A general design of magnetic coupling resonant wireless power transmission circuit

A general design of magnetic coupling resonant wireless power transmission circuit

Wenxu Yan and Jingjing Chen*

Institute of Electrical Engineering and Intelligent Equipment, School of Internet of Things Engineering, Jiangnan University, 214122, Wuxi Jiangs, China

*Corresponding author's email: 865642983@qq.com

Abstract. As a new kind of power transmission way, wireless power transmission technology has great advantages compared with traditional power transmission way.This paper introduces the basic structure and working principle of magnetic coupling resonant wireless power transmission. Based on this, main circuit design and analysis of the transmission system is given. What's more, about the future research work is its functional operation accomplishment.

1 Introduction

Wireless power transfer（WPT）,also known as no contact power transmission, is a new type of power transmission way, which can realize from the power to the load without electrical contact through the electromagnetic field effect. Compared with traditional wire transmission has the problems of transmission loss, the aging and point discharge[1,2], WPT can improve the reliability and safety of power supply equipment and achieve low power to high power, long distance to short distance and different power demand applications.

The main realization of WPT and its classification are shown in Figure 1. Among them, the near-field coupling type comprises a magnetic inductive coupling, magnetic coupling resonant electric field coupled.And far-field radiation type including microwave radiation type and laser type, other ways including changing the material of the coil, a circuit topology or transport structure improve energy transmission efficiency.

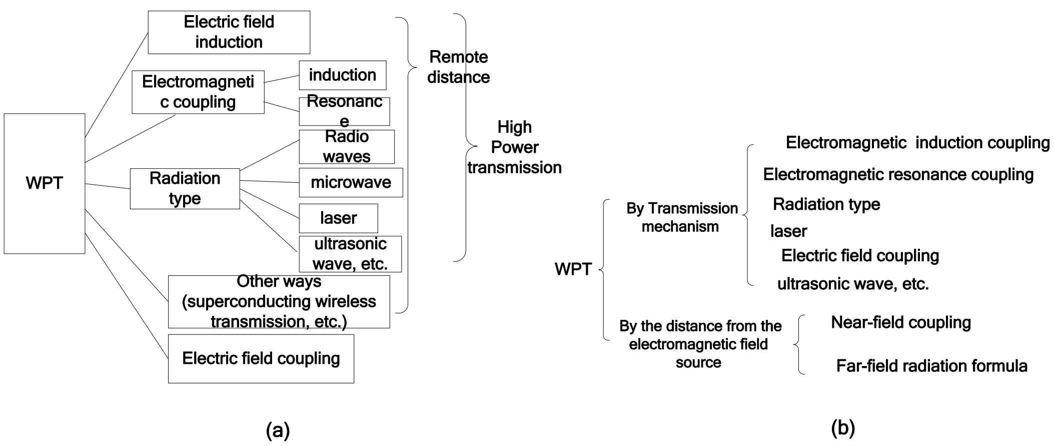

Figure 1. The main methods of realization of WPT and its classification

In the above several transmission modes, the electric field coupling and the magnetic field coupling wireless power transmission uses the near field transmission, and the electric field to the human body is more serious harm than the magnetic field, therefore the present research is relatively few. Now more research is on the magnetic field coupling wireless power transmission. The magnetically coupled resonant wireless power transfer (MCR-WPT) uses the resonant principle to achieve high transmission efficiency and large power at medium distances (transmission distances typically several times than the transmission coil diameter), and the power transmission is not affected by the space non-magnetic obstacles.

2 Basic Outline of Magnetic Resonance Coupled Wireless Power Transmission

A magnetic resonance coupled WPT is using the principle of resonance to set corresponding transmitting device and receiving device related parameters[3], therefore promote the transmit coil, the corresponding receiving coil and the overall system are in the same resonant frequency (i.e. to achieve "electrical resonant" state) to make corresponding energy-efficient transmission. The basic structure of WPT is shown in Figure 2.

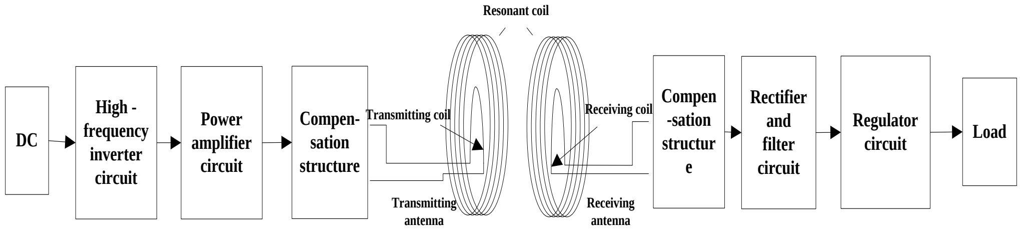

Figure 2. The basic structure of WPT

MCR-WPT systems are mainly realized by the high frequency AC power supply, the resonance coil, the rectifying filter circuit and the compensation network structure of the receiving and transmitting end. The improvement of each part can achieve the high power, high efficiency, and long-distance transmission of the whole system.

2.1 The design of high-frequency inverter power supply

High-frequency inverter circuit is able to convert the input DC into high-frequency AC, which needs have advantages of high efficiency, high stability, simple control, good security, etc. The common high-frequency inverter circuit includes a positive inverter, full-bridge inverter circuit, fly-back inverter, half-bridge inverter circuit, E-type inverter circuit. Compared with the other inverter circuit, E-type inverter has single inverter control circuit and simple structure, it also does not need to set the dead time and meet the requirements of WPT. The structure of Class E circuit[4] shown in Figure 3.

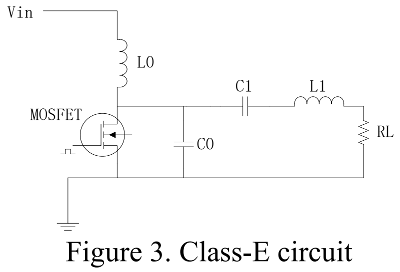

Figure 3. Class-E circuit

2.2 The design of coil and transport structures

Existing studies have concluded that the way to change the coil winding geometry, shape and structure, material and coil diameter, conductivity have an impact on the effectiveness of WCR-WPT. The main parameters of the coil are wire diameter and conductivity, coil winding method (rectangular, circular, spiral, etc.) ,or adding magnetic material between the coils[5].

In order to achieve the power to load matching, isolate the affection of power and load on the coil, the design of system includes four coil structures with a power coil and loading coil or add relay coil, thereby lengthening the transmission distance [6].

2.3 Compensation Topology

The MCR-WPT has four compensation topology (shown in Figure4), the SP-type is more suitable for low-frequency, high load, long-distance, the SS-type is more suitable for close range, higher frequency and smaller load [7]. Consider the choice of SP-type.

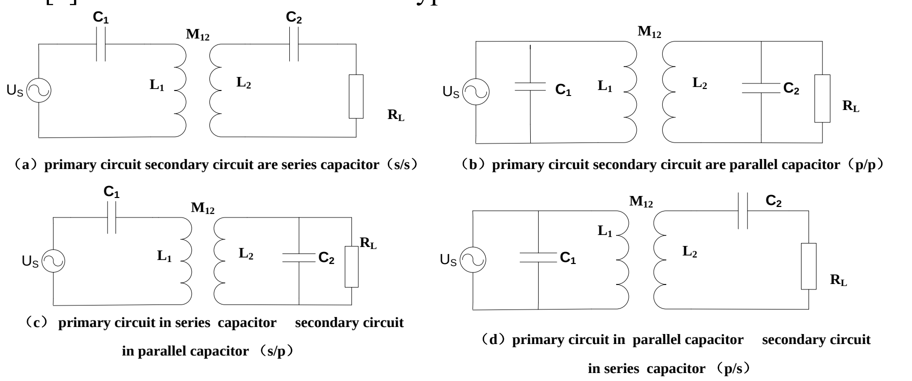

Figure 4. Four compensation topology

2.4 Rectifier and filter voltage regulator circuit

Rectifier circuit is able to covert the high-frequency alternating current into pulsating direct current, such as: half-wave rectifier, voltage double rectifier, full-bridge rectifier. Although the half-wave rectifier circuit has simple structure and a small number of diodes, the circuit is only used effectively for half cycle of the AC voltage, the efficiency and the output voltage is low. Full-bridge rectifier circuit using the full cycle of AC voltage, and it has high output voltage, small pulsation, high-efficiency circuit and the better protection of the diode circuit, its generally used for large load resistance of the occasion, as shown in Figure 5.

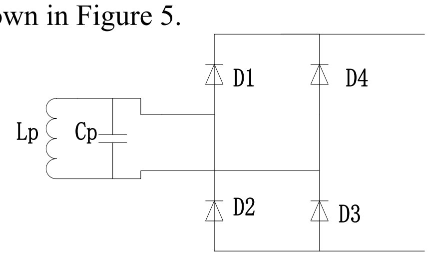

Figure 5. Full-bridge rectifier circuit

High-frequency alternating current through the rectifier circuit, if supply the load directly, harmonic interference will damage the load, so we need to add the rectifier circuit after the filter circuit to ensure a more stable DC voltage output. Filter circuit is mainly divided into active filtering and passive filtering. Active filtering is mainly applied to the requirements of high precision signal processing occasions, and wireless power transmission system voltage signal processing requirements to allow fluctuations in precision, so the rectifier voltage regulator module used passive filtering. Among the existing passive filter given a certain circuit frequency, as RC-π type filter, the larger is R1, the greater is C1, the smaller is the pulsation coefficient, the better is the filtering effect. While R1 increases, it will increase the resistance on DC voltage drop and the overall circuit loss, so RC-π type filter circuit is generally used for small load current, output voltage pulsation of small occasions, as shown in Figure6.

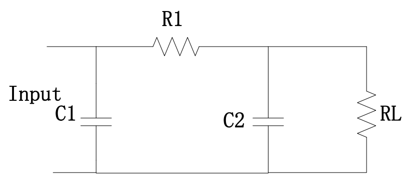

Figure 6. RC-π type filter

3 Analysis of magnetic resonance coupling of wireless power transmission system as a whole circuit

The overall circuit design of MCR-WPT is shown in Figure 7.

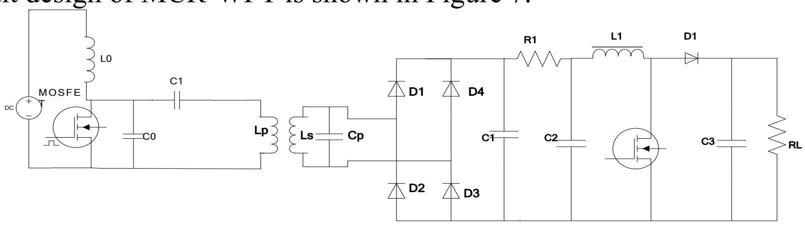

Figure 7. The overall circuit design of the magnetic resonance coupling WPT system

In the whole wireless power transmission system, the resonance coil is able to achieve the maximum energy conversion. At high-frequency situation, the coil high-frequency resistors include high-frequency loss resistance and high-frequency radiation resistance, the formula is as follows:

Resonance coil High-frequency loss resistance:

$$R_{\mathrm{loss}} = \sqrt{\frac{\omega\mu_0}{2\sigma}}\frac{l}{2\pi a} = \sqrt{\frac{\omega\mu_0}{2\sigma}}\frac{Nr}{a} \qquad (1)$$

Resonance coil High frequency radiation resistance:

$$R_{\mathrm{radiation}} = \sqrt{\frac{\mu_0}{\varepsilon_0}}\left[\frac{\pi}{12}N^2\left(\frac{\omega r}{c}\right)^4 + \frac{2}{3\pi^2}\left(\frac{\omega h}{c}\right)^2\right] \qquad (2)$$

The turn-to-turn capacitance between two turns is:

$$C_1 = \frac{2\pi^2 r\varepsilon_0}{\ln\left(\frac{h}{2a} + \sqrt{\left(\frac{h}{2a}\right)^2 - 1}\right)} \qquad (3)$$

The distributed capacitance of the N-turn coil:

$$C = \frac{C_1}{N - 1} \qquad (4)$$

The two resonant coil coaxial parallel, mutual inductance between the coil:

$$M = M_{12} = M_{21} = \frac{\pi\mu_0 N_1 N_2 \left(R_1 R_2\right)^2}{2D^3} \qquad (5)$$

When transmit and receive parameters are same,

$$M = \frac{\pi\mu_0 N^2 r^4}{2D^3} \qquad (6)$$

Coupling coefficient:

$$k = \frac{M}{\sqrt{L_1 L_2}} \qquad (7)$$

Where, $\mu_0 = 4\pi * 10^{-7}$ is the vacuum permeability, $\sigma_0 = 5.92 * 10^7$ S / m is the coil copper wire conductivity, l is the wire length, r is the average radius of the resonant coil, a is the coil wire cross-section radius,ωis transmission system angular frequency, $\varepsilon_0 = 8.854 * 10^{-12}$ F / m is the air dielectric constant, $c = 3 * 10^8$ m / s is the speed of light, h is the resonance coil width. In the high-frequency phase, the coil high-frequency radiation resistance is much smaller than the high-frequency loss resistance, so the resonant coil resistance can be approximately equal to R_{loss}. As the distance increases, the coupling coefficient k will decreases and affects the transmission efficiency of the wireless power transmission system.

Analysis of E-type inverter circuit: In a switching cycle, the switch is turned on, the drain current with no voltage, the switch is turned off, the drain voltage of no current, that is, voltage and current can not exist, in theory Switch does not consume power, the conversion efficiency of 100%, then the DC power and fundamental output power equal [8], that

$$V_{in} I = \frac{I_R^2}{2} Z_{eq} \tag{8}$$

By

$$I = I_R \sin\varphi \tag{9}$$

So

$$V_{in} \frac{2}{\sqrt{\pi^2 + 4}} I_R = \frac{I_R^2}{2} Z_{eq} \tag{10}$$

And then get the load network amplitude:

$$I_R = \frac{4}{\sqrt{\pi^2 + 4}} = \frac{V_{in}}{Z_{eq}} \tag{11}$$

Filter out higher harmonics BOOST circuit output voltage to the load is about:

$$U_0 = \frac{t_{on} + t_{off}}{T} U_d = \frac{T}{t_{off}} U_d = \frac{1}{1 - D} U_d \tag{12}$$

Where, D is BOOST circuit duty cycle. Impedance analysis of the whole circuit transmission, the receiver model coupled impedance：

$$Zs = j\omega Ls + \frac{1}{j\omega Cs} + r_s \tag{13}$$

$$Zp = j\omega Lp + j\omega Cp + R1 + \frac{1}{j\omega \frac{C_1 \cdot C_2}{C_1 + C_2}} + \frac{1}{j\omega C_3} + r_P + R_L \tag{14}$$

$$I_{in} = \frac{U_{in}}{Zs} \tag{15}$$

System transmission efficiency is:

$$\eta = \frac{P_{out}}{P_{in}} \times 100\% = \frac{I_R^2 R_L}{U_{in} I_{in}} \times 100\% \tag{16}$$

The parameters into the type, we can see, by setting the various parameters can be part of the system to achieve higher transmission efficiency.

4 Resonant frequency automatically tracking the wireless power transmission

4.1 The concept of resonant frequency automatic tracking

When the system is operating at the resonant frequency, it has the smallest impedance value, and the maximum transmission efficiency point of the system can be approximated as the resonant frequency of the transmitting or receiving coil. Therefore, in order to ensure the system work in the maximum transmission efficiency point, circuit must ensure that the current and voltage with the same phase, in the ideal environment, current and high frequency power supply with the same phase means current and high frequency signal generator in the same frequency phase. In other words, if the receiver or transmitter to add a signal processing link into the current feedback signal, whether the system operates at the resonant frequency, the direct use of current feedback signal as a high-frequency signal generation source instead of the previous high-frequency signal generator, so the system can work directly after exemption from the previous high-frequency signal generator[9].

4.2 Fundamental Structure of Resonant Frequency Auto – Tracking System

The general structure of the resonant frequency automatic tracking system is shown in Figure 8.

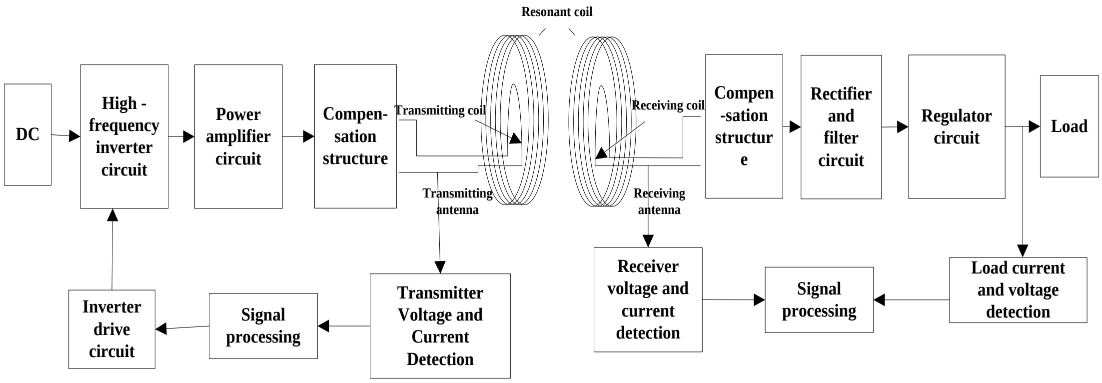

Figure 8. the general structure of the resonant frequency automatic tracking system

System by detecting the transmitter voltage and current signals, according to design requirements set the signal processing link, change the high-frequency inverter circuit drive control circuit. Among them, the signal processing link basically includes: Current signal detection, signal amplitude, phase, waveform conversion processing.

The receiver and the load side of the voltage and current detection together, compared with the expected effect of the feedback signal processing, wireless transmission of information can be transmitted to the transmitter.

5 Wireless power transmission applications and development prospects

5.1 electric vehicle wireless charging technology

Electric vehicles are the key components of smart grid, the scale of electric vehicles can become energy storage devices. The charging method of electric vehicle wireless charging technology is flexible and safe, can fully reduce the impact on the power grid, can reasonably disperse the charging time, and has a great significance to the sustainable development of smart grid.

There are many research teams in China and oversees. For instance, the University of Auckland, New Zealand-owned company has applied this technology on electric passenger, and their scholars design and verify the equivalent circuit model of MCR-WPT, the final experimental results shows: the transmission distance of the system is 30 cm, output power of 220W, the transmission efficiency of 95% [10]. In China, Institute of Electrical Engineering Chinese Academy of Sciences developed the main parameters of electric vehicle wireless charging system: output power of 3.3 kW, transmission distance of 20 cm, the maximum machine efficiency of 90.5% [11].

5.2 Medical equipment

WPT is also one of the main research fields in medical equipment application. It is mainly applied to the wireless power supply of implantable medical devices such as cardiac pacemaker, nerve simulator, artificial heart, cochlear implant and Retinal prosthesis, etc [12-14].

Advantages are as follows: (1) There is no physical connection in the power supply, which avoids the direct contact between the wire and the skin and prevents the complications caused by the infection. (2) The power supply has no physical connection, which avoids the direct contact between the wire and the skin. (3) Solve the implanted battery power depletion after surgery to replace the problem, improve the patient's quality of life after surgery.

5.3 Smart home

Smart home has gradually been concerned in recent years, in order to get rid of the limitations of traditional charging cables, maximize the convenience of human been proposed. Such as "free battery" wireless mouse and mobile phone, notebook computers, wireless charging terminals.

5.4 Industrial applications

Wireless power transmission technology in the industry for some special occasions, such as chemical equipment, detection devices, underwater robots, distributed sensor power supply problems, etc [15]. These occasions, the electricity consumption of the device is generally used for battery mode or cable transmission, to the normal use and maintenance of equipment has brought a lot of inconvenience, and wireless power transmission technology to overcome the above shortcomings became the domestic and foreign scholars and companies in recent years of a new hot spot.

6. Conclusion

This paper designs a new topology of the WPT. Transmitter using DC input by E class amplification is able to achieve smaller DC voltage amplification and power increase. The alternating current of the receiving end by rectifier filter and BOOST circuit output to the load, can achieve greater efficiency of power transmission. On this basis, this paper proposes a conjecture automatically follow the resonant frequency, that is, through detecting the voltage and current signals of the transmitter and the receiver separately from the expected value, and realizing the control of the drive circuit of the inverter circuit, so that the whole system can achieve higher efficiency.

Acknowledgment

This work is supported by National Key Research and Development Program (2016YFD0400300), the Fundamental Research Funds for the Central Universities (JUSRP51406A).The Practice Innovation Project of Jiangsu Province (SJLX15_0570).

References

[1] Yu Weiguo, Xiong Youjing, Zhou Xinfeng, et al. Analysis on technical line losses of power grids and countermeasures to reduce line losses [J]. Power System Technology, (2006).
[2] Wang Tao, Zhang Jianmin, Li Xiaoping. Calculate of scheduled loss ratio and its assessment [J]. Power System Technology, (2003).
[3] Zhao Zhengming, Zhang Yiming, Chen Kainan. New progress of magnetically-coupled resonant wireless power transfer technology[J]. Proceedings of the CSEE，(2013).
[4] Li yanhong, Zhang chao, Liu guoqiang, et al. Design of Resonant Wireless Power Transmission Control Based on Class-E[J]. Advanced Technology of Electrical Engineering and Energy (2015).
[5] Wen Huiqing, Zhang Chi. Investigation on transmission efficiency for magnetic materials in a wireless power transfer system[C]. 2015 IEEE 11th International Conference on Power Electronics and Drive Systems.
[6] Marco Dionigi, Mauro Mongiardo. Magnetically Coupled Resonant Wireless Power Transmission Systems with Relay Elements[C]. 2012 IEEE MTT-S International.
[7] Jaros V., Drgona P., Kozacek B., Piri M. Analytical comparison of topology configuration of wireless power transfer system[C]. 2016 International Conference on Applied Electronics (AE).
[8] Chu jianglong. Design and Implementation of E - Class Power Amplifier for Magnetic Coupled Resonant Wireless Power Transmission System[D]. Hangzhou: Zhejiang University,(2014).
[9] Hu shihao. Design of High Frequency Power Supply Based on Resonance in Wireless Energy Transmission System[D]. Beijing: North China Electric Power University,(2015).
[10] Liao chenglin,Li jufeng,Tao chengxun, et al. A Survey of Control Methods for Wireless Power Transmission Systems[J]. Journal of Electrical Engineering, (2015).
[11] Fan xingming, Mo xiaoyong, Zhang xin. Research Status and Application of Wireless Power Transmission Technology [J]. Journal of Electrical Engineering,(2015).
[12] Yan Guozheng, Zan Peng, Ye Dongdong,et al. Design of Transcutaneous Energy Transmission System for Artificial Anal Sphincter[C]. 2007 International Conference on Mechatronics and Automation.
[13] Chaimanonart N, Olszens K R, Zimmerman M D, et al. Implantable RF power converter for small animal in vivo biological monitoring[C]. IEEE Conference of Engineering in Medicine and Biology, 2005.
[14] Lim H G, Yoon Y H, Lee C W, et al. Implementation of a transcutaneous charger for fully

implantable middle ear hearing device[C]. IEEE Conference of Engineering in Medicine and Biology, (2005).
[15] David L Mascarenas, Eric B Flynn, Michael D Todd, et al. Experimental studies of using wireless energy transmission for powering embedded sensor nodes[J]. Journal of Sound and Vibration, 2010.
[16] Li Zesong, Li Dejun, Lin Lin, et al. Design considerations for electromagnetic couplers in contact-less power transmission systems for deep-sea applications[J]. Journal of Zhejiang University- Science C-Computers & Electronics,(2010).