil output different high-frequency AC. Figure 5 shows the signal waveform of the 0/1 signal and the FSK modulated signal. The system can demodulate the digital signal after analyzing and determining the decision voltage according to the different voltage amplitude of the receiver. The envelope waveform with obvious characteristics can be obtained by picking up the voltage envelope of the digital signal and filtering out the carrier component and other noise components by the low-pass filter. finally, the comparator which determines the threshold voltage is connected to realize the restoration of the original digital signal.

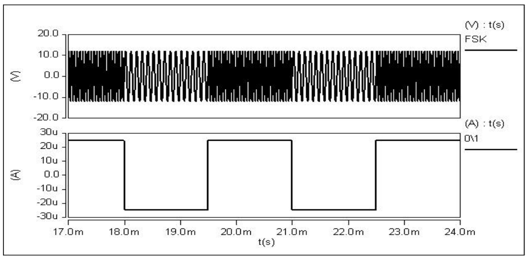

Figure. 5 FSK signal waveform

C. data signal acquisition process

When there is no signal transmission, the system is always in the resonant state, that is, the idle output high level (outputting of higher frequency carrier); when the system starts to transmit the signal, the MCU sends a starting signal receiver to start collecting the signal. When transmitting the data code, one bit of data (0 or 1) is transmitted per 1ms, while the starting code is formed by the high level of the 1.5ms (controlling the higher frequency carrier) and the low level of the 0.5ms (controlling the sub-high frequency carrier), and the termination code is formed by the high level of the 0.5ms and the low level of the 1.5ms. When the receiving detects the stop signal, the MCU does not process the signal, stopping receiving the signal and the system returns to the original resonant state. Figure 6 shows the digital signal transmission process.

Figure. 6 Digital signal transmission

IV. SIMULATION RESULTS AND ANALYSIS

In order to verify the rationality and feasibility of the system proposed in this paper, a circuit is built for simulation.The simulation parameters are as follows:DC voltage source 15.0V, two-coil internal resistance Rt=Rr=0.1 Ω , coupling coefficient K=0.25, load resistance RL=100 Ω , two compensation capacitors fixed to 250nF(C1=C2=250nF),and two-coil inductance 1mH. The natural resonant frequencies of the two circuits are calculated, and the square waves with frequencies of f1=10kHz and f2=11kHz are used as the two carriers of the signal modulation circuit.Figure 7 shows the transmitted digital signal and the voltage waveform of the coil at the transmitting . The voltage waveform of the transmission system changes when different digital signals are transmitted at 0 and 1. In figure 8, the voltage waveform of the coil at the receiving end, the voltage envelope waveform extracted by the voltage envelope extractor after passing through the low-pass filter, and the recovered digital signal are shown in turn.

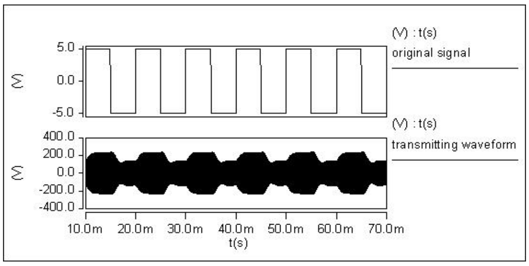

Figure. 7 the digital signal to be received and the voltage waveform of the coil at the transmitting end

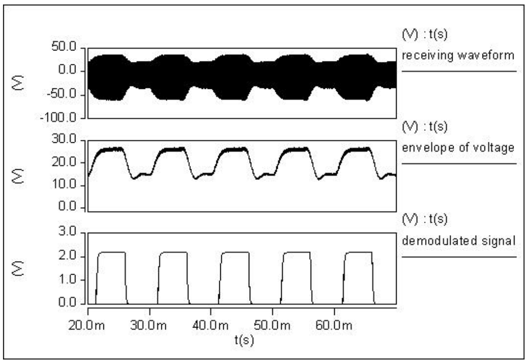

Figure. 8 receiver coil voltage waveform and signal extraction module waveform

V. CONCLUSION

Based on the magnetically coupled resonant radio energy transmission system, a method of synchronous transmission of energy and signal is proposed. In this method, the switching state of the inverter circuit is controlled by FSK modulated signal pulse to adjust the working frequency of the system, so that the energy wave in the circuit carries the digital signal for transmission, and the receiving end not only receives the electric energy but also detects the receiving voltage waveform to demodulate and restore the signal.The two working frequency points, frequency 1 is the resonant frequency of MCR-WPT, and the frequency 2 is slightly higher than the resonant frequency, which can not only meet the system requirements, but also reduce the influence of the loaded signal on the original energy transmission system. The simulation results show that the system can realize the synchronous transmission of energy and signal.

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