Research on Magnetic Coupled Resonant Wireless Charging Technology Applied To Intelligent Patrol Robots

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Abstract. Magnetic coupled resonance wireless charging technology can realize high power and high efficiency energy transmission at medium distance, which is highly suitable for wireless charging of patrol robots. In this paper, a magnetic-coupled resonant wireless charging system applied in the patrol robot is designed and researched. The working principle of magnetic coupled resonant wireless charging technology is firstly introduced. Then, based on the theory of equivalent circuit modeling, the transmission efficiency and load power of the system are deduced. Moreover, the coil resonance frequency is calculated, and the coil field is analyzed by using Maxwell electromagnetic field software. Finally, the simulation software of Simplorer and Maxwell is used to verify the feasibility and efficiency of wireless charging technology.

1. Introduction
In recent years, intelligent patrol robots have been widely used in the transformer substation, chemical plant and coal mine, which are beneficial to reduce the manpower and enhance the patrol reliability [1]. For the most patrol robots, they generally adopt the traditional wired (contacted) charging method, which inevitably introduces a serial problems such as electric spark, cable aging and inaccuracy docking. Therefore, for increasing the safety of charging for patrol robots, the wireless charging has been of increasing interest in the last decade. Compared with the traditional wired charging, wireless charging technology avoids the potential hazards of aging and loss of transmission line and electric spark caused by plugging and unplugging, which improves the security and reliability of the charging system. What is more important, the wireless charging can adapt to a variety of harsh environments and weather conditions, which is essential for the outdoor inspection [2]. At present, there are mainly two feasible wireless charging technologies are suitable for the patrol robot, which are electromagnetic induction coupled radio energy transmission and magnetic coupled resonant radio energy transmission[3,4]. Compared with the electromagnetic induction coupled radio energy transmission, magnetic coupled resonance radio energy transmission has the advantages of high transmission efficiency, long distance and strong anti-migration [5], hence, it is a more promising candidate than the counterpart. In this paper, a magnetic-coupled resonant wireless charging system applied in the patrol robot is designed and researched, and the performance of it is verified by use of combined simulation software of Simplorer and Maxwell.
2. Wireless charging system based on MCR-WPT

Magnetically coupled resonant wireless power transmission is based on resonance principle [6]. The AC voltage generated by the traditional power grid is converted into DC voltage after rectifying and filtering, which is converted into high-frequency AC voltage of specific frequency through the inverter device, then converted to AC electric quantity at specific frequency through resonant circuit and transmitted to the receiving coil through the transmitting coil. Since two coils with the same frequency, high frequency resonance are produced by coil inductance and compensation capacitor, so as to maximize the transmission of energy to the receiving end. After the receiving coil induces the AC voltage and current, it supplies power to the patrol robot after rectifying by the secondary side rectifying circuit. According to the connection mode of coil inductance and compensation capacitor, there are mainly four topologies [7]. Among them, the SS patch structure is the most common used in Wireless charging system, and the equivalent circuit model is shown in Figure 1.

![Wireless charging system equivalent circuit model](image)

**Figure 1.** Wireless charging system equivalent circuit model

In figure 1, \( U_s \) is an AC voltage source. \( R_1 \) is the internal impedance of the voltage source. \( L_T \) and \( L_r \) are the equivalent self-inductance of the transmitting and receiving coils, \( M \) is the mutual inductance between two coils. The coil’s internal resistance are \( R_T \) and \( R_r \) respectively. \( C_1 \) and \( C_2 \) are the primary and secondary resonant capacitors respectively. \( R_L \) is the equivalent resistance of the charging load. \( I_T \) and \( I_r \) are primary and secondary currents. According to Kirchhoff’s voltage law:

\[
\begin{align*}
Z_T I_T + j \omega M I_r &= U_s \\
Z_r I_r + j \omega M I_T &= 0
\end{align*}
\]

(1)

Where \( Z_T = R_T + j \omega L_T - j \frac{1}{\omega C_1} \), \( Z_r = R_r + j \omega L_r - j \frac{1}{\omega C_2} \). The mapping impedance from the secondary side to the primary side \( Z_f \) is:

\[
Z_f = \frac{(\omega M)^2}{Z_r}
\]

(2)

According to equation (1) and (2), the current of the primary side and the secondary side are:

\[
\begin{align*}
I_T &= \frac{U_s}{Z_T + Z_f} = \frac{U_s Z_r}{Z_T Z_r + (\omega M)^2} \\
I_r &= \frac{j \omega M U_s}{(Z_T + Z_f)Z_r} = \frac{j \omega M U_s}{Z_T Z_r + (\omega M)^2}
\end{align*}
\]

(3)
The system output power $P_{\text{out}}$, the input power $P_{\text{in}}$ and transmission efficiency $\eta$ can be calculated by the formula, such as type (4):

$$
\begin{align*}
P_{\text{in}} &= |V| |U| = \frac{U \omega^2 Z_r}{Z_T Z_r + \omega^2 M^2} \\
P_{\text{out}} &= |V| R_L = \left( \frac{\omega M U}{Z_T + Z_r} \right) R_L = \frac{U \omega^2 M^2 R_L}{(Z_T Z_r + \omega^2 M^2)^2} \\
\eta &= \frac{P_{\text{out}}}{P_{\text{in}}} \times 100\% = \frac{\omega^2 M^2 R_L}{(Z_T Z_r + \omega^2 M^2) Z_r} \times 100\%
\end{align*}
$$

(4)

3. Coil design of wireless charging system

Transmitting and receiving coils are the core components of wireless charging system, and it can be seen from the above analysis that whether the coil parameters are designed reasonably or not has an important impact on the power and efficiency of the system. According to coil inductance and compensation capacitance, the resonance frequency of the system can be calculated and its formula is:

$$
f = \frac{1}{2\pi \sqrt{LC}}
$$

(5)

In order to facilitate the installation of coils on the inspection robot, the system adopts flat spiral coils and the coils are wound by multi-strand Liz wire, which effectively reduces the skin effect and the coil resistance. Meanwhile, for improving the coil mutual inductance and increasing the transmission distance, plate ferrite core is adopted, which has the advantages of light weight and high permeability [8]. The schematic diagram of coil structure is shown in Figure 2.

![Coil model of wireless charging system](image)

**Figure 2.** Coil model of wireless charging system

As mentioned in [2], the flux density directly affects the transmission efficiency of wireless charging system. Therefore, the flux distribution of coil with ferrite core is investigated by used of finite-element method, as shown in Figure 3. It can be seen that, due to the ferrite magnetic core plays a good role of shielding and magnetic flux short circuit, most of the magnetic inductance lines are concentrated between the two coils, hence, there exists high flux density on the inside of the coil. Consequently, the planar spiral coil with ferrite core can realize the efficient transmission of energy...
between the transceiver coils, which is a promising choice for the wireless charging circuit designed in this paper.

![Coil magnetic field distribution](image)

**Figure 3.** Coil magnetic field distribution

4. Simulation Verification

Based on the above analysis, the designed wireless charging system is investigated by using the combined simulation software of Simplorer and Maxwell. As shown in Figure 4, a wireless charging circuit based on the SS patch structure was built in Simplorer, and a coil simulation model was built in Maxwell. Coil inductance is 0.13mH measured by Maxwell. In order to make the system work at a fixed resonant frequency $f=60$KHz, compensation capacitor $c= 54.1243nf$ was used for resonance compensation.

![The joint simulation circuit of Simplorer and Maxwell](image)

**Figure 4.** The joint simulation circuit of Simplorer and Maxwell

The results of combined simulation are shown in Figure 5. For a clearly analysis of the simulation results, Figure 5 (a) (d) show the simulation images of 0 to 50ms, and (b), (c) show the simulation images of 20 to 20.2ms. The three-phase input voltage and the DC voltage rectified by the bridge diode are shown in Figure 5 a. The amplitude of the three-phase input voltage is 220V and its frequency is 50Hz. The DC voltage obtained after rectifying by the three-phase bridge rectifier circuit fluctuates in amplitude between 310V and 370V. WM2. V and WM2. I represent the AC voltage and current obtained after the full bridge inverter circuit, whose frequency is equal to the resonant frequency of the coil is 60Hz, WM3. V and WM3. I are respectively the induced voltage and induced current of the secondary side of the coil. The voltage and current in Figure5b and Figure 5c operate at the same frequency, indicating that the system has reached a resonant state. In Figure5d, WM4.P is the load output power, and WM1.P is the system input power. It can be seen that the system has a high transmission efficiency, which is about 88.1% after calculation.
5. Conclusion
In this paper, a magnetic-coupled resonant wireless charging system applied in the patrol robot is designed. Based on the equivalent circuit theory, the topological circuit of wireless charging system is analyzed. Then the flux distribution of the charging coil is investigated by using the finite element method. Finally, based on the combined simulation software of Simploter and Maxwell, the electronics performance of the charging system is investigated. The simulation results show that the designed wireless charging system has high transmission efficiency and stable output power, which are highly desirable for patrol robots.

References
[1] Ahmad Bala Alhassan, Xiaodong Zhang, Haiming Shen, Haibo Xu. Power transmission line inspection robots: A review, trends and challenges for future research [J]. International Journal of Electrical Power and Energy Systems, 2020, 118.
[2] Songyan Niu, Haiqi Xu, Zhirui Sun, Z.Y. Shao, Linni Jian. The state-of-the-arts of wireless electric vehicle charging via magnetic resonance: principles, standards and core technologies [J]. Renewable and Sustainable Energy Reviews, 2019, 114.

[3] Chunsen T, Pengqi D, Zhihui W, et al. Parameter optimization method for the wireless charging system of mowing robot [C]. 2017 IEEE PELS Workshop on Emerging Technologies: Wireless Power Transfer (WoW). IEEE, 2017.

[4] Yang M, Yang G, Li E, et al. Modeling and analysis of wireless power transmission system for inspection robot [C]. IEEE International Symposium on Industrial Electronics. IEEE, 2013.

[5] Songyan Niu, Haiqi Xu, Zhirui Sun, Z.Y. Shao, Linni Jian. The state-of-the-arts of wireless electric vehicle charging via magnetic resonance: principles, standards and core technologies [J]. Renewable and Sustainable Energy Reviews, 2019, 114.

[6] In-Kui Cho. Wireless Power Transfer System for Docent Robot by using Magnetic Resonant Coils [C]. IEEE Beijing Section, IEEE AP-S, Beijing Jiaotong University. Proceedings of 2013 IEEE 5th International Symposium on Microwave, Antenna, Propagation and EMC Technologies for Wireless Communications. IEEE Beijing Section, IEEE AP-S, Beijing Jiaotong University: IEEE BEIJING SECTION, 2013: 511-514.

[7] Mohammed Al-Saadi, Ammar Ibrahim, Ali Al-Omari, Ammar Al-Gizi, Aurelian Craciunescu. Analysis and Comparison of Resonance Topologies in 6.6kW Inductive Wireless Charging for Electric Vehicles Batteries [J]. Procedia Manufacturing, 2019, 32.

[8] Aqueel Ahmad, Mohammad Saad Alam. Magnetic Analysis of Copper Coil Power Pad with Ferrite Core for Wireless Charging Application [J]. Aqueel Ahmad; Mohammad Saad Alam, 2019, 20(2).