Magnetic Coupling Resonant Wireless Charging Principle Case Study

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Abstract. With the development of wireless charging, it is now widely used in small electronic products, but it has largely untapped potential due to the limitation of charging distance. To make wireless charging realize the application value is greater, magnetic coupling resonant wireless charging due to the distance moderate and high efficiency become the future development trend of wireless charging. The essay analyzes the principle of magnetic coupling resonant wireless charging and two cases of Magmimo and Implantable medical devices charging to analyze forms of application. This essay analyzes the three major technical problems of safety, compatibility and efficiency at this stage, and gives the corresponding solutions. Finally, this essay looks forward to the development of this technology, pointing out that this technology can optimize transmission efficiency in the future and promote the development of marketization.

Keywords: Magnetically Coupled Resonance, Wireless Power Transmission, Artificial Heart Power Supply, Transmission Efficiency

1 Introduction

Wireless charging is now widely used in cell phones, watches, and other electronic products. Wireless charging will be developed for more distance charging, to get rid of electronic devices, such as wire wear and tear, placement battery aging and environmental protection problems. However, at this stage, the effective charging distance of wireless charging generated by Magnetic Inductive Coupled Wireless Power Transfer (MICPT) is only a few millimetres to a few centimetres. Longer distance transmission can be achieved mainly through the magnetic resonance coupled Wireless Power Transfer (MRCPT) and Microwave Wireless Power Transfer (MWPT) technology. MWPT is more suitable for long-distance high-power transmission, but not for short-distance wireless transmission in terminals because of low transmission efficiency and large transmitter module. In contrast, magnetically coupled resonant wireless charging, which is characterized by relatively long transmission distance, good offset resistance and environmental adaptability, has higher practical value in multiple fields [1]. In 2007, the team of Professor Marin Soljacic at MIT proposed the strongly coupled magnetic resonance (SCMR) technique for mid-range WPT. Light a 60W bulb 2m away with 40% wireless

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transmission efficiency. The concept of MCRWPT is proposed for the first time, which leads to a new direction of WPT technology research. [2]. In addition, resonant magnetic coupling can charge multiple devices at the same time by tuning the coupled resonators of multiple receiving coils [3]. This technology is nowadays rapidly developing in electric vehicles, inspection robots, unmanned aerial vehicles (UAVs), implantable medical devices and other intelligent devices for power systems. This essay will focus on the principle and application analysis of magnetically coupled resonant wireless energy transmission, point out the existing technical pain points, and propose the corresponding solutions and future technology outlook.

2 Principle Overview

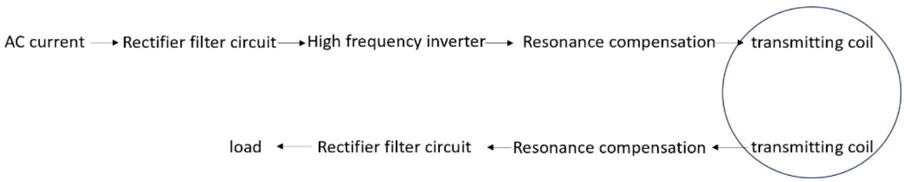

Figure. 1. Magnetic coupling resonant principle of operation.

The main working principle of the magnetically coupled resonant type is shown in the block diagram of wireless energy transmission in Figure 1. Firstly, the household 220V AC is rectified to DC, and in the high-frequency inverter circuit, the driving signal of the switching tube in the inverter bridge is provided by the DSP minimum system. The signal is first isolated from the main circuit by an isolation circuit, then amplified by the driver circuit, and finally enters the inverter bridge to drive the switching tube. The high-frequency square-wave voltage output from the inverter bridge is added to both ends of the primary winding, forming a high-frequency alternating current in the winding. The current causes a high-frequency alternating magnetic field in the air gap, and the induced alternating current is obtained in the secondary winding through magnetic field coupling, and the current is rectified and filtered through the secondary output to obtain DC output. The output voltage value is obtained through the detection circuit and the value is fed back to the DSP minimum system for sampling control to improve the DC output [4].

In the compensation circuit, both sides of the coupler are connected in series with a capacitor, so that it resonates with the leakage inductance of the side at a certain operating frequency, eliminating the phase difference between the voltage vector and the current vector in the side, at which time the operating frequency is known as the resonance frequency of the circuit, the capacitance is known as the resonant frequency of the circuit, and the capacitance is known as the resonance compensation capacitor. Resonance compensation can improve the load impedance characteristics of the coupling device, indirectly improve the coupling coefficient, and ultimately achieve the purpose of enhancing the system power transmission [5].

3 Case Studies

3.1 Magmimo Desktop Wireless Charging

Scientists at the Massachusetts Institute of Technology have invented wireless charging technology called Magmimo. In Magmimo, a receiving coil is built into the cell phone end and multiple coils are placed on the transmitting end, where the currents in the individual coils are coordinated so that their magnetic fields combine efficiently on the cell phone coils, i.e., to produce a beam of light directed towards the cell phone. The generated beam is spatially controlled according to the position of the cell phone. Due to the magnetic coupling between the transmitter and the receiver, the signal source can measure the beamforming parameters by simply measuring the load applied by the receiver circuit to the transmitter circuit, thus eliminating the need for a specific positioning and wireless transmission system [6].

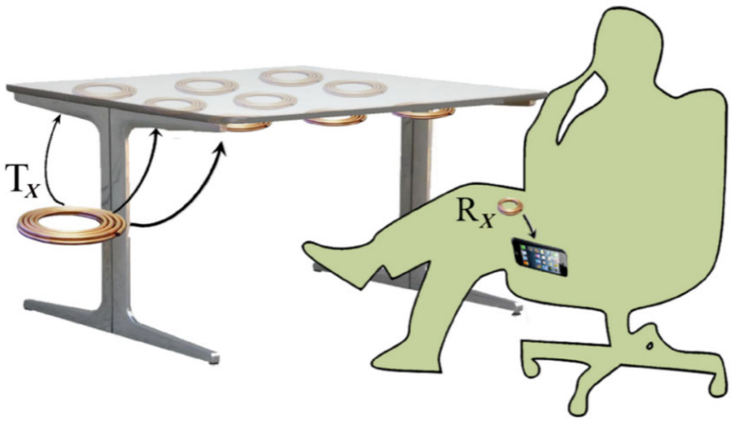

Figure. 2. An array of Tx coils mounted below the surface of a desk connected to the Rx coils of an electronic device to provide power [6].

As shown in Fig. 2, 30-40 coils are placed underneath a tabletop whose surface is not made of conductive metal to satisfy wireless charging of electronic devices at distances between 30 cm and 40 cm. MagMIMO uses multi-coil magnetic-beamforming to focus the magnetic flux along the beam to transmit over longer distances and also adjusts the direction of the magnetic flux to align with the coils at the receiving end to achieve higher transmission efficiency [6]. The direction of the magnetic flux can also be adjusted to align the coils at the receiving end to achieve higher transmission efficiency [6].

MagMIMO does not require specific modifications to the phone and can be used with today's cell phones by incorporating small receiver coils (and circuitry) into a sleeve that is fixed to the phone with no compatibility issues.

3.2 Implantable medical devices

In the medical field, most implantable medical devices are externally powered connected batteries or internal batteries, which creates problems of regular replacement and increased risk of infection, rejection, and inconvenience for patients. Magnetically coupled resonant wireless charging technology can greatly reduce the risk of patient infection and provide a more convenient and safer charging method.

In existing studies, the transmission efficiency can reach up to 85% when the transmission distance is 8cm [5]. In the study, the curved coil structure is established by different radii to achieve higher efficiency. Finally, the coupling coefficients and transmission efficiency during simulation are experimentally analyzed to determine the accuracy of the relative displacement between the coils.3D printing of curved coils with different curvatures to complete the simulation and experiments verifies the theoretical feasibility of the curved coil coupling mechanism for use in the artificial heart [7]. As for the potential harm of wireless charging to the human body. Studies have shown that the magnetic induction intensity, electric field intensity and SAR value of cardiac pacemakers during wireless charging are lower than the ICNIRP standard limits, and have no obvious effect on heart health. However, there is a caveat. In the tissue layer between the two coils, the magnetic induction exceeds the ICNIRP standard limits. Therefore, when using wireless charging equipment, appropriate electromagnetic protection measures should be taken. And limit charging time[8].

4 Technical Pain Points and Problems Faced

4.1 Security Issues

Wireless charging technology has several important safety concerns. First, because it typically involves the transmission of electromagnetic fields, the uncertainty of the possible effects on human health of long-term exposure of the human body to electromagnetic radiation can still deter users, although there is not yet sufficient evidence of its severity. Second, the device will generate heat when transmitting energy, and there is a risk of overheating and fire, especially if the device is not properly designed or used, which puts a high demand on overheating protection equipment requirements. In addition, wireless charging technology has some potential safety hazards, such as data security issues. Since wireless charging devices often need to communicate with smartphones or other devices for energy transfer, this may lead to the risk of data leakage or hacking. Therefore, ensuring communication encryption and data security becomes critical. Finally, electromagnetic interference during the charging process may affect the normal operation of other electronic devices in the vicinity, especially for devices that require high stability of the surrounding magnetic field.

4.2 Compatibility Issues

When facing compatibility challenges, spaced charging technology is not only affected by differences in device standardization, differences in charging distance and power, and matching of devices and accessories but also other challenges. Devices produced by different manufacturers use different charging standards and technologies, resulting in limited compatibility of charging products. Charging distance and power differences also vary from device to device, and environmental factors such as electromagnetic interference and metal obstacles may further affect charging effectiveness and stability. In addition, differences in communication protocols are accompanied by security challenges. Differences in communication protocols may increase the chances of attackers exploiting security holes for malicious attacks. If the communication protocols used by a particular device have vulnerabilities or flaws, attackers may take advantage of these loopholes to conduct malicious behaviours such as cyberattacks, information theft, or data tampering. Addressing these challenges requires the development of uniform technical standards, communication protocols, and security specifications, as well as the strengthening of cooperation among all parties, in order to promote the widespread application and popularization of space-vacuum charging technology.

4.3 Efficiency Issues

In terms of energy transfer, the efficiency of energy transfer decreases as the transmission distance increases. This is because there are problems such as electromagnetic depletion and radiation losses due to the air medium during the energy transmission process, and these losses increase as the distance increases, thereby reducing the efficiency of energy transmission from the coil. In addition, spaced wireless charging technology usually relies on principles such as electromagnetic induction and electromagnetic resonance to realize energy transfer. However, the electromagnetic coupling between devices is inefficient in practical applications, which can lead to the dissipation of a portion of the input energy, thereby reducing the charging efficiency. Finally, in terms of materials, the selection of appropriate materials is also an important factor affecting charging efficiency. For example, high-cost coil materials can improve the electromagnetic coupling efficiency, but at a higher cost, whereas using low-cost materials may lead to increased losses in the energy transfer process, affecting the charging efficiency. Therefore, when designing a spaced charging system, it is necessary to find a balance between giving due consideration to the energy transfer distance, electromagnetic coupling efficiency, and material cost in order to improve charging efficiency and reduce cost.

5 Solutions and Prospects

5.1 Solutions

Solutions for Circuit Overheating Protection. Firstly, temperature sensors are installed at critical parts such as circuit capacitors and inductor coils for real-time temperature monitoring to ensure that the equipment will not overheat during the charging process. By installing an overload protection mechanism, such as a temperature wall, the system will automatically stop charging once the temperature exceeds the safe range, preventing the device from fire or damage due to overheating. Secondly, high-temperature resistant and flame-retardant materials are selected to manufacture the equipment to ensure that the equipment will not melt or cause deflagration in a high-temperature environment, thus reducing the risk of fire. Comprehensive safety testing and certification are conducted during the manufacturing process to ensure that the equipment complies with relevant safety standards and regulations while improving the durability and stability of the equipment. Finally, at the product design stage, safety factors need to be fully considered and appropriate measures taken to reduce the risk of fire. Provide users with detailed instruction manuals and emphasize safety precautions, such as not stacking flammable and explosive items near the charger and avoiding long periods of continuous use, in order to enhance users' safety awareness and preventive capabilities.

Programs for Compatibility Issues. Wireless air separation charging can be completed through intermediary accessories to complete the compatibility of new and old devices. For example, wireless air separation charging on the desktop. You can design a small receiver intermediary device that matches with electronic products such as computers and mobile phones. To offset some model mismatches. At the same time the intermediary accessories need to be negotiated by various manufacturers, the development of a unified interface standard, to ensure consistency of communication protocols and conduct adequate compatibility testing. The space charging products need for the space charging products itself, also needs to provide a variety of upgrades and update mechanisms to adapt to changing market demand and technological development. Provide users with timely and adequate instructions and guidance to help them properly use and maintain the charging equipment, thereby improving the user experience and ensuring the safety and reliability of the product.

Programs for Efficiency Issues. The air gap between the coupling coils results in high leakage inductance and low mutual inductance, which leads to the need for large input currents to transfer the quantized power. This high current increases system losses, which leads to inefficiency. The use of capacitor-compensated reactive elements overcomes this problem by keeping only resistive elements in the system, reducing losses due to circulating currents and thus improving efficiency. Primary side compensation reduces the VA rating of the source side converter thus ensuring power transfer per unit power factor while secondary compensation enhances the power transfer capability of the system [9].

For the problem of electrically coupled spaced charging efficiency, the calculation of impedance can be used to further improve the efficiency. By accurately calculating and optimizing the impedance matching between the transmitting end and the receiving end, the loss in the energy transmission process can be minimized, thus improving the charging efficiency. When performing impedance matching, it is necessary to consider the circuit characteristics of the transmitter and receiver as well as the operating frequency and other factors. Using circuit analysis and simulation tools, the optimal impedance matching scheme can be accurately calculated to ensure the maximization of energy transfer [10].

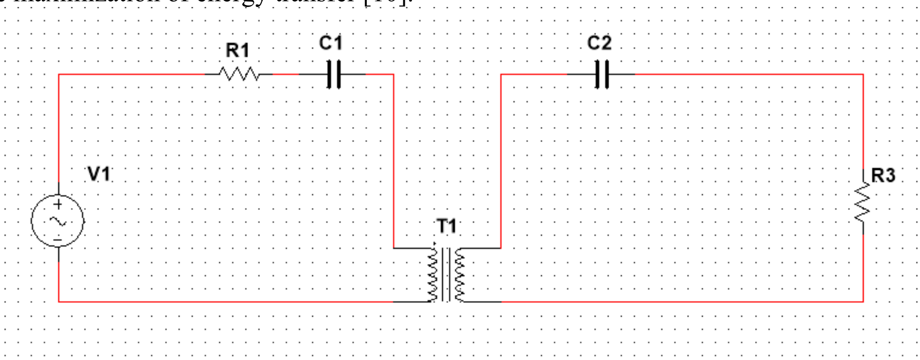

Figure. 3. Schematic diagram of the magnetically coupled resonant circuit.

In the topology, the U_1 is the input voltage, and R_1 denotes the emitter resistance, and R_2 denotes the load resistance, and I_1 denotes the input current, and I_0 denotes the output current, and M is the mutual inductance S is the apparent power η is the efficiency, and P is the output power

The mesh analysis as well as the circuit resonance leads to the following equations:

$$\left(R_1 + j\omega L_1 + \frac{1}{j\omega C_1}\right) I_1 + j\omega M I_0 = U_1 \#(1)$$

$$\left(R_2 + j\omega L_2 + \frac{1}{j\omega C_2}\right) I_0 + j\omega M I_1 = 0 \#(2)$$

$$\omega L_1 = \frac{1}{\omega C_1} \#(3)$$

$$\omega L_1 = \frac{1}{\omega C_1} \#(4)$$

The magnitude of the two mesh currents was calculated:

$$I_1 = \frac{R_2 U_1}{R_1 R_2 + (\omega M)^2} \#(5)$$

$$I_0 = \frac{-j\omega MU_1}{R_1R_2 + (\omega M)^2} \#(6)$$

Then the apparent power, the output power are:

$$S = UI = U_1U_2 = \frac{R_2{U_1}^2}{R_1R_2 + (\omega M)^2} \#(7)$$

$$P = R_1{I_0}^2 = \frac{R_2(\omega MU_1)^2}{[R_1R_2 + (\omega M)^2]^2} \#(8)$$

The efficiency of the network is:

$$\eta = \frac{P}{S} = \frac{(\omega M)^2}{R_1R_2 + (\omega M)^2} \#(9)$$

Impedance analysis of the network shows that when the system resonates the frequency of the receiving and transmitting ends are the same and determined, therefore, reducing the resistance of the wireless charging transmitting end within a certain range can significantly improve the efficiency of the network.

5.2 Directions for Development

Optimize transmission systems and control algorithms by improving efficiency to reduce energy loss and signal attenuation. Second, expand the charging distance by researching new transmission methods and materials, such as utilizing higher frequency electromagnetic waves or new resonant devices. Third, higher power transmitters and receivers and improved power management techniques are used to increase the power transmission level for faster charging. In addition, cost reduction is also key, to optimizing manufacturing processes, material costs and production scale, as well as strengthening standardization and large-scale production to reduce technology costs. Finally, strengthening safety monitoring and protection mechanisms to ensure the safety of the charging process, including real-time monitoring of parameters such as temperature, voltage and current, and timely adjustment of power transfer to avoid overheating or other safety issues. By comprehensively utilizing the above methods, the various pain points faced by the electrically coupled spaced wireless charging technology can be gradually solved to promote its wide application and popularization in practical applications.

6 Conclusion

This essay provides a discussion of the theoretical principles of magnetically coupled resonant wireless charging and demonstrates its importance and challenges in terms of the forms of application and potential problems through two case studies, namely, Magmimo and wireless charging of the artificial heart. In addition, this study provides research on three key technical issues, including safety, compatibility and efficiency. For safety issues, this paper explores the potential risks in electromagnetic radiation and electrical safety and proposes a series of effective safety measures and technical means to ensure the safety and reliability of wireless charging systems. As for compatibility, this essay analyzes the charging compatibility problem between different devices and explores solutions such as intermediary accessories and standardization of communication protocols, to promote interoperability between different brands and models of devices and enhance user experience. In terms of efficiency issues, this essay proposes optimization solutions by exploring key technologies such as resonator design and impedance matching, to improve the energy transfer efficiency of the wireless charging system, reduce energy loss, and achieve more efficient wireless charging. This study highlights the pain points and limitations faced by the current technology in practical applications and proposes corresponding solutions In the current study, the risks of electromagnetic radiation and electrical safety were targeted. Current security measures and technical means have not fully covered a variety of complex scenarios. In terms of charging compatibility and device interoperability, there are some cases where the charging efficiency between devices is not high, which needs to be further improved and optimized. Therefore, future research will focus on the efficiency and safety of wireless space.

Authors Contribution

All the authors contributed equally and their names were listed in alphabetical order.

References

1. Jiang, B.,Wei, B., He, H.: Application of magnetically coupled resonant wireless energy transmission technology in power systems. Power Generation Technology 43(01), 32-43 (2022).
2. Kurs, A., Karalis, A., Moffatt, R.: Wireless power transfer via strongly coupled magnetic resonances. Science 317, 83-86 (2007).
3. Lu, X., Niyato, D., Wang, P.: Wireless charger networking for mobile devices: fundamentals, standards, and applications. IEEE Wireless Communications 22(2), 126-135 (2015).
4. Liu, F., Dong, B., Liu, K.: Magnetic resonance-based wireless energy transmission technology for implantable medical devices. China Science and Technology Paper 11(07), 794-798 (2016).
5. Zhang, J.: Topological study on resonance compensation of wireless charging system based on multiple resonant circuits. Zhejiang University (2022).
6. Jadidi, J., Katabi, D.: Magnetic MIMO: How to charge your phone in your pocket. in Proceedings of the 20th annual international conference on Mobile computing and networking 9, 495-506 (2014).
7. Hu, JK.: Research on wireless energy transmission system of artificial heart based on curved coil coupling. Zhejiang Institute of Science and Technology (2024).

8. Zhao, X.M.: Safety assessment of electromagnetic exposure for wireless charging of cardiac pacemakers. Lanzhou Jiaotong University (2022).
9. Zhang, J.: Variable Capacitance Tuning Control Method for Magnetically coupled Resonant Wireless Power Transfer System, Xi'an University of Technology (2023).
10. Fan, X.: A review of research status and application of wireless energy transmission technology. Journal of Electrotechnology 34(07), 1353-1380 (2019).