

Study on Frequency Adaptive Wireless Energy Transmission System

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Abstract

Frequency is an important parameter that affects the efficiency of a wireless energy transmitting system. By derivation, an expression is presented which can indicate the relation among efficiency, capacitance and resonant frequency. Be aimed at a simulation model for a loosely coupled transformer, curves of the expression show detuning of the primary circuit will significantly affect system efficiency. Then a frequency tracking module is specially designed to add into a wireless energy transmission system to constitute an experimental platform. Experiments confirm that the frequency tracking module can help the system get higher efficiency which is measured to be 2.527%.

Key Words: Wireless Energy Transmitting, Compensation, Resonant, Frequency Tracking

1. Introduction

Nowadays more and more novel implantable medical electronic devices are employed such as cardiac pacemaker, artificial heart and artificial cochlea [1]. In recent years researchers try to use wireless power transmission technology to power the implantable devices instead of chemical cells which have several big disadvantages such as limited capacity, large volume and low security [2–5]. Loosely coupled transformer which can enable power transfer across space is the key component of a wireless power transmission system. In order to improve transmission efficiency and keep the efficiency stable, multi-dimensional structure was adopted in the loosely coupled transformer and studied by many researchers [6–9]. It is proved that multi-dimensional wireless power transmission system can make energy transfer effectively regardless of the relative posture between the primary coil and the second coil of the loosely coupled transformer [7]. These systems usually operate in high frequency (100 KHz~5G Hz) [10], then a high impedance will oc-

cur in circuit unless the system is well compensated by capacitors connected in series or in paralleling. If well compensated, system will resonate and its impedance become a pure resistance in a certain frequency. But in practice, system inductances are difficult to remain unchanged due to the fact that the relative posture between the primary coil and the second coil of the loosely coupled transformer changes continually when working.

Thus there are two selectable ways to keep system resonating, adjusting compensation capacitance value or working frequency according to the inductance. But for the receiving part implanted or ingest in body, the interspace is rather cramped to set an extra adjustable capacitor which is difficult to be adjusted in fact. To sum up, frequency control is a feasible method to make system resonate.

2. Multi-dimensional Wireless Transmission System

2.1 Reason of Detuning

Wireless energy transmitting system utilizes electromagnetic induction between the primary coil and the sec-

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ondary coil to transmit electrical energy. On the one hand, coil inductions are benefit to energy transmitting, on the other hand, they introduce large inductive impedance into system circuit. In order to eliminate negative affect of inductive impedances, enhance active power and transmitting efficiency, inductive impedances need to be compensated by capacitors and a LC resonant circuit is obtained then. The resonant frequency f can be determined by $f = 1/2\pi LC$, where L and C are inductance and capacitance. However, in the practical application, value L affected by surrounding magneto conductivity, temperature and other parasitic parameters, will change accordingly. Meanwhile, the transmitting coil outside body has large geometry, so notable distributed capacitance and parasitic capacitance appear in the circuit and cannot be neglected. The above two factors make system natural frequency deviate from the working frequency and enter detuning state. As a result, the primary circuit and the secondary circuit are no longer in pure resistance state and the transmit efficiency consequently declines.

2.2 Effect of Detuning on Transmitting Efficiency

For the three-dimensional wireless energy transmitting system studied in present paper, three windings included in the receiving coil are placed in the same in-vivo environment, and parameters of the three winding can be considered to be consistent. To simplify the derivation and calculation, changes in both inductance and capacitance are treated as change only in inductance. Set the inductance deviation value from the resonant state of ΔL . Transmitting efficiency of 3D wireless energy transmitting system can be calculated according [11], which are expressed as

$$\eta = \frac{P_{out}}{P_{in}} = \frac{\sum_{i=1}^3 \frac{\omega^2 M_i^2}{Z_{ri}^2} R_{li}}{Z_t + \sum_{i=1}^3 \frac{\omega^2 M_i^2}{Z_{ri}}} \quad (1)$$

$$= \frac{R_L \sum_{i=1}^3 \frac{\omega^2 M_i^2}{\left[j \left(\omega L_{ri} - \frac{1}{\omega C_{ri}} \right) + R + R_L \right]^2}}{R_t + j \left(\omega L_t - \frac{1}{\omega C_t} \right) + \sum_{i=1}^3 \frac{\omega^2 M_i^2}{j \left(\omega L_{ri} - \frac{1}{\omega C_{ri}} \right) + R + R_L}}$$

where, R_t and L_t are internal resistance and inductance

of the primary coil, C_t is compensation capacitance of the primary circuit, L_{ri} and C_{ri} ($i = 1, 2, 3$) are inductance of three windings in the secondary coil and compensating capacitance for the three circuits, R and R_L are internal resistance of the three windings and system load, M_i ($i = 1, 2, 3$) are mutual inductance between the primary coil and the windings in the secondary coil, ω is angular frequency.

According to the above transmitting efficiency expression, meanwhile, suppose the inductance and capacitance of the primary coil in the resonant state are L_p and C_p , the inductance and capacitance of the three windings included in secondary coil in the resonant state are L_{ni} and C_{ni} ($i = 1, 2, 3$). Combined with different detuning situations, the specific analysis are as follows:

When the transmitting circuit resonates, the receiving circuits do not resonate, that is,

$$\omega L_p - \frac{1}{\omega C_p} = 0, \quad (2)$$

$$\omega(L_{ni} + \Delta L) - \frac{1}{\omega C_{ni}} = \omega \Delta L, (i = 1, 2, 3)$$

Then, the above equations are substituted into Eq. (1) and results in a new expression for efficiency,

$$\eta = \frac{P_{out}}{P_{in}} = \frac{R_L \sum_{i=1}^3 \frac{\omega^2 M_i^2}{\left\{ j \left(\omega L_{ni} - \frac{1}{\omega C_{ni}} \right) + R + R_L \right\}^2}}{R_t + j \left(\omega L_p - \frac{1}{\omega C_p} \right) + \sum_{i=1}^3 \frac{\omega^2 M_i^2}{j \left(\omega L_{ni} - \frac{1}{\omega C_{ni}} \right) + R + R_L}} \quad (3)$$

$$= \frac{R_L \sum_{i=1}^3 \frac{\omega^2 M_i^2}{(j\omega \Delta L + R + R_L)^2}}{R_t + \sum_{i=1}^3 \frac{\omega^2 M_i^2}{j\omega \Delta L + R + R_L}}$$

$$= \frac{\omega^2 R_L \sum_{i=1}^3 \frac{M_i^2}{|j\omega \Delta L + R + R_L|}}{\left| (j\omega \Delta L + R + R_L) R_t + \omega^2 \sum_{i=1}^3 M_i^2 \right|}$$

When neither the transmitting circuit nor the receiving

circuits work in resonance state, that is,

$$\begin{aligned}\omega(L_p + \Delta L) - \frac{1}{\omega C_p} &= \omega \Delta L, \\ \omega(L_{ni} + \Delta L) - \frac{1}{\omega C_{ni}} &= \omega \Delta L, (i = 1, 2, 3)\end{aligned}\quad (4)$$

Substitute Eq. (4) into Eq. (1), we can get efficiency expression as follows

$$\begin{aligned}\eta &= \frac{P_{out}}{P_{in}} \\ &= \frac{R_L \sum_{i=1}^3 \frac{\omega^2 M_i^2}{\left\{ j \left(\omega L_{ni} - \frac{1}{\omega C_{ni}} \right) + R + R_L \right\}^2}}{R_i + j \left(\omega L_p - \frac{1}{\omega C_p} \right) + \sum_{i=1}^3 \frac{\omega^2 M_i^2}{j \left(\omega L_{ni} - \frac{1}{\omega C_{ni}} \right) + R + R_L}} \\ &= \frac{R_L \sum_{i=1}^3 \frac{\omega^2 M_i^2}{(j\omega \Delta L + R + R_L)^2}}{R_i + j\omega \Delta L + \sum_{i=1}^3 \frac{\omega^2 M_i^2}{j\omega \Delta L + R + R_L}} \\ &= \frac{\omega^2 R_L \sum_{i=1}^3 \frac{M_i^2}{|j\omega \Delta L + R + R_L|}}{\left| (j\omega \Delta L + R + R_L)(R_i + j\omega \Delta L) + \omega^2 \sum_{i=1}^3 M_i^2 \right|}\end{aligned}\quad (5)$$

When the receiving circuits resonate, but the transmitting circuit does not resonate, that is,

$$\omega(L_p + \Delta L) - \frac{1}{\omega C_p} = \omega \Delta L, \omega L_{ni} - \frac{1}{\omega C_{ni}} = 0, (i = 1, 2, 3) \quad (6)$$

According to Eq. (1), under this condition we can get

$$\begin{aligned}\eta &= \frac{P_{out}}{P_{in}} \\ &= \frac{R_L \sum_{i=1}^3 \frac{\omega^2 M_i^2}{\left\{ j \left(\omega L_{ni} - \frac{1}{\omega C_{ni}} \right) + R + R_L \right\}^2}}{R_i + j \left(\omega L_p - \frac{1}{\omega C_p} \right) + \sum_{i=1}^3 \frac{\omega^2 M_i^2}{j \left(\omega L_{ni} - \frac{1}{\omega C_{ni}} \right) + R + R_L}}\end{aligned}$$

$$\begin{aligned}&= \frac{R_L \sum_{i=1}^3 \frac{\omega^2 M_i^2}{(R + R_L)^2}}{R_i + j\omega \Delta L + \sum_{i=1}^3 \frac{\omega^2 M_i^2}{R + R_L}} \\ &= \frac{\omega^2 R_L \sum_{i=1}^3 \frac{M_i^2}{R + R_L}}{\left| (R + R_L)(R_i + j\omega \Delta L) + \omega^2 \sum_{i=1}^3 M_i^2 \right|}\end{aligned}\quad (7)$$

For further research, a loosely coupled transformer is designed and produced out, as shown in Figure 1.

By measuring, a series of parameters can be obtained, $R_p = 0.55 \Omega$, $L_p = 453.4 \mu\text{H}$, $R = 0.85 \Omega$, $L_1 = 66.57 \mu\text{H}$, $L_2 = 68.74 \mu\text{H}$, $L_3 = 60.53 \mu\text{H}$. In addition, let the system work in the frequency $f_0 = 366 \text{ kHz}$ and under the load $R_L = 51 \Omega$. In the loosely coupled transformer, mutual inductance between the primary coil and each secondary winding is not a fixed value, but changes along with the secondary coil position and posture, then we take any one of the positions to study. Using finite element software for simulation calculation (simulation model shown in Figure 2), three inductance values are obtained, $M_1 = 1.31 \mu\text{H}$, $M_2 = 1.52 \mu\text{H}$, $M_3 = 1.11 \mu\text{H}$. Then ΔL , as an independent variable, is substituted into Eq. (7), in which transmitting efficiency η is a dependent variable. As a result, transmitting efficiency curves with inductance values of the primary and the secondary coils are obtained which are shown in Figure 3.

In term of efficiency curve in Figure 3(a), at frequency $f = 366 \text{ kHz}$, if the inductance offset of each winding in the secondary coil is between $\pm 2 \mu\text{H}$, system efficiency η does not change much. Figure 3(b) shows that system efficiency suddenly drops by about 37% if the inductance offset of the primary coil is $\pm 2 \mu\text{H}$. In Figure 3(c), system efficiency also drops by about 37% if both the primary inductance and the secondary inductance

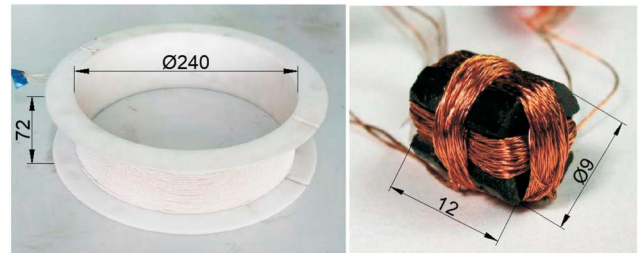


Figure 1. Primary coil and secondary coil of the loose coupling transformer.

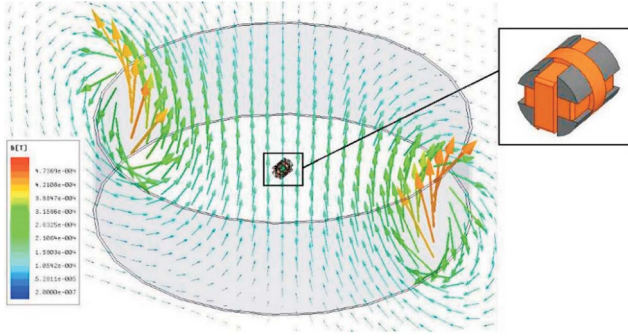


Figure 2. Simulation model of the loose coupling transformer.

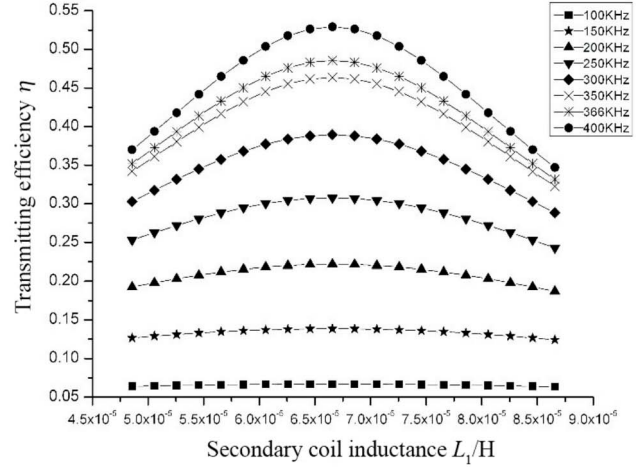
offset are $\pm 2 \mu\text{H}$. In summary, the secondary coil inductance and the compensation capacitance have little impact on transmitting efficiency, so the system can still maintain a high transmission efficiency when detuning occurs in the secondary circuit. But for the primary coil, the situation is just the opposite, when the primary circuit is detuned, the system will not work properly due to the low energy reception efficiency. Furthermore, it can be seen from Figure 3(a–c) that as the system operating frequency increases, the system transmission efficiency also increases. The above analyses are based on the ideal mathematical modeling. In an actual system, whether the above trends still exist needs to be verified. In the following, a three-dimensional wireless energy transmitting platform will be built to verify the above conclusions.

2.3 Experimental Verification

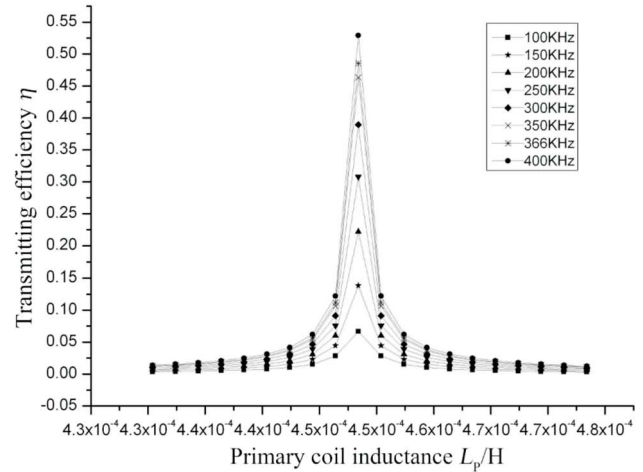
The experimental platform of the three-dimensional wireless energy transmission system, which is shown in Figure 4, are composed of a signal source, a power meter, a primary transmitting coil, a secondary receiving coil, compensation capacitor board, a rectifier circuit board and a multi-meter.

In this experiment, a 366 Hz excitation sine wave current provided by the signal source drives the transmitting coil to produce an alternating magnetic field which makes the three-dimensional secondary coil generate induced electromotive force with the same frequency. The electromotive force after being capacitive compensated, rectified and filtered, converts into a relatively stable voltage applied on the load.

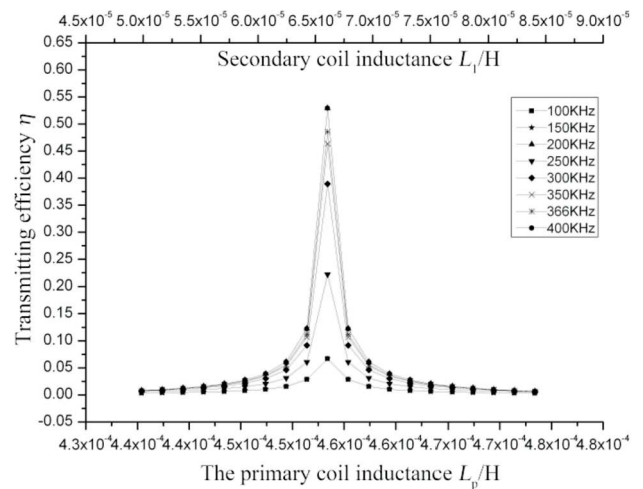
In order to simulate the actual operation of the system, it is necessary to adjust circuit resonant frequency to create a system of detuning state. There are two ways to



(a) The variation of transmitting efficiency with inductance of winding I in secondary coil



(b) The variation of transmitting efficiency with inductance of the primary coil



(c) The variation of transmitting efficiency with inductances of the primary coil and the secondary coil

Figure 3. The ideal relationship between transmitting efficiency and coil inductances.

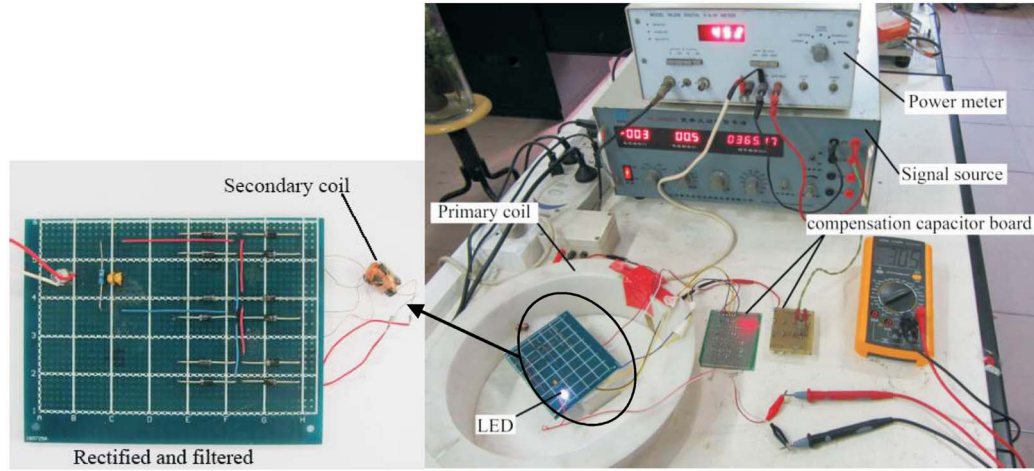


Figure 4. The experimental platform.

adjust the resonant frequency, one is to change coil inductance by adjusting coil turn, width, wire diameter and coil diameter, the other is to change the compensation capacitance, but it is more inconvenient to change coil parameters, so the latter way is used to adjust the resonant frequency in follow-up study. Figure 5 shows the primary compensation capacitor board and secondary compensation capacitor board. The primary board consists of 14 EACO high frequency non-inductive capacitors (4nF) connected in series and 15 contacts. Then adjustment for the compensation capacitance of the primary circuit will achieve conveniently by connecting different contacts in the circuit. The secondary board consists of 8 groups of chip capacitors and each group includes three capacitors with different specifications for the three windings (Table 1). So the secondary circuit can be compensated respectively by connecting different group.

In the course of experiments, adjust the secondary circuit to ensure that the three secondary windings operate in a resonant state and set the input voltage of the pri-

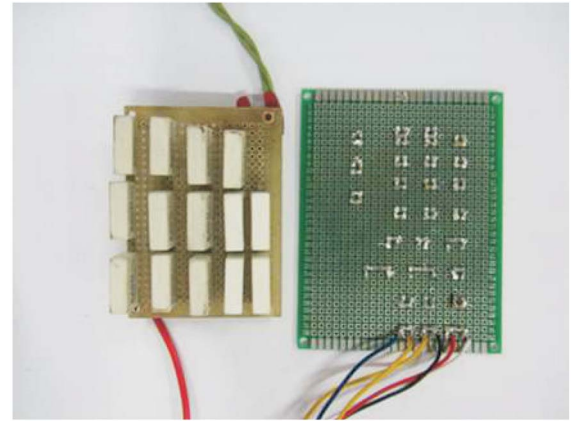


Figure 5. Compensation capacitors of the primary circuit and the secondary circuit.

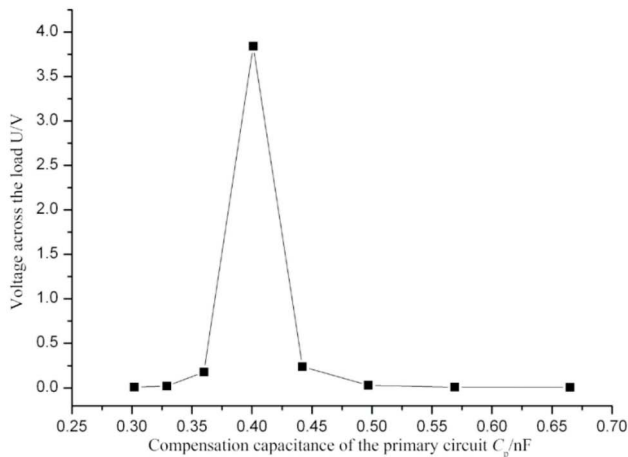
mary circuit to 8 V, then the voltage across the load is measured and shown in Figure 6(a) when different compensation capacitors are connected into the primary circuit. It is thus clear that if compensation capacitance for the primary circuit slightly deviates from the resonant capacitance value, the voltage across the load will drop

Table 1. Compensation capacitors

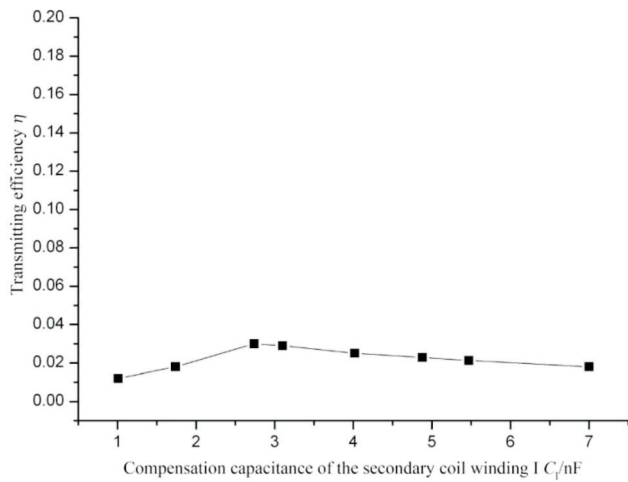
Compensation capacitor of the primary circuit C_p/nF	Compensation capacitor of the secondary circuit C_i/nF ($i = 1, 2, 3$)		
	Winding I	Winding II	Winding III
0.302	1.01	0.33	0.33
0.329	1.74	1.00	1.00
0.360	2.74	2.23	2.21
0.402	3.10	2.63	2.63
0.442	4.02	3.43	3.41
0.497	4.88	4.20	4.20
0.569	5.47	4.82	4.82
0.665	7.0	6.43	6.43

sharply, that is, if the resonant frequency of the primary circuit deviates from system operating frequency, the transmitting efficiency of the system will dropped sharply.

In the second stage of the experiment, let the primary circuit work in the resonant state and connect different groups of compensation capacitors (listed in Table 1) with the three windings, after this, adjust input power to make sure the voltage applied on the load is 3V at different compensations, system efficiency curve can be gained and given in Figure 6(b). It is observed the transmitting efficiency does not change greatly when the resonant frequency of the secondary coil deviates from the system frequency. Above all, system efficiency will be distinctly affected by the detuning occurred in energy transmitting coil but almost unaffected by that in energy receiving coil.



(a) The variation of transmitting efficiency with compensation inductance of the primary coil



(b) The variation of transmitting efficiency with compensation inductance of the secondary coil winding I

Figure 6. System detuning experiments.

2.4 Frequency Tracking Study

In the actual work, because of circuit temperature variation, parasitic capacitance variation, manufacturing error of capacitor, the resonant frequencies of the primary circuit and the secondary circuit are easy to change and deviate from the preset operating frequency. The deviations lead to system detuning which will reduce loop current used to generate alternating electromagnetic field, and then lead to sharply reduction in transmitting efficiency, ultimately cause the follow-up device to fail to work. Therefore, frequency tracing technology is considered introducing into energy transmitting system to ensure the circuits can operate in a resonant state.

From the previous study in present paper, it is known that system efficiency will be distinctly affected by the detuning occurred in energy transmitting coil but almost unaffected by that in energy receiving coil. So a frequency tracking circuit can be designed for the energy transmitting coil to keep working in a resonant state. The structure of the frequency tracking wireless energy transmission system is shown in Figure 7. On the basis of an open-loop wireless energy transmission system, voltage phase and current phase detection circuits, frequency tracking circuit are introduced in and constitute the frequency tracking system.

Considered commonly used frequency tracking technologies, phase-locked loop frequency tracking (PPL) is adopted in the wireless energy transmission system and its principle is shown in Figure 8. Firstly, using a current sensor, a voltage signal which is proportional to the current is obtained and shaped into a square wave signal (V_{Q1}) after passing a zero-crossing comparator. Likewise, using a voltage transducer, the voltage across the primary coil can be detected and shaped into another square wave signal (V_{Q2}). Secondly, these two square wave signals V_{Q1} and V_{Q2} are simultaneously fed into the phase-

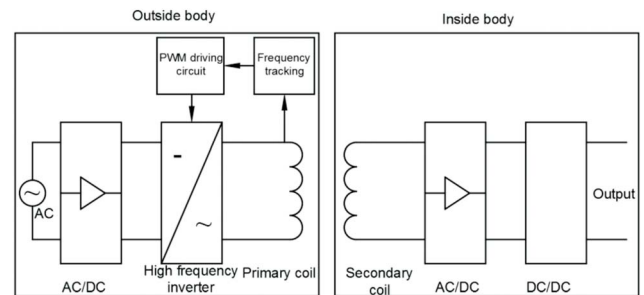


Figure 7. Frequency tracking scheme.

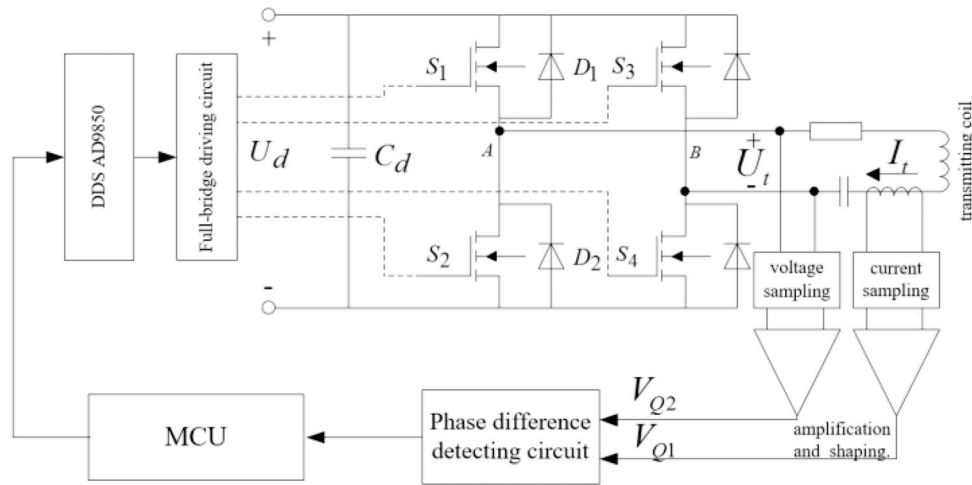


Figure 8. Frequency tracking inverter power supply based on MCU.

locked loop PLL for phase comparison. The resulting phase difference is passed into micro controller unit (MCU) and the MCU, after computations, will control a direct digital synthesizer chip (DDS AD9850) to adjust PWM frequency until the frequency allows the primary circuit to work in a resonant state.

3. Experiment

According to the PLL principle shown in Figure 8, a wireless energy transmitting experimental platform with frequency tracking module is fabricated as illustrated in Figure 9.

Based on this platform, with or without frequency tracking module, the current and voltage waveforms of the transmitting coil and system efficiency are obtained under the same operating conditions.

Firstly, disconnect frequency tracking module to the main circuit, the wireless energy transmitting system becomes an open loop system. Under this conditions, the voltage and the current across the primary coil are illustrated in Figure 10 when the input of the main circuit are 10 V, 366 kHz. It is clear that there is a significant phase difference between the current and the voltage, and because of its influence, system transmission efficiency is only 0.867%.

Secondly, connect frequency tracking module to the main circuit and let other circuit parameters remain unchanged. The initial frequency is also set to 366 kHz, sooner after the system starts, the operating frequency (shown in Figure 11) displayed on the oscilloscope

changes, and the current and voltage waveforms tend to overlap, meanwhile, the circuit current increased significantly. At this conditions, system transmission efficiency is up to 2.527%, much higher than the previous open-loop system (0.867%).

4. Conclusion

For a wireless energy transmitting system used to power subsequent devices, enough efficiency is crucial. In this paper, an expression of system transmitting efficiency η in the resonant state is obtained from derivation of circuits, which is used to analyze a multi-dimensional loose coupling transformer afterwards. The results show that the parameters of the primary coil, such as induc-

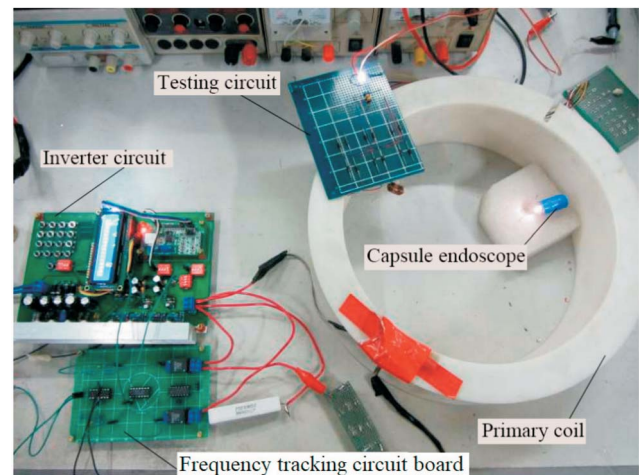


Figure 9. Wireless energy transmitting experimental platform.

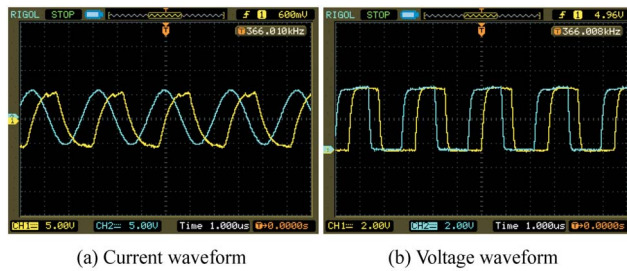


Figure 10. System output without frequency tracking module.

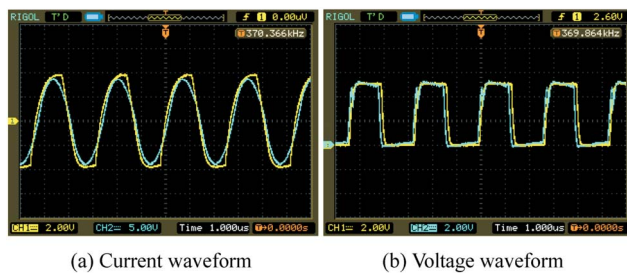


Figure 11. System output with frequency tracking module.

tance and compensation capacitance, have a greater impact on efficiency than those of the secondary coil. Furthermore, an experimental platform is developed in order to verify the effect of the frequency tracking module. Experiments show that using frequency tracking technology can effectively eliminate the difference between current and voltage, effectively maintain the stability of the system energy transmission, and the overall efficiency of the wireless energy transmitting system using frequency tracking module is measured to be 2.527%.

Acknowledgements

This work was supported by Shandong Provincial Natural Science Foundation, China (Grant No. ZR2016 HB59 and ZR2017LEE002).

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Manuscript Received: Mar. 22, 2018

Accepted: May 8, 2019