IOP Conference Series: Earth and Environmental Science

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To cite this article: Y J Hou *et al* 2018 *IOP Conf. Ser.: Earth Environ. Sci.* **188** 012032

IOP Conf. Series: Earth and Environmental Science **188** (2018) 012032 doi:10.1088/1755-1315/188/1/012032

High efficiency wireless charging system design for mobile robots

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Abstract. In order to solve the problems of difficult and unintelligent charging of the mobile robot after the exhaustion of battery power, this paper applies wireless power transfer (WPT) technology to the charging of robot, and designs a wireless charging system that meets the characteristics of the robot. In this paper, the basic theory of wireless charging system is analysed. The expressions of output power and efficiency are derived, and the expressions above are input as code into MATLAB. By the MATLAB code, the effects of parameters such as coil inductance and coupling coefficient on the output power and efficiency of the system are studied, and the relevant parameters of the system are determined. Through MATLAB Simulink simulation, it is found that the voltage of the battery pack of the robot is too low and frequency split occurs. This paper proposes a frequency control strategy to deal with the frequency split phenomenon. The overall scheme of the robot wireless charging system design is given, and the design and hardware implementation of the transmitter controller, the energy coupler, and the receiver controller are given respectively. Finally, through the installation experiment, the correctness and practicability of the robot wireless charging system designed in this paper are verified.

1. Introduction

With the development of science and technology, and the demand in the field of automation, more and more mobile robots are used in industrial and commercial fields. At present, rechargeable batteries are used to supply power in mobile robots. Generally, batteries power generally only maintain the robots working for hours. It is hoped that robots in industrial can maintain good operating capabilities and minimize manual interventions, but their charging problems have become a major problem. At present, the robot uses automatic plug-in or manual mode to charge: automatic plug-in charging often requires high positioning precision, and charging failure occurs when the plug-in is failed; artificial charging takes a lot of manpower and material resources and is not worth the loss [1-4]. How to realize automatic charging for robots in a safe, reliable, fast and efficient way without human intervention is a key technology to realize robot intelligence.

Compared to wired charging, wireless charging has advantages of easy to use, safety, no electric spark, no dust and contact loss, no mechanical wear and no need for human participation [5,6]. And it can be adapted to a variety of harsh environments and bad weather, which has become a research hotspot in recent years [7,8]. Therefore, the application of wireless charging technology to the charging of the robot can realize independent source searching, automatic charging and automatic end charging, which greatly improves the independence of the robots, reduces the dependence on human, and saves manpower and material resources.

At present, there are few researches on hectowatt wireless charging systems for robots, which still have some problems to be solved. The hectowatt wireless charging systems for robots are different from the kilowatt wireless charging systems for electric vehicle, which are less efficient, and have different transmission characteristics due to low battery voltage, so many studies are needed to solve these problems [9-12]. In this paper, a wireless charging system for robot is developed. The robots mentioned in this paper refer to autonomous robots that can be recharged, mobile, and can be applied to substations, restaurants, factories and other occasions, such as electric inspection robots. The basic principle of the wireless charging system is studied first, and the expressions of the output power and efficiency of the wireless charging system are derived. The effects of various parameters on output power and efficiency are quantified using MATLAB programming, and according to the theory, the relevant parameters of the robot wireless charging system are designed. Then the feasibility of the parameters is simulated by MATLAB Simulink, and the frequency adjustment control strategy is introduced into the robot wireless charging system, which solved the problems caused by frequency splitting and reduced the energy conversion link at the same time. Finally, the overall scheme of the robot wireless charging system design is given, and through the hardware implementation, the wireless charging system applied to the electric inspection robot is realized, and the practicality of the system is verified through a series of experiments.

2. Theoretical analysis of wireless charging system

2.1. Theoretical analysis

At present, the wireless charging system usually selects the SS topology, so the wireless charging system designed in this paper also adopts the SS topology. When the intrinsic resonance frequency of the inductors and capacitors at the transmitter and receiver of the wireless charging system is equal to the working frequency, the system resonates, and the energy is transmitted from the transmitting coil to the receiving coil. Since resistance, inductance, and capacitance (RLC) series circuits exhibit resistive characteristics when the inductance and capacitance resonate, for the convenience of calculation, the internal resistance R_s of the power supply is ignored, the resistance of the transmitter is replaced with R_1, and the resistance of the receiver is replaced with R_2. Simplified equivalent circuit is shown in figure 1.

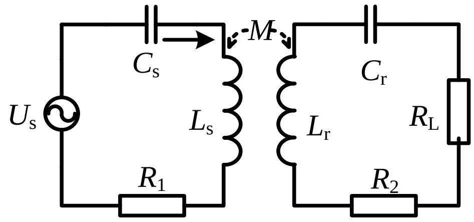

Figure 1. Simplified equivalent circuit of SS topology.

According to the equivalent circuit diagram of SS topology, the voltage equation of the transmitter and receiver can be written by Kirchhoff voltage law (KVL):

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$$\begin{bmatrix} U_s \\ 0 \end{bmatrix} = \begin{bmatrix} R_1 + \dfrac{1}{j\omega C_s} + j\omega L_s & -j\omega M \\ -j\omega M & R_2 + R_L + \dfrac{1}{j\omega C_r} + j\omega L_r \end{bmatrix} \begin{bmatrix} \dot{I}_s \\ \dot{I}_r \end{bmatrix} \tag{1}$$

The ω is the intrinsic frequency of the system, the I_s is the transmitter current and the I_r is the receiving current. The equivalent impedance of the transmitter Z_s and the equivalent impedance of the receiver Z_r can be obtained from (1):

$$\begin{cases} Z_s = R_1 + \dfrac{1}{j\omega C_s} + j\omega L_s \\ Z_r = R_2 + R_L + \dfrac{1}{j\omega C_r} + j\omega L_r \end{cases} \tag{2}$$

The currents of transmitter and receiver can be expressed by Z_s and Z_r as (3):

$$\begin{bmatrix} \dot{I}_s \\ \dot{I}_r \end{bmatrix} = \frac{1}{Z_s Z_r + (\omega M)^2} \begin{bmatrix} Z_r & -j\omega M \\ -j\omega M & Z_s \end{bmatrix} \begin{bmatrix} U_s \\ 0 \end{bmatrix} \tag{3}$$

From (2) and (3), the expression of the input power P_s at the transmitter and the power to the load P_o at the receiver can be obtained:

$$\begin{cases} P_s = U_s I_s = \dfrac{U_s^2 |Z_r|}{\left| Z_s Z_r + (\omega M)^2 \right|} \\ P_o = I_r^2 R_L = \dfrac{U_s^2 (\omega M)^2 R_L}{\left[Z_s Z_r + (\omega M)^2 \right]^2} \end{cases} \tag{4}$$

Since the RLC series circuit is externally equivalent to resistance when it is in resonance, that is, Z_s and Z_r are resistance when resonance. Then, Z_s=R_1 and Z_r= R_2+ R_L at this time, then P_s and P_o can be simplified as:

$$\begin{cases} P_s = \dfrac{U_s^2 (R_2 + R_L)}{R_1 (R_2 + R_L) + (\omega M)^2} \\ P_o = \dfrac{U_s^2 (\omega M)^2 R_L}{\left[R_1 (R_2 + R_L) + (\omega M)^2 \right]^2} \end{cases} \tag{5}$$

From (5), the overall efficiency of the wireless charging system can be obtained as:

$$\eta = \frac{P_o}{P_s} = \frac{(\omega M)^2 R_L}{\left[R_1 (R_2 + R_L) + (\omega M)^2 \right] (R_2 + R_L)} \times 100\% \tag{6}$$

The coupling coefficient k, mutual inductance M between transmitting and receiving coils, inductance L_s at transmitter, and inductance L_r at the receiver have the following relationship:

$$k=\frac{M}{\sqrt{L_\mathrm{s}L_\mathrm{r}}} \tag{7}$$

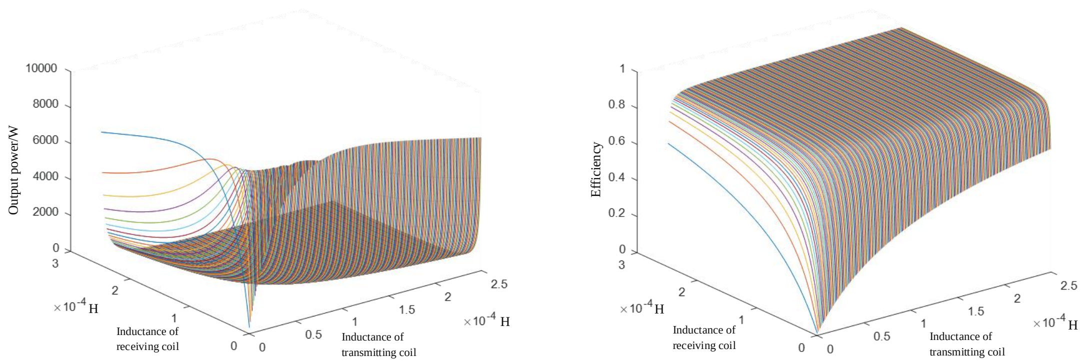
Substituting (7) into (5) and (6) yields (8):

$$\begin{cases} P_\mathrm{o}=\dfrac{U_\mathrm{s}^2\omega^2k^2L_\mathrm{s}L_\mathrm{r}R_\mathrm{L}}{\left[R_1\left(R_2+R_\mathrm{L}\right)+\omega^2k^2L_\mathrm{s}L_\mathrm{r}\right]^2} \\ \eta=\dfrac{\omega^2k^2L_\mathrm{s}L_\mathrm{r}R_\mathrm{L}}{\left[R_1\left(R_2+R_\mathrm{L}\right)+\omega^2k^2L_\mathrm{s}L_\mathrm{r}\right]\left(R_2+R_\mathrm{L}\right)}\times100\% \end{cases} \tag{8}$$

Equation (8) indicates that the output power and efficiency of the wireless charging system are mainly related to the input voltage of the system, the intrinsic frequency of the system, the coupling coefficient between the transmitting and receiving coils, the transmitter and receiver inductance, the value of the equivalent load, the resistance of transmitter and receiver. The MATLAB simulation software can be used to simulate the relationship between the parameters and output power and transmission efficiency of system.

2.2. Analysis by MATLAB programing

In this paper, a 300 W wireless charging system is developed based on electric inspection robot. The rated battery voltage of the power inspection robot is 24 V, and the equivalent load is between 2-3 Ω at charging power of 300 W. Due to the constraints of the robot chassis area, the coil area of the wireless charging system for robots is limited, so the coupling coefficient is generally fixed. In the case of chassis height of 15cm, generally k=0.1. Both the transmitting coil and the receiving coil are wound of Litz wire, which has good high frequency performance, and smaller line resistance can be obtained to reduce the influence on the system. When considering the influence of other parameters on the transmission performance of the system, R_1=0.11 Ω, R_2=0.08 Ω, Us=60V, f=85 kHz, R_L=3 Ω. Under the condition that the only variable is guaranteed, the effects of parameters such as coil inductance and coupling coefficient on the output power and efficiency of the system can be analysed. The above equations are programmed using MATLAB, and the effects of various parameters on the output power and efficiency of the wireless charging system can be clearly shown by curves.



(a) (b)

Figure 2. Influence of inductances on output power and efficiency of wireless charging system. (a) The relationship between the transmitter, receiver inductances and output power and (b) The relationship between the transmitter, receiver inductances and efficiency.

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2.2.1. Influence of inductances on wireless charging system. According to figure 2(a), the relationship between the output power and the inductance of the two coils is increased first and then reduced, while the wireless charging system for the robot needs output power of 300 W, so the inductance of the two coils should be slightly larger. But if the inductances of the two coils are too large, line consumption and economic cost will be increased. Therefore, the inductance of the transmitting coil can be larger, and the inductance of the receiving coil can be smaller.

According to figure 2(b), it can be seen that the transmission efficiency of the wireless charging system increases with the increase of the inductances, and the transmission efficiency of the system increases faster when the inductance is increased from 50 to 100 μH, and the transmission efficiency of the system increases slowly when the inductance is increased from 100 to 250 μH.

According to the above analysis, the inductance of the transmitting coil is set to 233.6 μH, and the inductance of the receiving coil is set to 140 μH.

2.2.2. Influence of coupling coefficient on wireless charging system. The above-determined inductance parameters are brought into the MATLAB program, and the coupling coefficient is set as a variable. The obtained results are shown in figure 3.

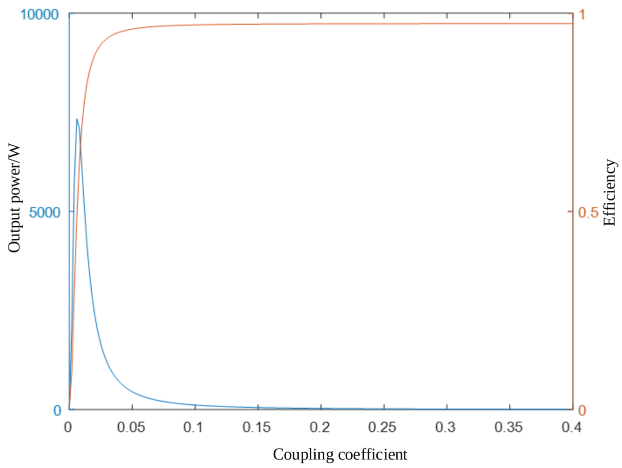

Figure 3. The influence of coupling coefficient on output power and efficiency of the wireless charging system.

According to figure 3, with the increase of the coupling coefficient, the transmission efficiency of the system is gradually improved, but the transmission power of the system tends to become larger and then decrease. When the coupling coefficient increases to 0.05, the efficiency exceeds 90%, and thereafter the coupling coefficient continues to increase, but the transmission efficiency increases more and more slowly, and the transmission power gradually decreases. When the coupling coefficient increases to about 0.1, the output power of the system is reduced to below 500 W. Considering the design requirements of the system, the coupling coefficient should be maintained at about 0.1.

3. Simulation analysis in MATLAB Simulink

In chapter 2, the wireless charging theory of SS topology and the influence of various parameters on the wireless charging system are analyzed, and the parameters such as the inductances of the wireless charging system are determined. In this chapter, according to the theory of wireless charging and related practices, building a MATLAB Simulink simulation model, as shown in figure 4. The simulation model is mainly composed of DC source, full-bridge inverter, coil coupling, rectifier and battery pack. Using Simulink simulation, results with little difference from the reality can be obtained, so as to verify the theory of wireless charging system and the rationality of parameter design in chapter 2.

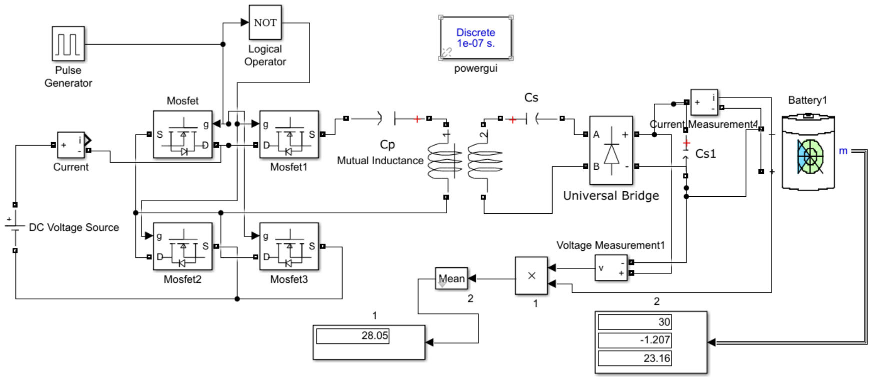

Figure 4. Simulation model of wireless charging system in Simulink.

First, according to the design parameters in chapter 2, R_1=0.11 Ω, R_2=0.08 Ω, Us=60 V, f=85 kHz, L_1=233.6 μH, L_2=140 μH, C_1=15 nF, C_2=25 nF, k=0.1, Us=60 V. The above parameters are brought into the Simulink model and debugged, so that the model can run normally.

According to figure 4, it can be seen that the output power of the system obtained according to the above parameters is 28 W, far less than the demand of output power of 300 W. This is because the battery voltage of the robot is low, and the equivalent resistance load is small, resulting in frequency splitting. Setting the frequency of the system as a variable, according to MATLAB programming the output power and efficiency curves can be obtained shown in figure 5. According to figure 5, the output power of the system is smaller at the resonance point, and a peak value appears on each side, namely the frequency splitting phenomenon [13].

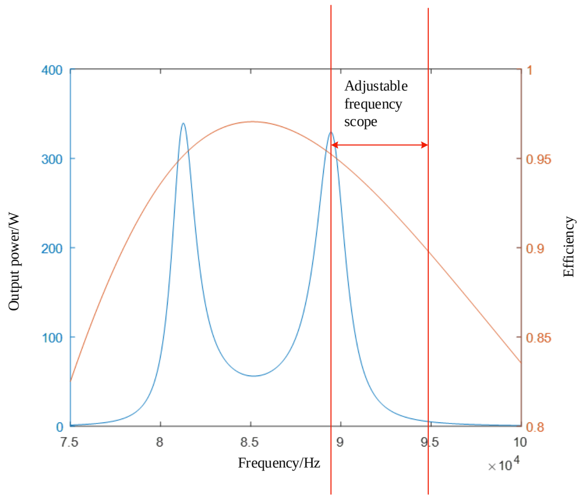

Figure 5. Frequency characteristics of wireless charging system under small load.

In order to achieve the 300W output power of the system design, this paper adopts frequency adjustment control strategy, that is, the frequency of the system is shifted to the resonant frequency to increase output power. The adjustable frequency scope is shown in figure 5. Moreover, the frequency adjustment control strategy can also achieve the control of the output power of the system, so that no DC-DC link is added, and the complexity of the circuit is reduced. But frequency adjustment control strategy will sacrifice a part of efficiency.

4. System design and hardware implementation

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4.1. The overall scheme

The robot wireless charging system designed in this paper consists of three parts: the transmitter controller, the energy coupler and the receiver controller, as shown in figure 6. The transmitter controller includes a DC stabilized power supply, a high frequency inverter, and an ARM controller. The energy coupler includes a transmitter coil and a receiver coil. The receiver controller includes a high frequency rectifier, a low voltage battery pack, a Mega8 controller, and voltage and current sampling circuit. The receiving coil is installed on the robot chassis, and the receiving controller is installed in the robot body, and the transmitting coil is buried underground in the charging point, and the transmitting controller is fixed near the charging point.

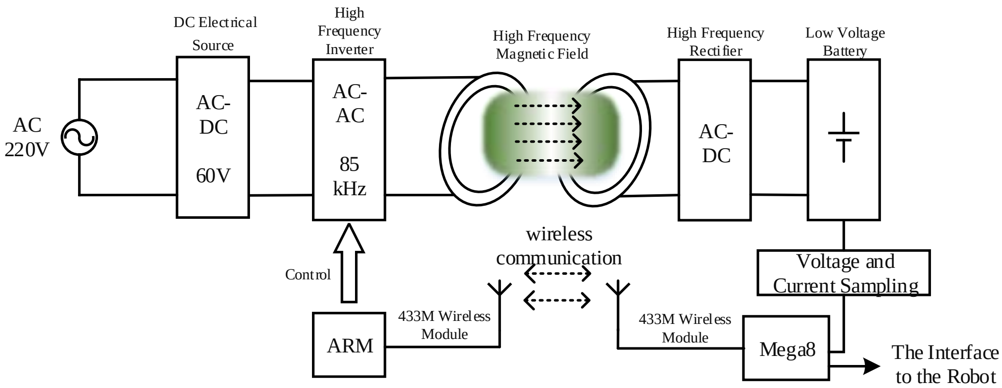

Figure 6. Overall structure schematic diagram of the robot wireless charging system.

The main functions of the system are as follows:

The first step, the robot equipped with the receiving coil is driving to the charging point according to its own navigation, and then sends the charging signal to the receiver controller of the wireless charging system. The receiver controller receives the charging signal and then communicate with the transmitter controller through the 433 M wireless communication module, then the transmitter controller launches the charging program and starts charging according to the program.

The second step, when the robot finishes the charging or the battery is full, it is necessary to send an end charging signal to the receiver controller of wireless charging system. The receiver controller communicates with the transmitting controller through the 433 M wireless communication module, and the transmitting controller stops sending power and finishes charging.

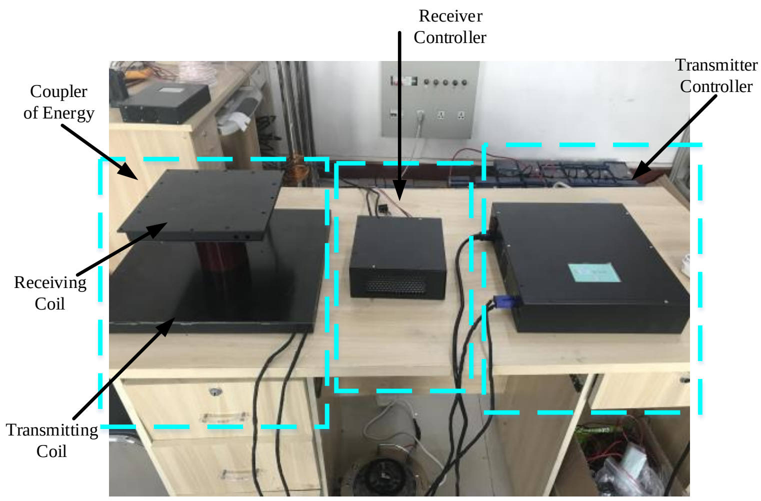

Figure 7. Robot wireless charging system.

Since the transmitting coil and the receiving coil of the wireless charging system allow a certain offset, the application of this system does not require a very accurate positioning system, and the positioning accuracy can be within ±50 mm.

The robot wireless charging system designed in this paper is shown in figure 7.

4.2. *The transmitting controller*

The diagram of transmitter controller is shown in figure 8. The main technical difficulties of the transmitter controller are as follows:

- Implementation of full bridge-inverter: to implement full-bridge inverter, it requires not only four MOSFETs, but also driver circuit and corresponding PWM signal generation circuit. In this paper, an advanced ARM chip based on the Cotex-M4 architecture (STM32F407zgt6) is used as main control chip, which can directly generate two PWM signals with opposite phases, eliminating the need for a PWM signal generation circuit. In addition, the device developed in this paper uses transformer MOSFETs drivers.
- Real-time update of current sampling. To know the real time current of transmitting coil, we must use current transformer. The turns ratio of current transformer is 1:100, that is, the current of second side is 0.01 of the primary side. After the current is reduced by 100 times, the suitable sampling resistance is selected, and the current signal is converted into a voltage signal, and the range of the voltage signal is within 0-3.3V, and the signal can be sampled by ARM directly. The ARM chip chosen in this article is equipped with a 12-bit high-precision analog-digital converter. Through the corresponding program and algorithm, the current of the transmitting coil is obtained in the ARM, and the current is judged in real time whether the current is normal and plays a role in protection.

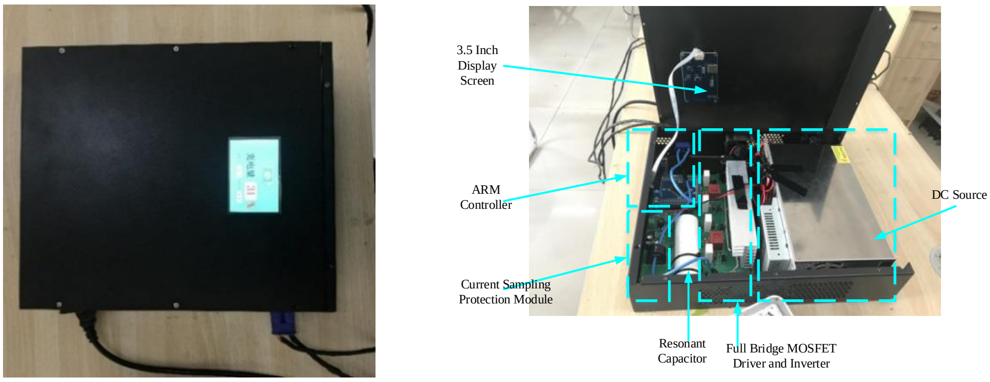

Figure 8. Diagram of transmitter controller.

Figure 9. Energy coupler.

The energy coupler is mainly composed of a transmitting coil and a receiving coil. Since the appropriate transmitting and receiving coil inductances have been designed in the previous analysis, the coils with suitable parameters can be wound. In order to reduce the cost, this paper uses the commonly used round coils and plate magnetic core structure, as shown in figure 9.

4.3. The receiver controller

The receiving controller is mainly composed of rectifier circuit, voltage and current sampling circuit and resonant capacitor, which is shown in figure 10. The main technical difficulties are as follows:

- The implementation of rectifier and filter. The rectifier must use the ultra-fast recovery diode, otherwise it will not work. Moreover, improper diode selection can lead to overheated of rectifier bridges and safety accidents.
- Voltage and current sampling circuit. First, we chose a relatively low-end microcontroller chip (Mega8) as the control chip of receiver. The voltage sampling selects resistance series connecting allotting circuit. Instead of selecting current transformers, current Hall chips are selected for current sampling. The sampling voltage signals and current signals are sent to mega8 through analog-digital conversion and calculated in real time to obtain the real voltage and current values.
- Wireless communication module. In this paper, 433 M wireless communication module is chosen for communication between transmitter and receiver. The corresponding communication statements are added to the microcontroller, and the real-time voltage and current values are sent to the transmitter controller.

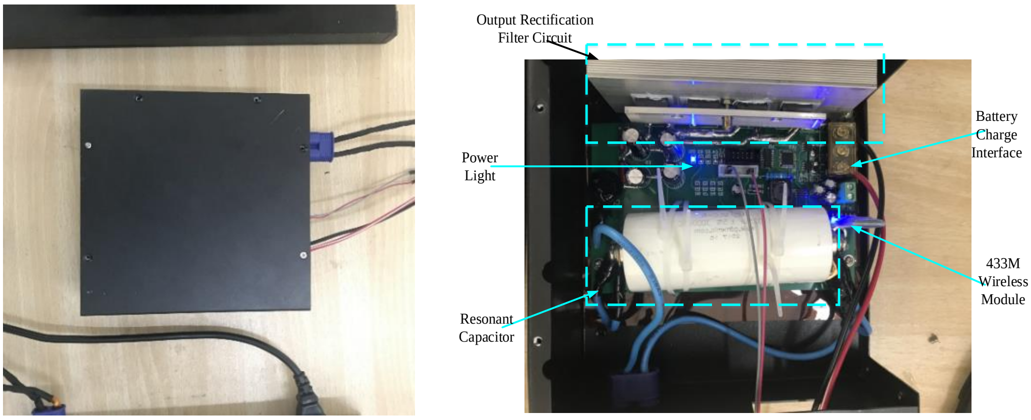

Figure 10. Diagram of receiver controller.

4.4. The installation experiment

Finally, after a series of experiments, the practicability and feasibility of the wireless charging system designed in this paper are verified. Figure 11 shows the test diagram of the system, and the photo of the receiving coil mounted on the chassis of the electric inspection robot. The output voltage and current waveforms of the inverter is shown in figure 11. The battery used in electric inspection robot is Li-ion battery pack. The chemical composition of the battery pack is lithium iron phosphate, the rated voltage is 24 V, the end-of-charge voltage is 29.6 V, and the maximum charging current is 10 A.

After repeated tests and calculations, the peak efficiency of this system is 80%, which is in a higher position in hectowatt wireless charging system.

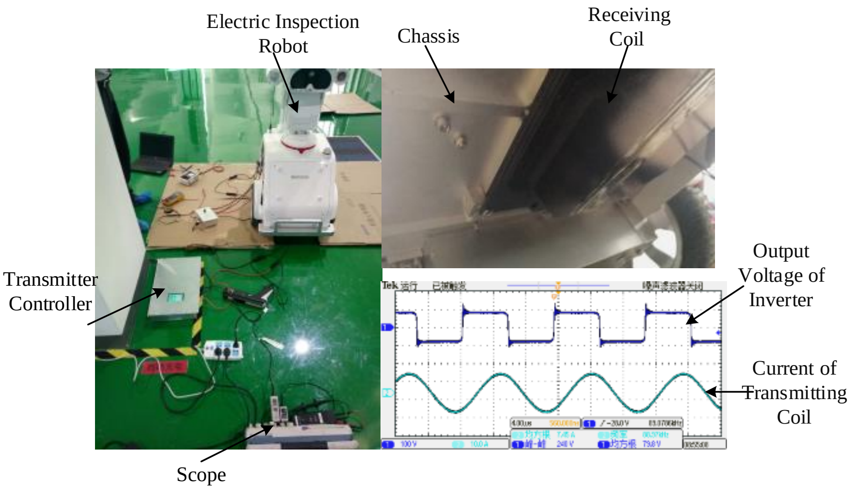

Figure 11. Installation experiments of wireless charging system.

5. Conclusion

In this paper, a 300 W wireless charging system for electric inspection robot is developed. First of all, the theory of wireless charging system in SS topology is deduced, and the expressions of output power and efficiency of wireless charging system are obtained. Secondly, the above equations are input to MATLAB by programming. The influence of inductances, coupling coefficient on the output power and efficiency is obtained, and the range of inductances and coupling coefficient is determined. Secondly, the model of wireless charging system is built in Simulink. The frequency splitting of the system is found through model simulation, and frequency adjustable control strategy is adopted to improve the frequency splitting, so as to achieve the system designed output power. Finally, the hardware design of the wireless charging system used in the robot is given, the transmitter controller, the energy coupler, the receiver controller are designed, and the current protection circuit and the battery voltage and current sampling circuit are designed to ensure the normal operation of the system. Finally, the feasibility and correctness of the system are proved by installation experiments.

At present, the wireless charging system applied to the electric inspection robot has matured technically, and our system has been tested on the electric inspection robot for half a year. The existing charging system is more expensive and requires manual intervention, but if the wireless charging system is used instead of the existing charging system, the cost will be greatly reduced.

Acknowledgments

This research has received funding from “Numerical simulation of solution flow and heat transfer in the growth of DKDP crystal” (2016QN005) & the Basic Research Grant (2015.4-2017.4) of Shandong Academy of Sciences.

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