Effect of Coil Design on Wireless Charging Efficiency

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Abstract. This article offers a comprehensive exploration of the design principles underlying wireless power transmission systems, with a particular focus on the intricate dynamics of coil design and their profound influence on energy transmission efficiency. It traverses the landscape of modern technological advancements, weaving together theoretical insights and practical applications to unveil optimized strategies for wireless charging system design. By scrutinizing the physical parameters governing coil design and meticulously evaluating the choice of materials, particularly the pivotal role of ferrite, the study sheds light on avenues to enhance transmission efficiency. Through a fusion of experimental data and numerical simulations, it elucidates key optimization pathways, offering a nuanced understanding of the challenges inherent in electric energy transmission systems. In doing so, the research endeavors to not only propel the evolution of sustainable energy transmission technologies but also to provide a robust theoretical and empirical foundation for the development and implementation of efficient, long-distance electric energy transmission systems, thus catalyzing progress in the realm of sustainable energy solutions.

Keywords: Design of the coil, Design of the energy wireless transmission system, Optimize the energy transmission efficiency.

1 Introduction

With the continuous development of society and the continuous growth of energy demand, the efficiency of electric energy transmission systems has become an important research area. Traditional power transmission systems mainly use conductors for transmission. However, due to the resistance and inductance of the conductors, the energy efficiency loss of long-distance transmission of electric energy is relatively large. In order to improve the efficiency of electric energy transmission, the coupled electric energy transmission system has been proposed and received widespread attention. The coupled electric energy transmission system is a wireless electric energy transmission technology, which transmits electric energy to the receiver through the principle of magnetic coupling or electromagnetic induction. Compared with the traditional conductor transmission, the coupled electric energy transmission system has the following advantages: no physical contact, which can

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avoid contact resistance and inductance loss; suitable for long-distance transmission, which can reduce energy loss; wireless transmission can achieve automated and intelligent control. In radio wave energy transmission, the coil plays a crucial role, mainly reflected in the following aspects: generating a magnetic field: When current passes through the coil, a magnetic field will be generated, which is the basis of radio wave energy transmission.

Receiving and sensing the magnetic field: The coil can receive and sense the change of the external magnetic field, so as to realize the reception and transfer of energy. Improve transmission efficiency: Suitable coil design can optimize the efficiency of energy transmission and reduce energy loss. As a key component of energy conversion: The coil converts electric energy into magnetic energy, or converts magnetic energy into electric energy to achieve the mutual conversion of energy. This thesis aims to propose optimization measures and design schemes to improve the efficiency of the electric energy transmission system. This will help to achieve long-distance and efficient electric energy transmission, and promote the development of sustainable energy transmission technology.

In summary, this study will focus on the analysis of the efficiency of the electric energy transmission system, and through the method of combining experiments and numerical simulation, comprehensively consider indicators such as transmission efficiency and energy loss rate, to provide theoretical and practical basis for solving the problem of low electric energy transmission efficiency. It is of great significance for promoting the development and application of electric energy transmission technology.

Wireless transmission mode is an important implementation way of electric energy transmission technology, which uses radio waves or magnetic fields to transmit electric energy and realizes wireless power supply to the equipment. Wireless transmission modes mainly include two principles: magnetic coupling and electromagnetic induction. As shown in Fig. 1, it is the schematic diagram of the magnetic coupling circuit.

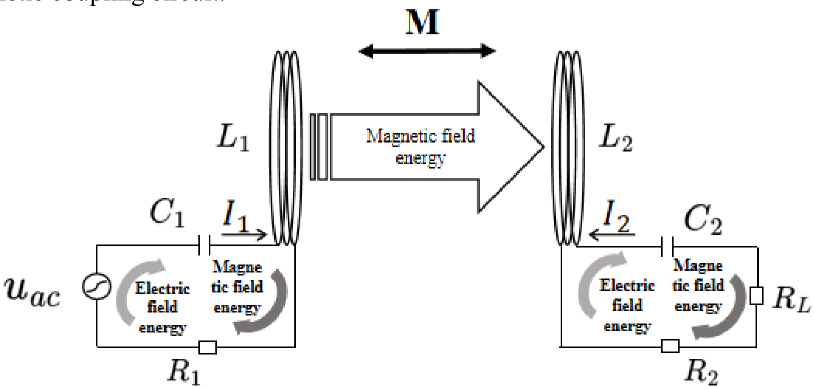

Fig. 1. Magnetic coupling principle diagram.

Magnetic coupling is a common wireless transmission mode, which uses the varying magnetic field generated by the transmitter to transmit energy to the receiver through a pair of rectifying coils. The magnetic coupling principle is based on Faraday's electromagnetic induction law, that is, when the magnetic flux of the magnetic field changes, an induced electromotive force will be generated in the conductor. In the coupled electric energy transmission system, the coil in the transmitter generates a varying magnetic field through alternating current, and this varying magnetic field will pass through the coil in the receiver, thereby generating an induced electromotive force in the receiver. Through the rectifying circuit, the induced electromotive force is converted into DC electric energy, thereby achieving wireless power supply.

Characteristics of the electric field coupling resonant wireless power transmission technology [1]: The cost is relatively low, this method does not require ferromagnetic and other materials and is simultaneously less affected by electromagnetic interference; it does not produce eddy currents, the system loss is relatively small, and the reliability is higher; it can have a relatively small effect on the efficiency when there are some metal substances within the transmission gap; when the transmission power of this method increases, the size of the electrode plate also needs to change accordingly, and the resulting impact is very complex; at this stage, this technology is less studied and not mature, and the practical application is more difficult.

Electromagnetic induction is another common wireless transmission mode, which uses the inductance coupling between the transmitter and the receiver to transmit energy. In the principle of electromagnetic induction, the energy transmission between the transmitter and the receiver is realized through inductance coupling. The power supply in the transmitter generates varying current and generates a varying magnetic field through the transmitting coil. The coil in the receiver and the coil in the transmitter form a magnetic link through inductance coupling. When the current in the transmitter changes, an induced electromotive force will be induced in the receiver. Through the rectifying circuit, the induced electromotive force is converted into DC electric energy, thereby achieving wireless power supply. The following Figure 2 is the schematic diagram of the electromagnetic induction principle.

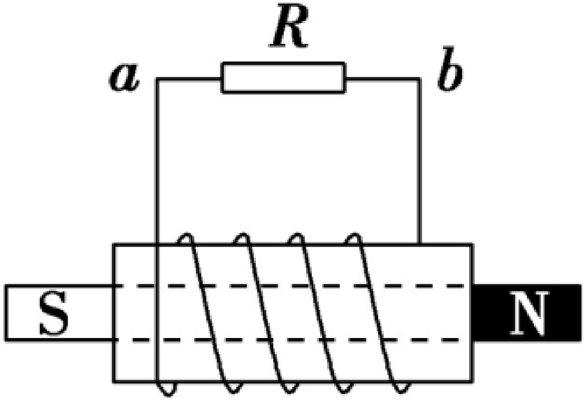

Fig. 2. The schematic diagram of the electromagnetic induction principle.

In the wireless transmission mode, some systems adopt modulation techniques, that is, to modulate the transmitted electric energy so that it can be transmitted within a specific frequency band. This modulation technique can improve the transmission efficiency and reduce energy leakage, while reducing interference to other devices. Through the wireless transmission mode, the coupled electric energy transmission system can achieve long-distance energy transmission without the need for physical contact. However, the wireless transmission mode also has problems such as limited transmission distance and energy attenuation, so system design and parameter optimization are required to improve transmission efficiency and reduce energy loss.

2 Basic Theory of Design of the Wireless Charging System

2.1 Magnetic Coupling System Design

Wireless charging magnetic coupling system is a technology that uses the principle of electromagnetic induction for energy transmission. Here is a detailed analysis of the design of the wireless charging magnetic coupling system:

Transmitter end design: The coil at the transmitter end is composed of multiple windings, usually using planar spiral windings or ring windings. The shape and size of the coil will affect the power transmission efficiency and directionality, so a reasonable design and optimization are required. Power supply and drive circuit: A power supply and drive circuit are required at the transmitter end to provide electrical energy and send the electrical energy to the coil through a power amplifier. The drive circuit needs to be able to adjust the frequency, voltage, and current to meet the needs of the receiving end device.

The transmitter end also needs to have control and communication functions, including power management, safety monitoring, data transmission, etc. This can realize the monitoring and management of the wireless charging system.

The receiver end also needs a coil to receive the electromagnetic energy from the transmitter end. The receiving coil usually matches the coil at the transmitter end to improve the energy transmission efficiency. The design and layout of the coil also need to consider the size and shape of the receiving device.

Rectification and electric energy management: The receiver end needs a rectifying circuit to convert the received AC signal into DC electric energy, and regulate and store the electric energy through the electric energy management circuit to supply the receiving device for use. The receiver end also needs corresponding control and communication functions to monitor the energy receiving situation and communicate with the transmitter end to achieve power regulation and data transmission and other functions. In order to improve the power transmission efficiency of the wireless charging system, in the design, it is necessary to select the appropriate coil size and structure, as well as a reasonable power supply and drive circuit. In addition, the application of magnetic materials and the optimization of matching capacitors will also affect the power transmission efficiency.

In the design, factors such as electromagnetic radiation control, overheating protection, and overload protection need to be considered to ensure that the wireless charging system can operate stably and safely. The transmission distance and transmission effect of the wireless charging system will be affected by the distance and position relationship between the coils. When designing, these factors need to be considered, and the distance and position effect of the system need to be optimized.

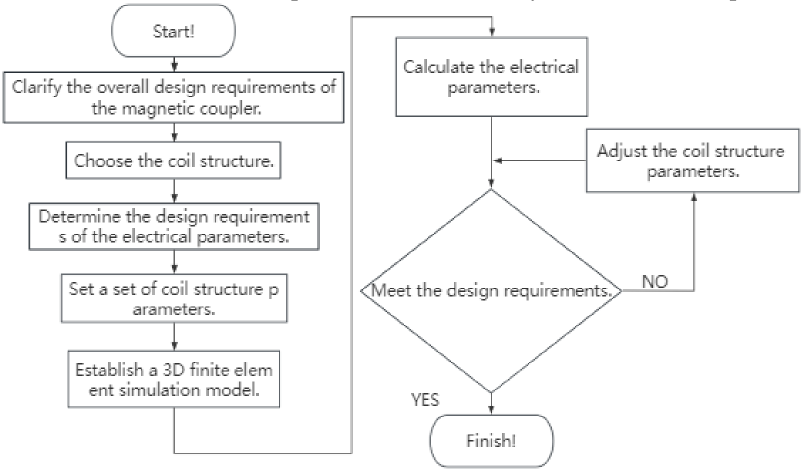

Fig. 3. The design process of the magnetic coupler coil.

In summary, the design of the wireless charging magnetic coupling system needs to comprehensively consider the design optimization of the transmitter end, the receiver end, and the overall system to improve the power transmission efficiency, ensure safety, and ensure the stable and reliable operation of the system.

2.2 Magnetic Induction Type Transmission Technology

Its main principle is that a part of the conductor of the closed circuit will produce induced electromotive force when it moves to cut the magnetic induction line in the magnetic field, and with the induced electromotive force, it will drive electrons to thereby form a current. The current generated by cutting the magnetic force line is called induced current, and this phenomenon is called electromagnetic induction. The generation of induced electromotive force is because there is a conductor in the changing magnetic flux. The essence is that the conductor makes changes in cutting the magnetic force line in the closed loop, resulting in corresponding changes in the magnetic flux of the closed loop. By this principle, if a coil has a constantly changing magnetic flux, it will allow another coil to produce induced current, and if this coil is integrated inside the mobile phone [2] and converted to direct current through rectification, it can charge the mobile phone battery. The ability of the mobile phone to wirelessly charge is to allow the transmitting coil of the wireless charger and the receiving coil at the mobile phone end to produce induced current and electromotive force, and the current and induced electromotive force are generated by the magnetic field coupling between the two coils.

2.3 Magnetic Resonance Type Transmission Technology

Resonant transmission technology is a wireless transmission technology that uses the resonant principle to achieve energy transmission or information transmission. Resonance refers to the state where the system can achieve the maximum response at a specific frequency. When the excitation frequency matches the resonance frequency, the system will present the maximum energy transmission efficiency [3].

In 2006, the "Science" journal published the research on the magnetic coupling resonant wireless energy transmission theory by scholars such as A. Kurs from the Massachusetts Institute of Technology [4]. This paper uses a novel coupling mode theory to conduct the research, and the concept of resonance is introduced into wireless energy transmission. The working frequency is highly consistent with the resonance frequency of the transmitting and receiving coils, which can allow the coil to be maintained in a strong coupling state. By using this technology, high-efficiency transmission is achieved, and the transmission distance is also increased simultaneously. This enables the wireless energy transmission system to maintain the efficiency while greatly increasing the transmission distance. Therefore, this method indicates the research direction of the new generation of wireless energy transmission systems, and many scientific researchers and engineers have conducted a large number of researches on the theory and application of this method, producing many results.

In resonant transmission technology [5], the transmitting coil and receiving coil are generally designed to be resonant to achieve efficient energy transmission. This technology is widely used in wireless power transmission, wireless charging, and wireless communication and other fields. The characteristics of resonant transmission technology include: efficient energy transmission: Through resonance adjustment, resonant transmission technology can achieve efficient energy transmission, reducing energy loss and increasing energy transmission efficiency. Transmission distance advantage: Resonant transmission technology can achieve a higher efficiency of energy transmission within a certain distance, so it has a certain transmission distance range advantage in wireless charging, wireless power transmission and other scenarios. Through precisely adjusting the coil parameters and frequency, resonant transmission technology has a high degree of controllability [6] and can adapt to different application scenarios and requirements. Interference suppression: Through the design of resonant conditions, resonant transmission technology can reduce the impact of external interference and improve the reliability of transmission. Resonant transmission technology has important applications in wireless charging, power transmission, data communication, etc. By reasonably designing the resonant state of the system, efficient energy transmission and information transmission can be achieved.

3 The Influence of Coil Design on Efficiency

3.1 Coil Design's Influence Factors on the Efficiency of Energy Transmission

Magnet coupling coil design has an important influence on efficiency [7]. Magnet coupling coil is a device that transmits energy or signals through magnetic field coupling, and is commonly found in wireless energy transmission, transformers, and inductance coupling communication systems.

Firstly, the structure and material selection of the magnet coupling coil have a direct impact on efficiency. The design of the coil should consider minimizing resistance and loss to increase the efficiency of energy transmission. The use of low-resistance materials and precise winding design can reduce the resistance of the wire and Joule loss. Secondly, the shape and size of the magnet coupling coil also have an impact on efficiency. The shape and size of the coil should be optimized according to the needs of specific applications. For example, in the wireless energy transmission system, the shorter the transmission distance, the larger the size of the coil, and the higher the efficiency. In addition, the distance between the coils and the relative position will also have an impact on the efficiency. A larger coupling coefficient and a smaller magnetic field funnel loss can increase the efficiency of energy transmission. Finally, the operating frequency of the magnet coupling coil also affects the efficiency. Within the appropriate frequency range, the efficiency of the coil will be higher. While in the case of exceeding the resonance frequency or being below the operating frequency, the efficiency will significantly decrease.

Taken together, the optimization of magnet coupling coil design can significantly increase the efficiency of energy transmission or signal transmission. Considering factors such as structure, material, shape, size, and operating frequency, it is possible to minimize the loss of energy or signals to a maximum extent, thereby increasing the overall efficiency of the system.

3.2 Coil Physical Parameters

The physical parameters of the coil play an important role in designing and analyzing the performance of the coil. Table 1 lists some common physical parameters of the coil.

Table 1. Coil physical parameters.

Types of physical parameters	Properties and characteristics
Diameter	The diameter of the coil refers to the diameter of the cylinder formed by the winding of the coil. The diameter determines the size and space requirements of the coil.
Turns	The turns of the coil refer to the number of turns in the winding of the coil. The turns determine the inductance value and resistance value of the

	coil.
Height	The height of the coil refers to the vertical height of the winding of the coil. The height determines the volume and three-dimensional shape of the coil.
Wire Diameter	The wire diameter of the coil refers to the diameter of the wire used in the winding of the coil. The wire diameter determines the resistance and capacitance characteristics of the wire.
Wire Length	The wire length of the coil refers to the total length of the wire used in the winding of the coil. The wire length is related to the resistance of the coil.
Core	For some coils, the core is an important parameter. The core can be made of materials such as ferrite and magnetic alloys, which increases the magnetic induction intensity and magnetic coupling effect of the coil.
Inductance	The inductance of the coil refers to the self-induced electromotive force generated when the current in the coil changes. The inductance is related to factors such as the number of turns of the coil, geometric dimensions, and the selection of magnetic materials.
Resistance	The resistance of the coil refers to the resistance of the wire itself used in the winding of the coil. The resistance of the wire is related to factors such as the resistivity of the material, wire diameter, and wire length.
Material	The material of the coil has an important influence on the performance of the coil. Common coil materials include copper, aluminum, ferrite, etc. Different materials have different conductivity, permeability, and thermal conductivity.

From Equation (1), it can be known that the smaller the wire radius, the more turns of the coil, and the larger the loss resistance R_0 of the coil itself, and this kind of loss is inevitable. Therefore, in the design, thick wires should be selected as much as possible, the number of turns should be reduced while ensuring the required self-resonant frequency, and silver-coated copper wires should be used to increase the conductivity and reduce the self-loss of the coil, thereby improving the efficiency. Under the same mutual inductance value, increasing the radius of the coil can increase the transmission distance [8]. The influence of the streaming resistance will be smaller [9]. And under the premise of the constraint of the coil size, the increase of the turn spacing will lead to the relative reduction of the number of turns and the coil inductance value under the same conditions.

$$R_0 = \sqrt{\frac{\omega\mu_0}{2\sigma}}\frac{l}{2\pi a} = \sqrt{\frac{\omega\mu_0}{2\sigma}}\frac{mr}{a} \tag{1}$$

In the (1), μ_0 is the vacuum permeability; a is the wire radius; r is the coil radius; m is the number of coils turns; σ is the conductivity; l is the wire length. A relay coil can also be introduced. The literature [9] starts from the perspective of circuit theory, and makes a more detailed study on the wireless energy transmission system of the single relay coil resonator based on magnetic coupling resonance for the wireless energy transmission system, and gives the critical coupling conditions of this threecoil (transmitter - relay - receiver) wireless energy transmission system and the condition for maximizing the load power at the receiving end. By adding a coil with the same resonant frequency between the transmitting coil and the receiving coil, the energy conversion efficiency can be greatly improved [10].

3.3 The Material Selection of the Coil

In the design of wireless charging, the material selection of the coil is crucial as it directly affects the transmission efficiency and cost. Copper is one of the most commonly used coil materials, which has good conductivity and thermal conductivity. It is very suitable for high-power wireless charging systems because it can withstand high currents and high temperatures. However, copper coils are more expensive and heavier than other materials.

Aluminum is another common coil material. Compared with copper, the conductivity and thermal conductivity of aluminum are slightly worse, but it has a lighter weight and lower cost. Aluminum coils are suitable for low-power wireless charging devices, such as mobile phone chargers.

Such as ferrite, can be used in the core of the coil to increase the magnetic induction intensity and transmission efficiency. They can attract and concentrate the magnetic field, thereby improving the effect of wireless energy transmission. Alloy materials: Some special alloy materials, such as nickel-zinc-iron alloy, have adjustable magnetic permeability and corrosion resistance, making them very suitable for wireless charging applications.

3.4 The Effect of Ferrite on the Coil

Ferrite is a kind of material with unique magnetic properties and is widely used as the coil material in the magnetic coupling electric energy transmission system. The following are the main advantages of ferrite as the coil material [11].

Ferrite has a higher magnetic permeability, which can effectively enhance the magnetic induction intensity of the coil and improve the energy transmission efficiency. This makes ferrite an excellent magnetic material choice.

Ferrite has a lower magnetic hysteresis loss, which means that when the frequency changes, the ferrite material can respond quickly and eliminate any residual effect of the magnetic field. This characteristic allows the coil to work at high frequencies and improve the operating efficiency of the system.

Ferrite has a higher resistance to interference from the external magnetic field. It can absorb the interference of the external magnetic field and reduce the impact on other electronic devices, maintaining the stability and transmission efficiency of the coil.

Ferrite has a higher high-temperature resistance and can maintain stable magnetic properties at higher temperatures. This makes ferrite coils suitable for applications in high-temperature environments, such as industrial production and automotive power systems.

Compared with other materials, ferrite has a relatively low cost. This reduces the manufacturing cost of the magnetic coupling electric energy transmission system and increases the feasibility of its commercial application.

In summary, ferrite as the coil material has many advantages in the magnetic coupling electric energy transmission system, including high magnetic permeability, low magnetic hysteresis loss, high resistance to magnetic field interference, high-temperature resistance, and cost-effectiveness. These characteristics make ferrite an ideal material choice, which improves the performance and reliability of the magnetic coupling electric energy transmission system.

The application of ferrite can increase the magnetic permeability, and both the bottom of the transmitting and receiving coils can be simultaneously added with ferrite to guide the magnetic field and simultaneously increase the quality factor of the coil inductance. Since the transmitting and receiving coils are an open magnetic field space during energy transmission, only a part of the energy enters the receiving system, so adding ferrite for magnetic conduction also has the effect of blocking magnetism to prevent too much magnetic leakage from being absorbed by the surrounding metal objects, thereby reducing energy loss.

In addition, the coil inductance has a certain equivalent resistance, and the current passing through the coil will generate heat, and the presence of heat will interfere with the stability of the system and is not conducive to the embedded coil in the mobile terminal, and the coil gasket ferrite also plays a role in heat dissipation to a certain extent. So, whether the presence of ferrite will have an impact on the inductance value of the coil requires simulation test verification, as shown in the following [10] simulation Figs. 4 and 5.

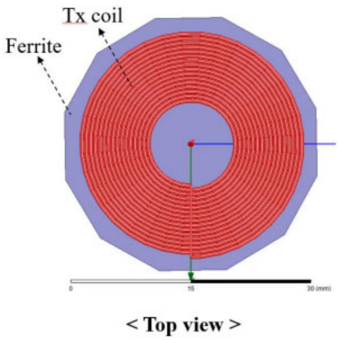

Fig. 4. The cross-sectional diagram of the coil.

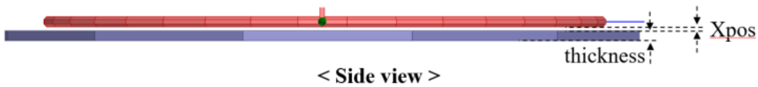

Fig. 5. The side view of the coil.

By setting different original inductance values of the coil, the effect of ferrite on the coil inductance value is compared, and the results are shown in Table 2.

Table 2. Inductance Value Test Results.

	1	2	3	4	5	6
No ferrite(uH)	2.39	2.47	2.53	2.65	2.78	3.02
With ferrite(uH)	3.89	3.77	3.99	4.12	4.36	4.56

From the results above in Table 2, it can be known that after pasting the ferrite on the coil, the inductance value of the coil will increase to a certain extent. In order to further verify the effects of the thickness of the ferrite and the distance between the ferrite and the hollow coil on the coil efficiency and temperature, refer to Table 3 to select different sizes of ferrite to design the experiment:

Table 3. The Design of Experimental Parameters.

	ferrite1	Ferrite2	Ferrite3	Ferrite4	Ferrite5
Size(mm)	50*50*0.105	50*50*0.125	50*50*0.15	50*50*0.13	50*50*0.065

The main testing instruments need to have adjustable DC power supply, electronic load, oscilloscope, USB power meter, accurate power analyzer to form the testing platform. The experimental results are shown in Figs. 6 and 7.

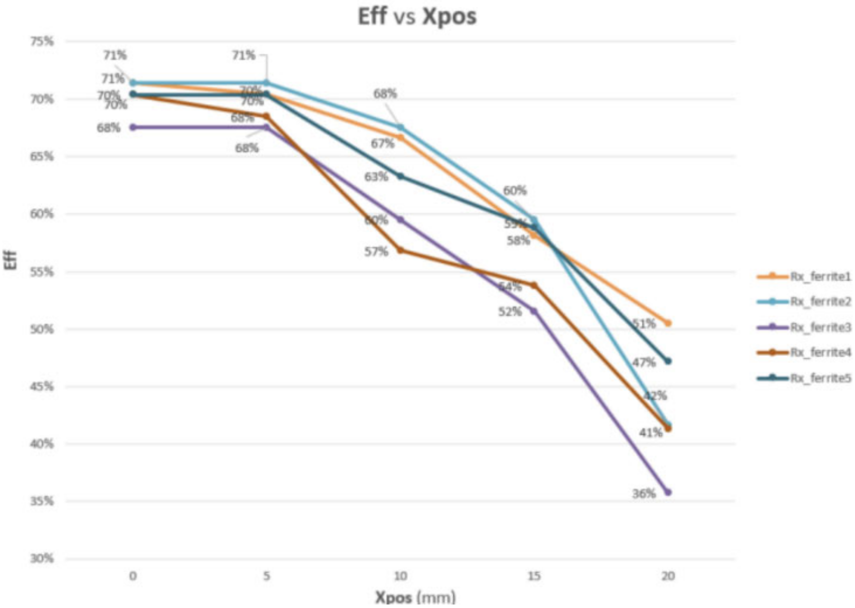

Fig. 6. Coil efficiency variation diagram.

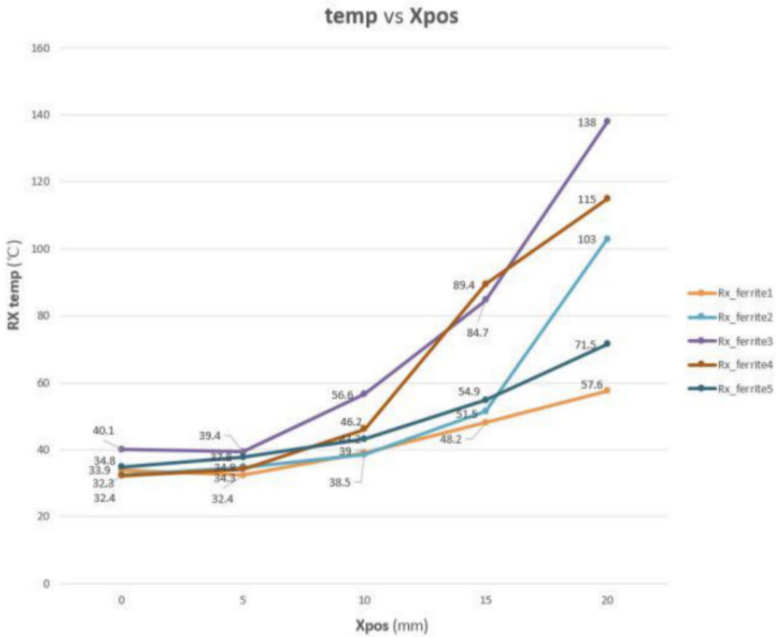

Fig. 7. Coil temperature variation diagram.

From the above two experimental result diagrams [10], it can be seen that when the ferrite is close to the coil (within 5mm), the coil efficiency hardly changes, and as the distance increases, the efficiency of the coil gradually decreases; when the thickness of the ferrite is about 0.125mm, the coil has the best efficiency; when the ferrite is close to the coil (within 5mm), the temperature of the coil hardly changes with the distance, and as the distance increases, the ferrite and the coil gradually detach, and the temperature of the coil becomes higher and higher.

4 Conclusion

Efficiency in coil design is paramount. A deep dive into the expression of coil efficiency reveals that enhancing it hinges on optimizing the coil and their quality factors. This optimization journey involves both theoretical derivations and parameter adjustments. Furthermore, delving into the impact of physical parameters on coil quality factors underscores the significance of considerations like coil turns, inner and outer diameters, and other variables. To achieve optimal outcomes, a holistic approach that comprehensively evaluates these physical parameters is imperative. Material selection for the coil also emerges as a crucial aspect in design, necessitating meticulous analysis to meet specific requirements.

Additionally, external conditions profoundly influence coil efficiency. Hence, this article meticulously examines the influence of ferrite on coils, exploring aspects like ferrite thickness and distance from the hollow coil through simulation tests.

In recent times, magnetic coupling wireless charging systems have gained widespread acclaim for their convenience and efficiency. These systems, rooted in electromagnetic induction principles, facilitate energy transmission between transmitting and receiving coils. Moreover, advancements have enabled these systems to support multi-device charging, catering to diverse scenarios like home, office, and public places. The latter has seen the integration of wireless charging plates in various establishments, providing users with convenient charging experiences on the go. To foster further development, standard organizations have formulated wireless charging standards, such as the Qi standard, ensuring compatibility and enhancing user convenience.

Technological breakthroughs have propelled the magnetic coupling wireless charging system's evolution, enhancing transmission efficiency, increasing range, and relaxing device positioning requirements. This has led to widespread adoption across various sectors, including smartphones, unmanned aerial vehicles, and electric vehicles. Emerging fields like smart homes and medical devices are also exploring wireless charging applications, driving the need for standardized protocols.

The interdisciplinary collaboration of disciplines like materials science, electrical engineering, and wireless communication technology has spurred innovation in the magnetic coupling wireless charging system, enhancing safety and portability while advancing technology and application. As new materials and technologies continue to emerge, the magnetic coupling wireless charging system is poised to revolutionize various industries, offering unparalleled convenience and innovation in people's lives.

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