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Design and Analysis of Efficient Pulse-driven Magnetically Coupled Resonant Wireless Power Transmission System

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Abstract

As a new power transmission technology, magnetically coupled resonant wireless power transmission technology can achieve mid-range wireless power transmission with the advantage of high transmission efficiency. As known, the driving source has a significant impact on the overall performance of wireless power transmission system. With this consideration, a pulse-driven magnetically coupled resonant wireless power transmission system is proposed herein. The circuit model of the system is established on mutual inductance coupling theory. Through the analysis of its working mode the mathematical models of load power and transmission efficiency are established and the relationships among load power, transmission efficiency and driving signal frequency, duty cycle and transmission distance are revealed. Subsequently, a pulse-driven magnetically coupled resonant wireless power transmission prototype is designed and the experiment is conducted by using control variables method. The authenticity of the theory is verified as well by experiments. In the experiment, the system realizes wireless power transmission of load power 1.17W and transmission efficiency 76.13% under the condition of DC voltage 12V, driving signal frequency 94 KHz and duty cycle 15%.

Keywords: *magnetically coupled resonant, wireless power transmission, load power, transmission efficiency*

1. Introduction

With the rapid development of small mobile devices, the bondage of cable charging and the limitation of a heavy bump charge have become a more serious problem during the past few years. Meanwhile, it is difficult for the traditional cable transmission to meet the demand of power supply under some specific conditions, such as underwater, mines, isolated islands, *etc*. Therefore, as one of the most active research directions in the field of electrical engineering[1], the wireless power transmission (WPT) technology is becoming increasingly important and urgent. It is evaluated as one of the ten emerging technologies in the future [2].

Since Nikola Tesla proposed the conception of WPT, extensive researches have been carried out and many measures have been proposed to realize the WPT. In order to well understand the implications for range, adaptation, and efficiency, it is, therefore, necessary to classify these researches by the underlying power-transfer mechanism, which will fall into three categories: electromagnetic induction, electromagnetic radiation and magnetic coupling resonance. The electromagnetic induction WPT uses isolated transformer as transmission equipment and the

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transmission of electrical energy is achieved through electromagnetic coupling process, that is, mutual inductance. As a relatively mature WPT technology, it is easy to be implemented and controlled, and has high transmission efficiency in close range. However, due to the loose coupling between coils and power transferring through non-magnetic material, the magnetic field energy and coupling coefficient are rapidly attenuated with the distance increasing, resulting in a short transmission distance limited to centimeters, even millimeters level. Currently the applications of electromagnetic induction WPT have attracted a wide range of explorations and developments not only in domestic area but also across the world [3-6], which mainly focus on the wireless charge system [7-8], medical treatment equipment [9-11], and so on.

The electromagnetic radiation WPT, mainly including microwave transmission and laser transmission, can realize long-distance, high-power transmission. The mechanism of microwave transmission is that the electrical energy is converted into microwave by the microwave generator, efficiently emitted by the transmitting antenna to the receiving antenna through free space transmission and finally the microwave is converted back and energy is exported under the action of rectifying antenna [12-13]. The higher the frequency, the more the energy transmitted. And the transmission loss in atmosphere is very small. But the long wavelength of microwave can cause serious scattering in long distance transmission and therefore cause debasement of transmission efficiency. What’s even worse, the poor directionality is difficult to be solved [14-15]. Presently microwave transmission has shown a good application prospect in wireless charging [16-17], Solar Power Satellite (SPS), Space Solar Power (SSP) [18-20], and so on. Laser transmission has the advantages of better directional property, small scatter and bigger power carrying capability, and so on. NASA demonstrated wireless power transmission from a laser to a model plane in 2003[21].But the efficiency of converting electrical energy to laser is not so high at moment and the obstacles have a significant influence on laser transmission.

Comparing the disadvantages of above-mentioned WPT modes, people are eager to find a WPT mode which can realize efficient energy transmission within a few meters. In 2006 Prof. Marin Soljačić and his research team in MIT proposed the mid-range WPT technology based on magnetic coupling resonance in the AIP forum in the United States [22], and the theory was tested in 2007 with great success, transmitting 60 watts across 2 meters with 40 percent efficiency [23]. This technology opens up a new research direction for mid-range WPT with the advantages of high transmission efficiency, long distance and large transmission power and attracted researchers’ attention immediately. As an important part of the transmission system, the resonant-driven device has a significant impact on overall performance of WPT system. Authors in the literature [23] used colpitts oscillator as driving source, but the driving device has a large power loss and low transmission efficiency for its linear amplification working mode. In the study of literature [24-26], class E power amplifier was used to effectively improve the efficiency of driving source, but the relationship between transmission efficiency, driving signal and transmission distance was not introduced.

In this paper, in order to simplify the driving circuit and improve transmission efficiency, a pulse-driven single tube circuit is proposed. The frequency selective network is formed by tuning capacitor and transmitter coil in parallel manner. The circuit model of WPT system is established firstly on the principle of mutual inductance and the coupling theory. We conclude the key factors that affect the load power and transfer efficiency, such as resonance frequency, the distance between the coils and the valid value of the input voltage through detailed analysis. Then we design a prototype of pulse-driven magnetically coupled resonant wireless power transfer system and use it to conduct a series of experiments. The experimental results have a good consistency with the theoretical analysis.

2. Overview of the System

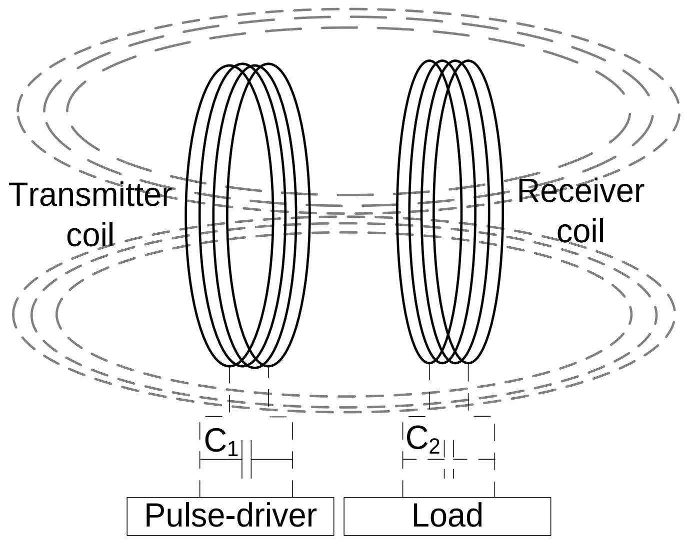

Figure 1. The Diagram of the Wireless Power Transmission System

Figure 1 shows the diagram of the pulse-driven magnetically coupled resonant wireless power transmission system. The system consists of two parts, the transmitting terminal and receiving terminal. The transmitting terminal is composed by a wire-wound coil paralleled with a capacitor, driven by high-frequency pulse signal. The receiving terminal comprises another wire-wound coil parallel with a capacitor and the load consuming the electromagnetic energy of the receiving coil.

The working principle of magnetically coupled resonant wireless power transfer system is elaborated as the followings. Under the drive of the high-frequency pulse signal, the energy in the transmitter resonant circuit oscillates freely at a certain resonance frequency between electric field and magnetic field and time-varying magnetic field is produced, which is centered within the coil utilizing air as the medium. The magnetic field inducted by the receiver resonant circuit with the same resonance frequency will oscillates freely at a certain resonance frequency between electric field and magnetic field, too. At the same time magnetic energy exchanges between the two resonant circuits. This is to say, electric and magnetic energy exchange within these two resonant circuits and at the same time, there also exists energy exchange with the same oscillation frequency.

3. The Circuit Model of Magnetically Coupled Resonant System

According to the coupled-mode theory, the parallel circuit model of magnetically coupled resonant system is shown as Figure 2. The valid value of the high-frequency power U_{in} provides energy for the system. The transmitter coil can be modeled as an inductor (L_1) with parasitic resistance R_1. A capacitor (C_1) parallel with the inductor is used to make the transmitter resonant circuit at the frequency of interest. The receive side is defined similarly. The transmitter coil and the receiver coil are linked by mutual inductance M. D is the distance between the two coils.

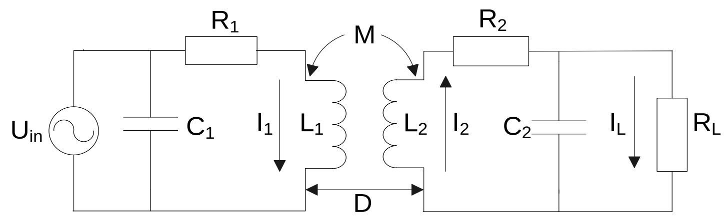

Figure 2. Equivalent Circuit Model of the Wireless Power System

Here, we define the resonant angular frequency of the system as ω, the valid values of the transmitter coil current, receiver coil current and load current respectively as I_1, I_2 and I_L. Then Kirchhoff's voltage and current law (KVL, KCL) can be used to get the following equations (1)-(3) according to Figure 2.

$$U_{in} = I_1(R_1 + j\omega L_1) - j\omega M I_2 \tag{1}$$

$$I_2 = I_L + \frac{I_L R_L}{1/j\omega C_2} \tag{2}$$

$$j\omega M I_1 = I_2\left(R_2 + j\omega L_2 + \frac{1}{j\omega C_2 + 1/R_L}\right) \tag{3}$$

The admittances of the transmitter circuit and receiver circuit are obtained respectively as:

$$Y_1 = j\omega C_1 + \frac{1}{R_1 + j\omega L_1} \tag{4}$$

$$Y_2 = j\omega C_2 + \frac{1}{R_2 + j\omega L_2} + \frac{1}{R_L} \tag{5}$$

When the transmitter and receiver coils are both in a state of self-resonant, the equivalent admittances of the two circuits are pure conductance, that is

$$\mathrm{Im}[Y_1] = 0 \quad , \quad \mathrm{Im}[Y_2] = 0 \tag{6}$$

Substituting (6) into (4), (5) respectively, the values of C_1, C_2 are obtained as:

$$C_1 = \frac{L_1}{R_1^2 + \omega^2 L_1^2} \tag{7}$$

$$C_2 = \frac{L_2}{R_2^2 + \omega^2 L_2^2} \tag{8}$$

The following can be obtained from equations (2), (3) and (8):

$$I_2 = \frac{\omega M I_1}{\omega^2 L_2^2 + R_2^2 + R_2 R_L}\sqrt{\frac{(\omega^2 L_2^2 + R_2^2)^2 + \omega^2 L_2^2 R_L^2}{\omega^2 L_2^2 + R_2^2}} \tag{9}$$

$$I_L = \frac{\omega M I_1 \sqrt{\omega^2 L_2^2 + R_2^2}}{\omega^2 L_2^2 + R_2^2 + R_2 R_L} \tag{10}$$

The fact that I_1 is proportional to the input voltage U_{in} can be seen from (1) and (3).

Therefore, the output power of the receiving circuit, namely power of load R_L is

$$P_o = I_L^2 R_L = \frac{\omega^2 M^2 I_1^2 (\omega^2 L_2^2 + R_2^2) R_L}{(\omega^2 L_2^2 + R_2^2 + R_2 R_L)^2} \tag{11}$$

The power losses of the transmitter and receiver coils are

$$P_1 = I_1^2 R_1 \tag{12}$$

$$P_2 = I_2^2 R_2 = \frac{\omega^2 M^2 I_1^2 R_2 [(\omega^2 L_2^2 + R_2^2)^2 + \omega^2 L_2^2 R_L^2]}{(\omega^2 L_2^2 + R_2^2 + R_2 R_L)^2 (\omega^2 L_2^2 + R_2^2)^2} \tag{13}$$

Then the system efficiency is calculated as:

$$\eta = \frac{P_o}{P_o + P_1 + P_2} = \frac{M^2 R_L}{[R_L + (1 + \frac{\omega^2 L_2^2 R_L^2}{(\omega^2 L_2^2 + R_2^2)^2}) R_2] M^2 + \frac{R_L^2 L_2^2 R_2}{(\omega^2 L_2^2 + R_2^2) Q^2}} \tag{14}$$

Q in formula (14) is the quality factor of the coil, and we can clearly see that the higher the quality factor, the higher the system efficiency.

It can be seen from formula (11) that the system load power P_o is related to the resonant frequency f ($f=2\pi\omega$), the parameters of the coil, the input voltage U_{in}, load resistance R_L and mutual inductance M. Improving U_{in}, f and M can effectively improve the load power. But in practice, the input voltage and resonant frequency will also be limited by the device parameters. When switching circuit is used to produce the high-frequency driving signal, the valid value of input voltage is related to the driving signal duty cycle. The formula (14) shows that the transfer efficiency mainly depends on mutual inductance and quality factor of the coil. The formula of mutual inductance [27] is

$$M \approx \frac{\pi u_0 n r^4}{2D^3} \tag{15}$$

Where:

$u_0 = 4\pi \times 10^{-7}$ — permeability of vacuum (H/m);

n — coil turns;

r — the radius of coil (m);

D — the distance of coils (m).

Therefore, when the input DC voltage and coil parameters (including radius of coil r, wire diameter d_w and coil turns n) are certain, the impact factors of the system load power and transfer efficiency can be simplified to three parts: system resonant frequency f, duty cycle of driving signal d and the distance between the two coils D.

4. Design of Experimental Prototype and Discussion

4.1. The Design of Experimental Prototype

Based on the theoretical analysis before, an experimental prototype of magnetically coupled resonant wireless power transfer system will be designed here, which includes the

DC power supply, switch driving circuit, high-frequency inverter, transmitter resonant coil, receiver resonant coil and load. Switch driving circuit mainly provides adjustable high-frequency pulse driving signals for the transmitter coil resonant circuit and the circuit mainly comprises the DDS signal generator based on FPGA and high-frequency operational amplifier THS4001, as shown in Figure 3. In this system, the related parameters of the high-frequency pulse driving signal (the frequency of pulse driving signal f_s and duty cycle D_{on}) are adjusted to control the switching frequency and on-off time of the switch tube, in order to make the power supply V_{cc} continually provide energy for the transmitter LC resonant circuit under the drive of high-frequency pulse signal to ensure the efficient and controllable transmission of electric power.

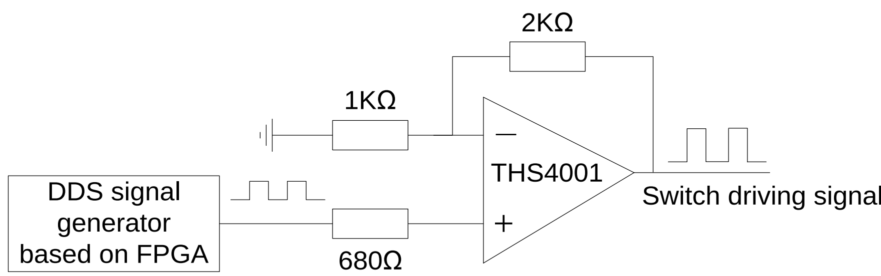

Figure 3. Diagram of Switch Driving Circuit

The transmitting terminal and receiving terminal consist of two LC resonant circuits with the same structure and parameters, as shown in Figure 4. The inverter circuit is used to provide power supply for the transmitter coil and adjust the working frequency of circuit until the coil reaches resonant state. The transmitter resonant coil continuously emits electromagnetic waves into the surrounding space and creates a non-radiation alternating magnetic field in near-field region. In the end, the resonant circuit composed of L_2 and C_2 receives the electric power through strong coupling.

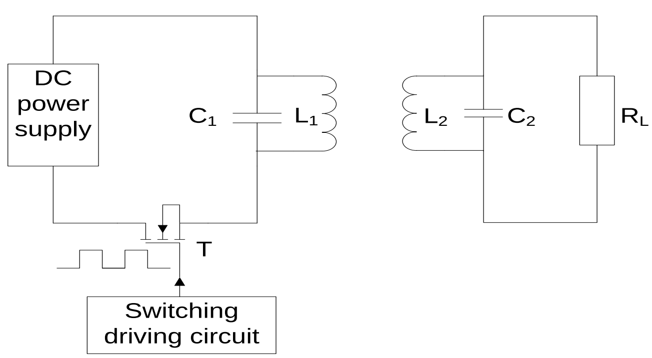

Figure 4. Diagram of the Main Circuit

Table 1 shows parameters of the resonant coil, where the load is replaced by a 100Ω adjustable resistor.

Table 1. Parameters of LC Resonant Circuit

Coil diameter	Wire diameter	Coil turns	Inductance	Capacitor	Resonant frequency
7cm	1mm	13	24.5uH	110nF	~94KHz

The picture of magnetically coupled resonant wireless power transfer system is shown in Figure 5.

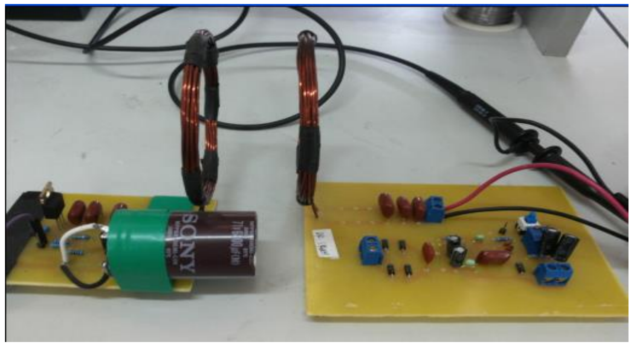

Figure 5. Photograph of the Experimental Prototype

4.2. Discussion of Experiment Results

In order to verify the correctness of theoretical analysis, the control variables method is applied in the experiment and the variables are the frequency of the driving signal, the duty cycle and the distance between the two coils, while the transmitter coil and the receiver coil always keep unchanged.

4.2.1. The Relationship among the Driving Signal Frequency, the Load Power and Transmission Efficiency

When verifying the relationship among the driving signal frequency, the load power and the transmission efficiency, we fix the distance of the two coils at 1.5cm, the duty cycle of the driving signal to 2.0% and the load resistance at 15Ω. The driving signal frequency is tunable in the range of 85 KHz~100 KHz. Measured data processed with curve fitting is shown in Figure 6.

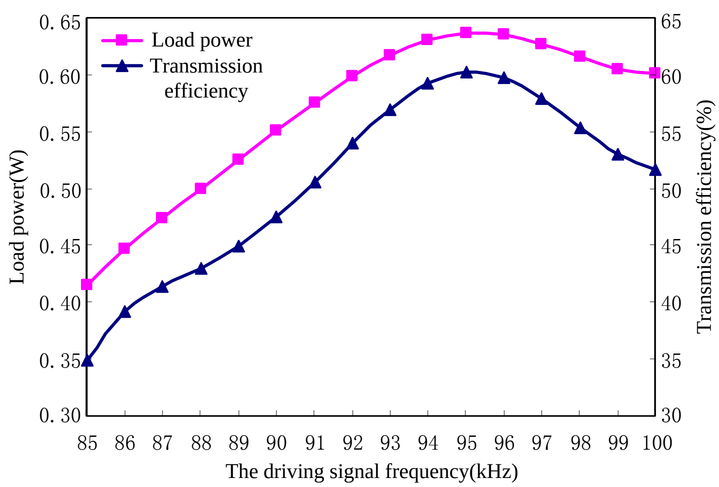

Figure 6. The Relationship Diagram among the Driving Signal Frequency, Load Power and Transmission Efficiency

It can be seen from Figure 6 that when the driving signal frequency increases from 85 KHz to 95 KHz, the load power increases from 0.41 W to 0.64 W and transmission efficiency increases from 34.9% to 58.4%; when the frequency continues to increase to 100 KHz, load power is down to 0.6 W and transmission efficiency drops to 52.7%. Load power and transmission efficiency increase firstly and decrease afterwards with the increase of the driving signal frequency and maximum points appear near the resonant frequency.

With the gradual increase of the driving signal frequency and tending to reach the resonant frequency point, the signal generated in the transmitter resonant circuit tends to be a more and more standard sine wave. So the fundamental wave is increasingly enlarged and makes the alternating magnetic field in near-field region gradually become strong coupling. At the same time, the magnetic field inducted by the receiver coil also gradually strengthens, leading to the increase of load power and transmission efficiency. And they basically achieve the maximum when the frequency increases to the resonant frequency. When the driving signal frequency exceeds the resonant frequency, due to skin effect, the equivalent resistance of the coil increases gradually, resulting in the decrease of load power and transmission efficiency.

4.2.2. The Relationship among the Duty Cycle, Driving Signal and the Load Power and Transmission Efficiency

When verifying the relationship among the duty cycle of driving signal and the load power and transmission efficiency, we fixed the distance of the two coils at 1.0cm, the driving signal frequency at 94 KHz and the load resistance to 15Ω. The duty cycle of driving signal is tunable within the range of 1%~50%. The result processed with curve fitting is shown in Figure 7.

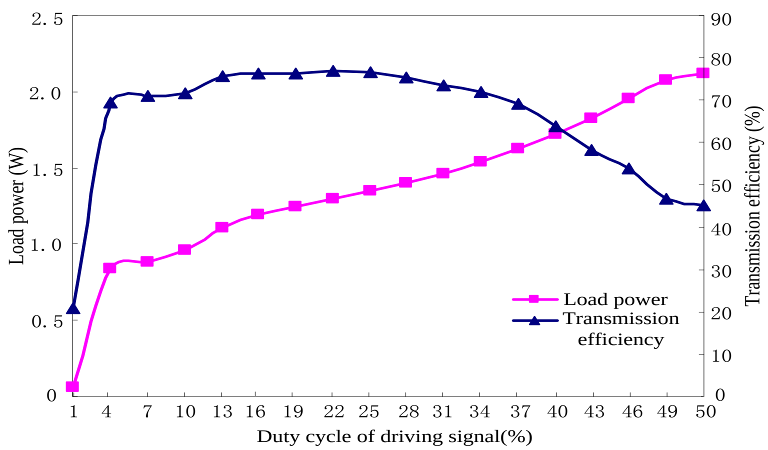

Figure 7. The Relationship Diagram among Duty Cycle of Driving Signal, Load Power and Transmission Efficiency

It can be seen from Figure 7: 1) When the duty cycle of driving signal increases from 1% to 50%, load power increases from 0.15 W to 2.12 W, so we can control the output of load power by adjusting the duty cycle of driving signal; 2) The transmission efficiency increases rapidly from 26.5% to 75.7% when the duty cycle of driving signal changes in the range of 1%~13% and keeps stable with the range of 75.7%~74% along with the change from 13% to 30% for the duty cycle and at last decreases from 74% to 45.1% when the duty cycle changes within the scope of 30%~50%.

The increase of the duty cycle gives rise to the increase of energy provided by the power supply for the transmitting resonant circuit and enhances the magnetic field strength in near-field region. The alternating current inducted by the alternating magnetic field in receiver coil increases, the same to the voltage of the paralleled capacitor, leading to load power becoming larger. When the duty cycle of driving signal is too low, the power supply provides less energy for the transmitting resonant circuit. The power loss in the process of wireless transmission accounts for a large part of the energy. When the duty cycle of driving signal is too high, the switch tube will keep conductive for a long time and the power supply discharges to ground, resulting in power loss and the decrease of transmission efficiency.

4.2.3. The Relationship among the Transmission Distance, the Load Power and Transmission Efficiency

When verifying the relationship among the transmission distance and the load power and transmission efficiency, we fixed the driving signal frequency at 94 KHz, the duty cycle of driving signal at 15% and the load resistance to 15Ω. The transmission distance is tunable within the range of 0.2cm~8.0cm. Measured data processed with curve fitting is shown in Figure 8.

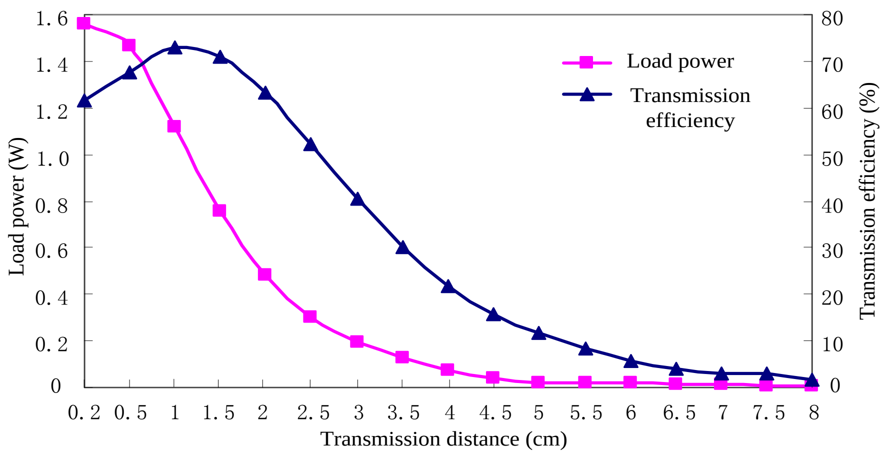

Figure 8. The Relationship Diagram among Transmission Distance, Load Power and Transmission Efficiency

It can be seen from Figure 8: 1) the load power is reduced from 1.52W to approximately 0W when the transmission distance increases from 0.2cm to 8.0cm, that is, load power reduces gradually along with the increase of transmission distance. 2) The transmission efficiency increases from 60.2% to 73.6% when the transmission distance increases from 0.2cm to 1.0cm, but drops to 1.8% when the transmission distance further increases to 8.0cm. Transmission efficiency increases first and decreases afterward with the increase of transmission distance.

When the duty cycle of driving signal is fixed, the energy provided by the power supply for the transmitting resonant circuit is constant and the same to the magnetic field strength in near-field region. As the transmission distance increases gradually, the number of the magnetic field lines passing through the receiver coil decreases, so the alternating current inducted by the alternating magnetic field in receiver coil becomes smaller and the voltage of the paralleled capacitor is reduced, leading to the reduction of load power. When the transmission distance is too small, the transmission energy is very large. But at the moment, the two coils are in a state of over coupling. The waveform in the transmitter coil distorts and keeps in a state of mismatch. So there is a part of power losing on the equivalent resistance of inductance coil and the lost power heat the inductance coil. On the other hand, when the transmission distance is too large, the power loss of the coils themselves and in the process of transmission account for a large proportion. All the above reasons lead to the reduction of transmission efficiency.

5. Conclusions

Our work provides a thorough investigation of the principle of magnetically coupled resonant wireless power transmission. Parameters which contribute to the load power and transmission efficiency are analyzed through theoretical derivation of the circuit model. Furthermore, on the basis of such analysis, experimental devices of transmitting and receiving are proposed. The specific impacts of driving signal frequency, duty cycle and transmission distance on the load power and transmission efficiency of the system are explored respectively in detail through experiments. As discovered for the load power, the increase of driving signal duty cycle will lead to its increasing while it has a reversal proportion to the transmission distance. Moreover, load power will increase first and decrease afterwards with the increasing of driving signal frequency. Regarding the transmission efficiency, the influence from these three parameters may be quite similar: with the increase of the corresponding factor’s value, transmission efficiency will firstly increase and then drop. In addition, causes of these effects are explained in detail. In one word, this study has offer a significant guide for further research about magnetically coupled resonant wireless power transmission.

Acknowledgements

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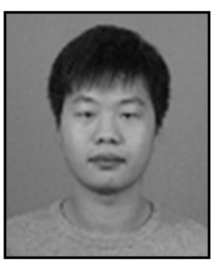

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