

Dynamic Frequency Tracking Method for Anti-offset Wireless Power Transfer System Based on Phase Comparison

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Abstract. In this paper, a dynamic frequency tracking method for the anti-offset wireless power transfer system based on phase comparison is proposed. The anti-offset characteristics of the system are realized by the structural design of the transmitting coil. The proposed anti-offset coil is verified in both simulation and experiment. However, in order to solve the frequency shift caused by the change of system parameters, a dynamic frequency tracking method is proposed in this paper, which continuously captures and calculates the phase difference between the current and voltage at the transmitting unit through the STM32 chip, adjusts the output frequency in time, and finally keeps the working frequency near the slightly inductive area. This paper establishes an experimental prototype and achieves an efficiency improvement of 6% to 8% through the proposed control method.

1. Introduction

In recent years, with the widespread use of various types of portable electronic products, the drawbacks of the wired charging method have gradually emerged, and people began to pursue a wireless way to obtain energy. Due to its safety and convenience, the magnetic coupling technology of magnetic coupling resonance has been gradually applied to electric wireless charging vehicles, transmission line equipment and biological implant equipment [1-3], even if there are some obstacles in the transmission channel, the power transfer will not be affected, ensuring the stability and reliability of the system [4].

However, the research on the wireless power transfer technology of the magnetic coupling resonance mode is mostly established in the case where the transmitting coil and the receiving coil are symmetrical, but in most cases, especially in the wireless power transfer of portable electronic products, limited by the size of the receiving device, the absolute symmetry of the transmitting coil and the receiving coil cannot be achieved [5].

For asymmetric coupling, due to the asymmetry in the size of the transmitting coil and the receiving coil, once the offset between the transmitting coil and the receiving coil occurs, the transmission effect of the wireless power transmission will be greatly affected. Therefore, it is necessary to increase the offset resistance of the transmitting coil. In this regard, there are mainly two ways to achieve, one is to design the structure of the transmitting coil to produce a uniform magnetic field [6,7]; the other is to control through changing the topology of the system [8].

For the wireless power transfer of the magnetic coupling resonance mode, there is an inherent resonant frequency, and the system has the largest transmission power at its inherent resonant frequency. However, during power transmission, the resonant frequency may change for various reasons, such as changes in parasitic parameters, offset of the receiving coil, rise in coil temperature,



and so on. The above phenomenon is called detuning. Once detuning occurs, the efficiency of the system drops rapidly, and the input frequency must be changed by the frequency tracking module to accommodate changes in the resonant frequency.

2. Analysis of System Model

2.1. Analysis of Coil Anti-Offset Characteristics

For the conventional coil, a horizontal spiral type winding method is often used, so that the coil inductance can be calculated according to an empirical formula:

$$L = 2.15 \times 10^{-6} \frac{R_1 + R_2}{2} N^{\frac{5}{3}} \ln \frac{8a}{R_2 - R_1} \quad (1)$$

where R_1 is the inner radius of the planar spiral coil and R_2 is the outer radius of the planar spiral coil.

However, at the same size, if the winding is performed in a conventional way, more turns will be required, thereby increasing the inductance of the coil, resulting in a small matching resonant capacitor, which seriously affects the system. However, if the number of winding turns of the coil is reduced in order to reduce the inductance of the coil, the coil will form a "concave" magnetic field distribution in the central region, which cannot achieve the uniform of the magnetic field [9].

In order to make the magnetic field distribution on the coil surface uniform, the current density distribution of the coil should satisfy:

$$\sigma(r, R) = i_0 r (R^2 - r^2)^{-\frac{1}{2}} H(R - r) \quad (2)$$

where R is the radius of the transmitting coil, r is the distance between the center point of the receiving coil and the center point of the transmitting coil, h is the vertical distance, the magnetic field on the surface of the coil is:

$$B_z = \frac{\mu_0 i_0 \pi}{4} (r < R) \quad (3)$$

After determining the target magnetic field distribution, the current density distribution of the coil can be reversed by the magnetic field distribution. The area under the current density curve is divided into N equal parts, and each part is replaced by one turn. The turn position f_n is determined by the coefficient a ($0 \leq a \leq 1$). When $a = 1$, the turn is placed at the rightmost place, and when $a = 0$, the turn is placed at the leftmost place [10].

The expression for the position where the n^{th} turn is placed is:

$$\frac{r_n}{R} = a \sqrt{1 - \left(\frac{N-n}{N}\right)^2} + (1-a) \sqrt{1 - \left(\frac{N-n+1}{N}\right)^2} \quad (4)$$

Through the above calculation, the structural distribution of the system transmitting coil can be obtained, and the anti-offset characteristics of the coil can be realized.

2.2. Analysis of Frequency Tracking

For the wireless power transfer system, the basic series-series compensation topology is shown in figure 1.

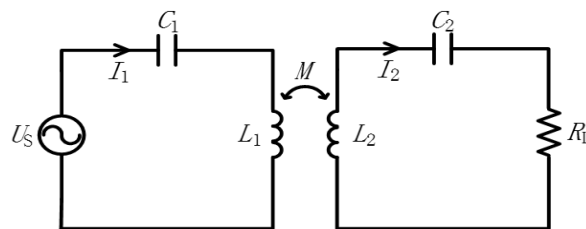


Figure 1. Basic topology diagram of the wireless power transfer system

For figure 1, the mesh current equation can be listed as follows:

$$\begin{cases} \dot{U}_s = \left(j\omega L_1 + \frac{1}{j\omega C_1} \right) \dot{I}_1 + j\omega M \dot{I}_2 \\ 0 = j\omega M \dot{I}_1 + \left(j\omega L_2 + \frac{1}{j\omega C_2} + R_L \right) \dot{I}_2 \end{cases} \quad (5)$$

Assume that the system operates at the resonant frequency. At this time, the primary and secondary currents are:

$$\begin{cases} \dot{I}_1 = \frac{R_L}{\omega^2 M^2} \dot{U}_s \\ \dot{I}_2 = \frac{\dot{U}_s}{j\omega M} \end{cases} \quad (6)$$

Taking the power supply voltage as the reference phasor, we can see from the above equation that when the wireless power transmission system operates at the resonant frequency, the primary current phase will be the same as the power supply voltage phase; and once the operating frequency of the system shifts, when $\omega > \omega_0$, the system will be in the inductive zone, at which time the voltage will lead the current; and when $\omega < \omega_0$, the system will be in the capacitive region, at which time the voltage will be behind the current.

From the above, we can know that when the operating frequency of the wireless power transfer system deviates from the resonant frequency of the system, it will cause a phase difference between the current and the voltage of the primary side of the system. Based on this, the primary side voltage and current phase of the wireless power transmission system are measured, thereby implementing frequency tracking of the wireless power transmission system.

3. Design and Simulation of the Coil Structure

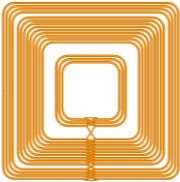

As described above, the design of the transmitting coil structure is mainly to reasonably distribute the pitch of the coils so that the current density distribution satisfies the obtained current density distribution, thereby realizing a uniform magnetic field of the coil and improving the anti-offset characteristics of the coil.

The transmitting coil designed in this paper is a square coil with a side length of 15 cm. The coil is uniformly wound with a Litz wire having a wire diameter of 1.6 mm, and mainly comprises three parts, wherein part I is the outermost 4 turns, which generates a "concave" type magnetic field; part II is the middle 9 turns, by which fill the magnetic field depression; part III is the innermost 3 turns, which further fills the magnetic field depression.

Taking into account the volume of the portable electronic product, the receiving coil has a circular design with a radius of 1 cm, a wire diameter of 1 mm, and a tight winding of 10 turns.

The parameters of the transmitting coil and receiving coil used in this paper are shown in table 1.

Table 1. Parameters of the coils in the experiment

	Type of coil	Transmitting coil
	Number of turns	16
	Outer radius / turns of part I	7.5cm/4
	Outer radius / turns of part II	6.5cm/9
	Outer radius / turns of part III	3cm/3
	Diameter of the wire	0.16cm
	Turn spacing	0.1cm
	Number of layers	2
	Type of coil	Receiving coil
	Number of turns	10
	Outer radius	2cm
	Diameter of the wire	0.1cm
	Number of layers	2

The simulation result of the coupling coefficient k with the horizontal displacement of the receiving coil is shown in figure 2. For comparison, three sets of control simulation groups were made at the same time, that is, only the part I of the transmitting coil, only the part I and part II of the transmitting coil, transmitting coil is wound 24 turns directly.

We can see that the coupling coefficient of only part I of the transmitting coil and only the part I and part II of the transmitting coil is low from figure 2, and depression occurs with the horizontal offset so that the anti-offset cannot be realized. When the transmitting coil is wound 24 turns, the coupling coefficient is too large when the offset is small, so the anti-offset effect is not ideal. However, the coil designed in this paper has better anti-offset characteristics and a high coupling coefficient.

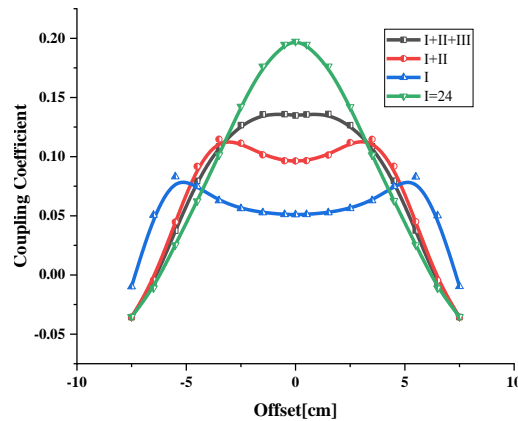


Figure 2. Diagram of coupling coefficient and horizontal offset relationship

4. Model Experiment Verification

According to the coil model designed in the previous section, the Litz wire is used to wind the transmitting coil and the receiving coil. The coils wound with the Litz wire can effectively reduce the effects of the proximity effect and the skin effect.

In order to verify the anti-offset of the proposed coil and the improvement of the frequency tracking to the whole system, the experimental prototype is set up as shown in figure 3.

The transmission distance is set to 5 mm, and the relationship between the coupling coefficient of the actual coil and the horizontal offset is measured as shown in figure 4. It can be seen that the coupling coefficient in the actual measurement is basically consistent with the variation of the coupling coefficient in the simulation.

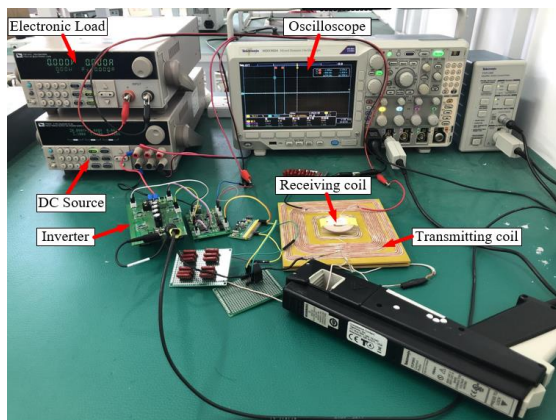


Figure 3. Diagram of the experimental prototype

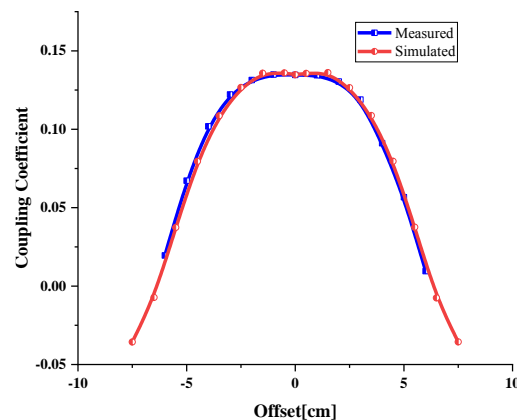


Figure 4. Diagram of coupling coefficient and horizontal offset relationship

Set the DC power supply voltage to 20 V, and the initial operating frequency of the system is 310 kHz. Take the case of no horizontal offset, the voltage and current waveforms of the system's transmitting unit are shown in figure 5(a). After the phase difference between voltage and current is captured and calculated by STM32, the output frequency is adjusted, and the adjusted voltage and current waveforms of the transmitting unit are shown in figure 5(b). At this time, the frequency is about 304 kHz, and the current becomes significantly larger, which is caused by the fact that the equivalent impedance of the LC loop is becoming smaller during the process of shifting to the resonance point. In order to prevent an excessive current from occurring during resonance, the final frequency stays in a slightly inductive region near the resonant point.

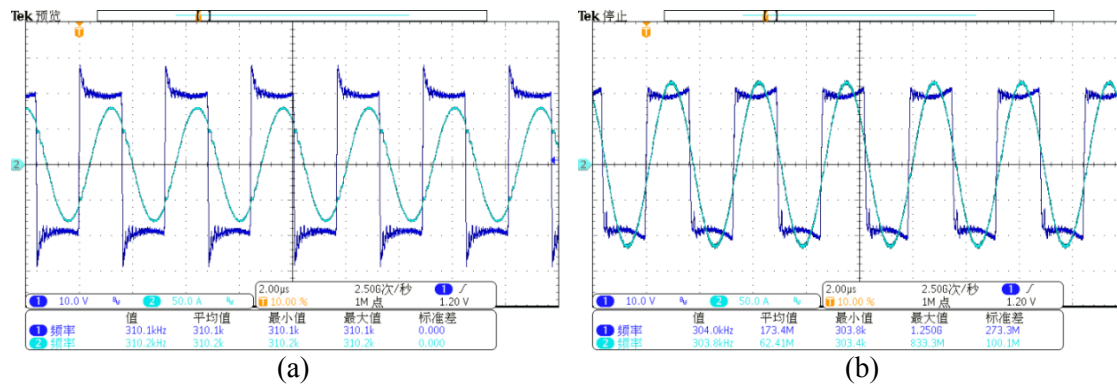


Figure 5. Waveforms of the voltage and current

The entire frequency tracking process is shown in figure 6. Firstly, the initial operating frequency f_0 of the inverter is given, and then the voltage and current phase of the transmitting unit are compared, thereby judging that it is in the inductive region or the capacitive region. If it is in the capacitive region, the frequency will be increased by Δf , and if it is in the inductive region, the frequency will be reduced by Δf until the phase difference meets the accuracy. Finally, the frequency is fine-tuned to operate the system in a slightly inductive region.

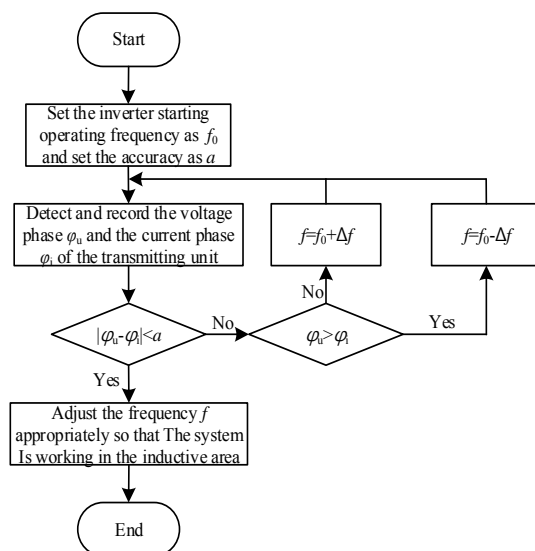


Figure 6. Workflow of the frequency tracking system

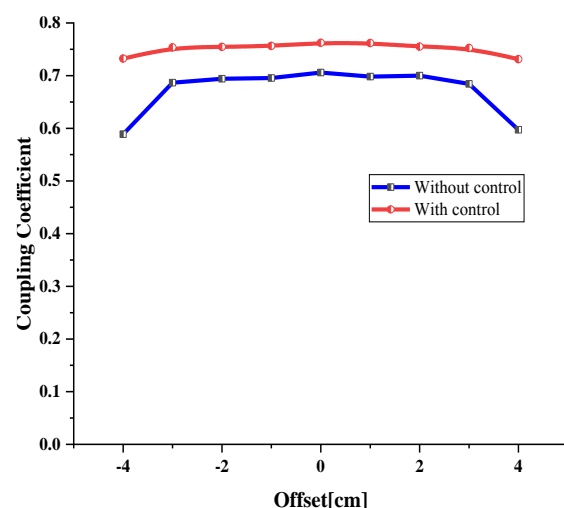


Figure 7. The transmission performance of the promoted wireless power transfer system

The transmission performance for a wireless power transfer system with or without frequency tracking control is shown in figure 7. The DC power supply is 20V. From the figure, we can see that under the effect of frequency tracking control, the transmission efficiency of the wireless charging system has been significantly improved. The transmission efficiency increases by about 6% to 8% on average, while the transmission efficiency does not change a lot in the effective charging area.

5. Conclusion

In this paper, a transmission coil design with anti-offset performance is proposed in order to solve the problem of the transmission efficiency reduce caused by the offset between the transmitting coil and receiving coil in the asymmetric wireless charging system, and the proposed transmitting coil is verified in simulation and experiment. Secondly, a frequency tracking control method based on voltage and current phase comparison is proposed for the problem of system parameter changes. The system can effectively improve the anti-offset characteristics of the wireless charging system, and at the same time ensure high transmission efficiency while ensuring anti-offset characteristics, and improve the flexibility and adaptability of the wireless charging system.

6. Acknowledgments

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7. References

- [1] Cai C, Wang J, Liu R, Fang Z, Zhang P, Long M, Hu M, Lin Z, Resonant Wireless Charging System Design for 110-kV High-Voltage Transmission Line Monitoring Equipment[J]. IEEE Transactions on Industrial Electronics, 2019, 66(5): 4118–4129.
- [2] Wang J, Cai C, Li L, Zhang P, Liu Q, Zhang F, Fang Z, Extended efficiency control method for WPT systems in smart grid under loose coupling extremes[J]. IET Power Electronics, 2019, 12(10): 2523-2533.
- [3] Cai C, Wang J, Fang Z, et al. Design and Optimization of Load-Independent Magnetic Resonant Wireless Charging System for Electric Vehicles[J]. IEEE Access, 2018, 6: 17264-17274.
- [4] Jiang, J., Zhu, C., Song, K., Wei, G., Zhang, Q.. (2016). Novel power receiver for dynamic wireless power transfer system. *Conference of the IEEE Industrial Electronics Society*. IEEE.
- [5] Lee G, Waters B H, Shi C, et al. Design considerations for asymmetric magnetically coupled resonators used in wireless power transfer applications[C]// Power Amplifiers for Wireless & Radio Applications. IEEE, 2013.
- [6] Kim J, Kim D H, Kim K H, et al. Free-positioning wireless charging system for hearing aids using a bowl-shaped transmitting coil[C]// Wireless Power Transfer Conference. IEEE, 2014
- [7] Jolani F, Yu Y Q, Chen Z. A planar positioning-free magnetically-coupled resonant wireless power transfer[C]// Wireless Power Transfer Conference. 2015.
- [8] Zhang W, Zhang T, Guo Q, et al. High-efficiency wireless power transfer system for 3D, unstationary free-positioning and multi-object charging[J]. IET Electric Power Applications, 2018, 12(5):658-665.
- [9] Li S, Niu P, Yu L, Mao R, et al. Design method of primary transmitting coil for realizing large uniform magnetic field distribution[C]// 3rd International Conference on Mechanical, Control and Computer Engineering. 2018.
- [10] Waffenschmidt E . Homogeneous Magnetic Coupling for Free Positioning in an Inductive Wireless Power System[J]. Emerging & Selected Topics in Power Electronics IEEE Journal of, 2015, 3(1):226-233.