Acta Technica 62 (2017), No. 4A, 591–600

The study of wireless charging model of magnetic coupling resonant electric vehicle

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Abstract. Energy crisis and environmental problems have been paid increasing attention. Electric vehicle(EV)are favored by its merits like energy saving, environmental protection, low noise and zero emission. At the same time, wireless power transfer(WPT)technology has the overwhelming advantages when compared with conventional contagious charging. So charging for EV by WPT is more conform to the development trend of our society.The electric vehicle wireless charging is a hot research direction. Based on the wireless power transmission principle of magnetic coupling resonance, a magnetic coupling resonant wireless charging device is designed, and the transmission power as well as the factors of transmission efficiency are analyzed. Moreover, the thesis also gives the design of the system, which conducts the research of electric vehicle wireless charging model of magnetic coupling resonance.

Key words. Electric vehicle, magnetic resonanes, equivalent model, wireless charging.

1. Introduction

With the progress of society and the development of science and technology, environmental and energy issues have become increasingly prominent, and the application of new energy vehicles is focused gradually. The production and sales of electric vehicles (EV) and plug-in hybrid electric vehicles (PHEV) at home and abroad have started.With the inventory increase of global electric vehicles, the electric vehicles are paid more and more attention. However, the charge mode is also one of the key technologies restricting its development. The main ways of charging currently include charging pile and electrical charging station. Not only the construction of charging pile or electrical charging station needs to consume huge costs of manpower

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and material, but also the bare conductors are easy to generate electrical sparkles, which hides trouble in safety and occupies a lot of space as well. Compared with wired charging, the wireless charging mode is more flexible, and free from space and location restrictions. Moreover, it is able to charge the electric vehicles safely and quickly, which makes up for the disadvantages of the traditional way of charging in adaptability and independent charging aspects. With further research, due to the obvious advantages, non-contact wireless charging technology will gradually replace the current contact charging technology.

At present, there are three main technologies of wireless power transmission: inductive coupling technology, magnetic resonance technology, and far field radiation technology. The inductive coupling technology has simple principle, and is easy to implement. However, its transmission distance is very short, and the coil displacement and frequency variation has great impact on the transmission efficiency. The far field radiation technology transmits the power by laser beam. The current research is still in the theoretical stage. At the same time, this wireless power transmission approach is not suitable for the wireless charging group of electric vehicles. While the magnetic coupling resonant wireless charging technology is the wireless power transmission technology with medium distance, which generates less energy loss under the relative position in space and has stable transmission.Therefore, it is a high-efficient, safe and stable choice for the electric vehicles to use magnetic coupling resonant wireless charging technology.

2. The Analysis of Wireless Charging Equivalent Model of Magnetic Coupling Resonance

According to the related theories of magnetic coupling resonant wireless power transmission, the resonant circuits on both sides of the transmission system are in series composed of transmitting coil, receiving coil as well as their own resonant capacitors, which possess the same resonant frequency. Within the range of wavelength, the energy transmission is conducted through magnetic coupling. The equivalent model of transmission system is shown in Figure1. Where, L1 is the transmitting coil inductance; L2 is receiving coil inductance; C1 and C2 are the corresponding resonant capacitors on both sides; M is the mutual inductance of these two coils; R1 and R2 are the equivalent resistances of transmitting coil and receiving coil; R1 is load equivalent resistance.

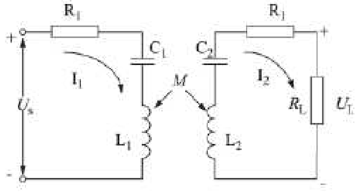

Fig. 1. The equivalent model of transmission system

On the basis of Kirchhoff Voltage Law (KVL), the equation of equivalent model is as below:

US=Z1I1-jωMI2

O= Z2I2-jωMI1 (1)

Where:

$$T_1 = \int_{-\frac{1}{2}}^{\frac{1}{2}} \int_{-\frac{c}{4b}+\frac{\xi}{2}-\frac{1}{4}-\frac{c\xi}{2b}}^{\frac{c}{4b}-\frac{\xi}{2}+\frac{1}{4}+\frac{c\xi}{2b}} p_1 p_2 \left[1-(1-\beta)\left(\xi+\frac{1}{2}\right)^2\right] w^2 \,\mathrm{d}\eta\,\mathrm{d}\xi\,, \tag{1}$$

Since the structures of transmitting coil and receiving coil are the same, the inductance and resistance of them are the same as well, that is L1=L2, and R1=R2. On the basis of resonant frequency f= $a * b$, the transmitter and receiver have the same resonant capacitors, that is C1=C2. Therefore, after selecting the appropriate parameters of L1 and L2, C1 and C2, the resonant frequency of the circuit can be determined. According to formula (1) as well as formula (2), it is :

$$V_1 = \int_{-\frac{1}{2}}^{\frac{1}{2}} \int_{-\frac{c}{4b}+\frac{\xi}{2}-\frac{1}{4}-\frac{c\xi}{2b}}^{\frac{c}{4b}-\frac{\xi}{2}+\frac{1}{4}+\frac{c\xi}{2b}} (p_1 p_2)^3 p_3 (G-2(1-\nu)H)\,\mathrm{d}\eta\,\mathrm{d}\xi\,, \tag{2}$$

Hereby, we can calculate the impedance of transmitter is:

$$\lambda^2 = \frac{12\omega^2 \rho_0 a^4 \left(1-\nu^2\right)}{E_0 h_0^2} \tag{3}$$

According to formula (4), the reflected impedance from the receiver to transmitter. When resonance occurs, the imaginary part of impedance is 0, that is Z1=R1, Z2=R2+RL. The reflected impedance from the receiver to transmitter is resistive. According to the result of formula (3), we can obtain the Electric Power PE and Load Power PL are as below:

$$V = \frac{ab}{2}\frac{E_0 h_0^3}{12\left(1-\nu^2\right)} \int_{-\frac{1}{2}}^{\frac{1}{2}} \int_{-\frac{c}{4b}+\frac{\xi}{2}-\frac{1}{4}-\frac{c\xi}{2b}}^{\frac{c}{4b}-\frac{\xi}{2}+\frac{1}{4}+\frac{c\xi}{2b}} (p_1 p_2)^3 p_3 (G-2(1-\nu)H)\,\mathrm{d}\eta\,\mathrm{d}\xi\,. \tag{4}$$

The mutual inductance M of transmitting coil and receiving coil can be approximately represented by the formula $\pi\mu??\gamma/$, where $\mu 0$ is space permeability; d is the distance between transmitting coil and receiving coil; γ is the coil radius; N is the turns per coil.

By formula(5)and (6), it can be seen that when the coil parameter and resonant capacitor are determined, the transmission power of the system and transmission efficiency only have relationship with ω and d, that is they are only related to the frequency and coil distance, but to have nothing to do with the transverse displacement of transmitting coil and receiving coil. Therefore, in the process of wireless power transmission, the circuit should be always in the resonance state, which enables to maintain the relative optimal transmission power when the transmitting coil and receiving coil with transverse displacement

3. The Wireless Charging System Design of Magnetic Coupling Resonance

3.1. The analysis of magnetic coupling resonant wireless charging system of electric vehicles

The magnetic coupling resonant wireless charging system of electric vehicles generally charge at the bottom of the vehicle, that is, the transmitter is installed under the ground. The transmitting coil is horizontally placed on the ground. The receiver is installed on the electric vehicles, and the receiving coil is placed under the vehicle. The distance between transmitting coil and receiving coil is d, and the transverse displacement distance of them is Z. The input power pass through the transmitting coil by energy transformation, which enables the transmitting coil generate resonance, so as to create a magnetic field coupling with the receiving coil to realize the power transmission. And then, through the energy conditioning at the receiver, the power is transmitted to the super capacitor for energy storage.

The magnetic coupling resonant wireless power transmission system consists of the main circuit and control circuit. In the main circuit, the single-phase AC input is converted to stable DC voltage U1 through non-control rectifier filter. Through power regulation, the DC voltage can be changed to adapt to the actual needs. After the full bridge inverter circuit being transformed into high-frequency alternating current, the output voltage is U1. The transmitting coil I,: and resonant capacitor C' form a series resonant circuit. When the AC frequency is f1,L1 and C1 generate resonance. The resonant frequencies of receiving coil and transmitting coil are the same, i.e. f1=f2. When the resonant circuit at the transmitter generates resonance, it creates magnetic field coupling with the receiver, which enables the receiving coil L2 at the receiver to create resonance with the resonant capacitor C2. Due to the same frequency, the receiver is impedance at this moment, and the transmission power is active power, so as to compensate the loss. The resonant circuit at the receiver generates an output voltage U2, which can be transformed into DC through high-frequency rectifier filter and then stored in the super capacitor.

In the control circuit, the power regulation uses DC chopping power regulation. We can obtain the voltage between 0-U1 through regulating the turn-on time of chopper's switch tube. Through the feedback current, the resonance loop current 1: at the transmitter detects the circuit to transform into the square-wave voltage with same frequency. Through the frequency tracking circuit, the frequency tracking signal is formed. And the circuit is generated by inputting PWM signals, and to create the PWM control signal with required resonant frequency. The switch tube of full bridge inverter circuit can be controlled by drive circuit. At the same time, in order to prevent the short circuit of bridge arm on the full bridge inverter circuit, we leave a small dead space among the drive signals on the bridge arm. Thus, when the transmitter circuit works in the sensibility state, namely voltage U1 is ahead of current I1, the zero voltage opening and small current turning-off can be realized.

In the wireless transmission system, the main factors that influence the transmission characteristics are high-frequency inverter link, coupling link and rectifier filter regulator link. At present, the most commonly used high-frequency inverter circuits mainly include full bridge inverter circuit, half bridge inverter circuit, D power amplifier, E power amplifier and the like. The followings are the simple analysis of inverter's circuit structure, so as to choose the high-frequency inverter in this thesis. The full bridge inverter circuit and half bridge inverter circuit are most commonly used in most occasions. According to the difference of energy storage elements, the inverters can be divided into voltage and current modes. The voltage inverter circuit has the characteristics of simple structure, convenient control and fast response, so that it is widely used in the small and medium power inverter system. The voltage full bridge inverter mainly consists of DC voltage source, capacitance, four switch tubes and series network LC. When the inverter is in the working state, it needs two driving pulses with certain dead time to drive two switch tubes. Switches T1 and T4 are controlled by one drive pulse. Besides, switches T2 and T3 are controlled by another drive pulse. The switch tubes realize the conduction alternately, and the conduction time lasts within half cycle.

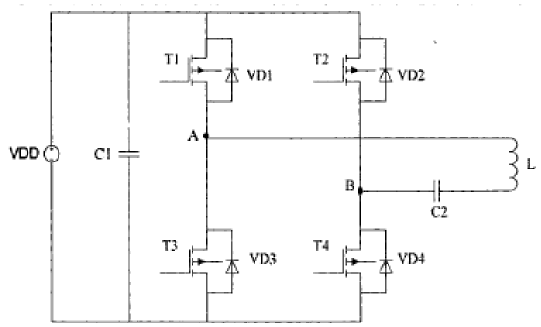

Fig. 2. The full bridge inverter schematic diagram

During the working process of full bridge inverter circuit, T1, T4 and T2, the T3 grid signals in one cycle realize the positively biased in half cycle and the reverse biased in the other half cycle, which complements each other. The amplitude produced on both ends of C-L is alternating voltage. When passing the LC resonant network filter, it will produce a sine current with the same control frequency as MOSFET, so as to generate the sinusoidal magnetic field in the coil. The half bridge inverter circuit is similar to full bridge transmitting circuit. The full bridge inverter circuit is composed of two half bridge inverter circuits. The main difference is that when the power supply voltage is the same as the load, the output power of full bridge transmitting circuit is 4 times as much as that of half bridge transmitting circuit. And the reverse voltages of switch tubes are all the power supply voltage, and are DC power supply voltage as well. However, the current passing through the switches in the full bridge transmitting circuit is twice than that in the half bridge inverter circuit. The switch voltage of full bridge inverter circuit is not high, but the output power is relatively large, so that it often uses the working mode of soft switching.

The construction of magnetic coupling resonant wireless charging system model increases the probability of the components' reliable operation, reduces the frequency of failure, decreases the maintenance cost, and extends the service life; In order to realize the magnetic FGC resonant wireless charging with higher charging efficiency,

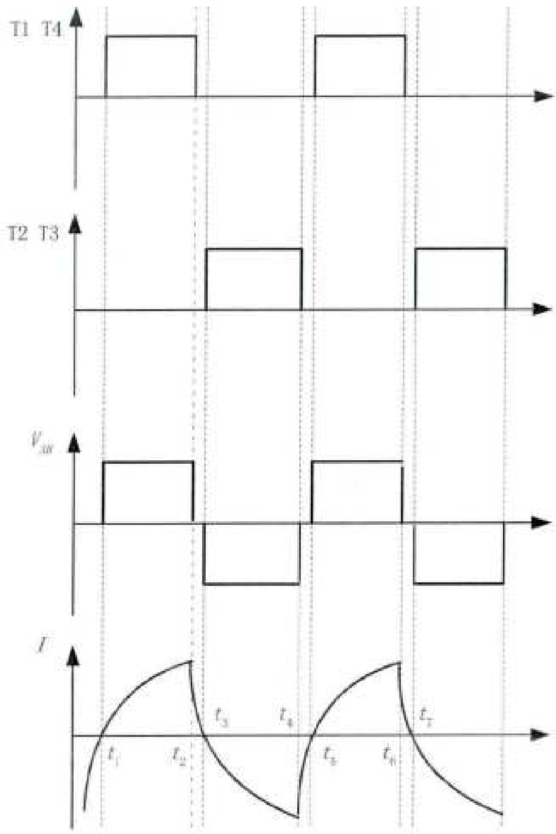

Fig. 3. The full bridge inverter working waveform

the working processes of the overall magnetic FGC resonant wireless charging system are as follows: firstly, offering the initial pulse to the drive circuit, so that the pulse will generate 4 pulses to meet full bridge inverter, and make the circuit work. After a period of time, sampling the current signals in the transmitter coil, and sending them to DSP and FPGA controllers after conditioning. By the controllers, it will again produce 4 corresponding pulses which meet the requirements of full bridge inverter, so as to realize the frequency tracking inverter, and improves the power transmission efficiency. The full bridge inverter circuit is shown in figure 4:

Since the magnetic coupling resonant wireless charging system requires the high-frequency inverter within the scope of 100kHz-500kHz, the inverter must possess high stability. Under the fixed DC power supply, the higher power are needed, so that we select the relatively mature full bridge inverter circuit. In the simple full bridge inverter circuit, there are parasitic oscillations, parasitic diode, switch shutting-off and other interferences, which will affect the reliability of the whole system. Thus, the real full bridge inverter main circuit is shown in Figure 5. A resistor connected in series at the grid contributes to reducing the parasitic oscillation. The D100-D400 respectively offset the parasitic diode of T1-T4. In order to reduce the interference

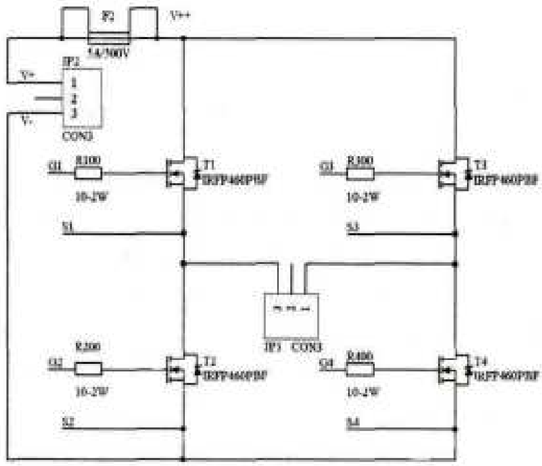

Fig. 4. The circuit diagram of full bridge inverter main circuit

of switch shutting-off, we need to add a buffer circuit. R102, D101 and C 100 consist of the buffer circuit of T1; R202, D201 and C200 consist of the buffer circuit of T2; R302, D301 and C300 consist of the buffer circuit of T3; R402, D401 and C400 consist of the buffer circuit of T4.

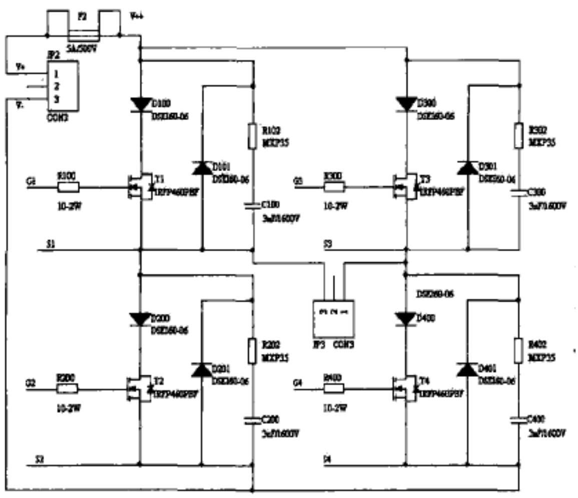

Fig. 5. The electrical diagram of full bridge inverter main circuit

3.2. Drive circuit

The driving requirements of power MOSFET: when selecting the MOSFET driver, we need to consider the following requirements. The P4L exists about 1300pF input capacitance between the gate and the source. In order to accelerate to establish the driving voltage, the driving circuit should have small resistance, and the front-edge and trailing-edge of grid-control voltage should be steep enough; the power of driving source to the grid should be large, so as to ensure that its power output is in saturation mode after MOSFET conducting; moreover, to guarantee that the switches of MOSFET are reliable, and prevent the damage due to the de-saturation when on conduction; to provide the proper positive driving voltage. The excessively high voltage between the gate and the source will lengthen the charging and discharging time of power MOSFET when turning on or shutting off the switches, and the switching speed will be reduced. In addition, the voltage between the gate and the source should not exceed the rated value of MOSFET (usually 20V). The driving voltage between the gate and the source is generally in 10˜18V, and the voltage in this these is about 12V; in order to avoid the fault conduction, we'd better offer the negative gate-to-source voltage when MOSFET is shutting-off; in addition to possessing the strong anti-interference ability, the driver should ensure the existence of a dead time, which guarantees to be on conduction after shutting-off, with the driving signals on the high-side and low-said bridge arms of voltage inverter.

3.3. The selection of coupling coil

The coupling coil possesses various structures and forms. According to the different application environment and system design requirements, the coupling coil's structure can be divided into detachable transformer type, solenoid coil type, and flat plate type. This thesis mainly adopts the air core coil produced by the solenoid type. To the coupling resonant wireless power supply system, the winding of air core coil plays a particularly important role in its parameters. The air core coil can be made into different shapes, such as circle, cylinder, "mosquito coil" and so on. Compared with the coils in other shapes, the cylindrical coil can generate the biggest magnetic field per unit volume winding. As for the winding method of cylindrical coil, there are two modes called "dense winding" and "loose winding". The "loose winding" mode can reduce the parasitic capacitance of the coil parameters. In order to save the volume, this thesis did not adopt the "loose winding" mode, but to use "dense winding".

3.4. Resonant capacitor

The compensation capacitors mainly include electrolytic capacitor, paper capacitor, ceramic capacitor and so forth. The main technical parameters of the capacitors are nominal capacity, the rated operational voltage with allowable deviation, insulation resistance, energy consumption, environmental temperature coefficient of different parameters, working frequency range and the like. Among these parameters, the most important characteristics are the nominal capacity and allowable deviation, the high voltage resistance of rated working and high temperature resistance. By testing different capacitors in a large number of experiments, we ultimately determine the SMD high voltage resistance NPO. NPO capacitor is the most commonly used monolithic ceramic capacitor with temperature compensation characteristics. The electric properties are stable and will not change with time, temperature and voltage, which is suitable for the capacitance in high frequency circuit. Making comprehensive consideration, NP0 has the excellent characteristics of no polarity, wide frequency range, small dielectric loss, and high insulation resistance.

4. Conclusion

The wireless charging electric vehicles are paid more and more attention by the public, which have more significant improvement on energy conservation, environmental protection as well as operation security than the conventional vehicles. Based on the analysis of the basic principle and transmission principle of magnetic coupling resonant wireless power supply technology on wireless power supply system, the theoretical analysis and experimental results show that the magnetic coupling resonant wireless charging technology meets the wireless charging requirements of medium transmission distance, high transmission efficiency, appropriate transmission frequency as well as kW energy level.

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Received November 16, 2016