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Influence of Coil Characteristics on Inductively Coupled Wireless Power Transfer Systems Efficiency

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Abstract:

The development of electric vehicles (EVs) is crucial to the sustainable development of global transportation. Wireless Power Transfer (WPT) technology is one effective means to improve the charging efficiency of electric vehicle. At the same time, the obstacles of the traditional wired system have been alleviated. Among them, the Inductive Power Transfer (IPT) system is a better choice in electric vehicle charging applications because of its anti-offset capability and high efficiency in transmission. The paper consists of the theoretical basis, optimization technology, and implementation strategy of IPT. In the technical principle part, a multi-physics coupling model is used to analyze the quantitative relationship between transmission efficiency and coil parameters in conjunction with Kirchhoff's law. In the structural optimization part, two coil optimization schemes, circular and square, are compared. By improving the magnetic permeability and optimizing the other parameters, the key parameters were improved by 50% and 25% respectively. Finally, this paper summarized the potential research directions of WPT and how it influences the advancement of EVs. This review is aimed at researchers and industry practitioners who are committed to innovate WPT in EVs industry, intending to provide valuable insights for them.

Keywords: Wireless Power Transfer (WPT); Electric Vehicles (EVs); Inductive Power Transfer (IPT); coil pad; coupling coefficient

1. Introduction

As the global ecological environment deteriorates and the energy crisis intensifies, reducing carbon emissions to address climate change has become a global priority. The large-scale application of electric vehicles (EVs) has alleviated the carbon emission pressure in the transportation sector to a certain extent. According to the International Energy Agency (IEA), the global EV market is experiencing explo-

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sive growth. Under the current policy framework, the IEA predicts that by 2030, EVs will account for more than 40% of global car sales, corresponding to a reduction in daily crude oil demand of more than 5 million barrels [1]. This trend indicates that EVs are transforming from a marginal green option to a mainstream energy solution.

However, existing charging technologies still face the dual challenges of range anxiety and charging efficiency bottlenecks. Limited by battery energy density and charging rate, the range of EVs is only 60-70% of that in traditional fuel vehicles. Traditional conductive charging has inherent defects such as mechanical wear of the interface, poor electromagnetic compatibility (EMC), and low space utilization. Wireless charging technology achieves contactless power supply through electromagnetic field energy coupling, showing significant technical advantages. Its spatial layout flexibility is improved by more than 40%, and the risk of electric shock caused by plugging and unplugging operations is completely eliminated [2].

At present, Wireless Power Transfer (WPT) mainly includes three technical paths: electromagnetic induction (IMPT), magnetic coupling resonance (MCR), and radio frequency radiation (RFWT). Among them, electromagnetic induction technology is based on the principle of loosely coupled transformers and shows significant advantages in near-field transmission scenarios. Its core efficiency depends on the geometric parameters of the transmitting/receiving coils (such as turns ratio, diameter ratio, axial offset) and coupling coefficient. To further explore the impact of various parameters on efficiency, an IPT system with S-S compensation topology can be introduced for analysis. The analytical expression of the transmission efficiency η can be derived by establishing an equivalent circuit model. The model shows that the coil mutual inductance M and the coupling coefficient k value are the key parameters affecting the efficiency. Regarding coil structure optimization, cutting-edge research shows three major technical trends: using Litz wire and nanocrystalline core to reduce skin effect losses, developing multi-coil array topologies to achieve dynamic coupling optimization, and introducing machine learning algorithms for adaptive impedance matching.

This review focuses on the inductive charging system with S-S compensation topology. By establishing a multi-physics field coupling model, the quantitative relationship between coil geometric parameters (turn ratio, diameter ratio, axial offset) and transmission efficiency is systematically analyzed. By comparing the optimization schemes of circular and square coils, the aim is to propose the optimal solution for the system coil in different scenarios to maximize efficiency.

2. Inductively Coupled Wireless Power Transfer Systems

IPT is an energy transmission technology based on the principle of electromagnetic induction, and is the key to electromagnetic induction wireless charging technology. This technology first generates a changing magnetic field by inputting alternating current, and then, according to Faraday's law of electromagnetic induction, the coil converts the field energy into electrical energy to achieve wireless energy transmission. The equipment required for this technology is easy to obtain, and only two coils or coil arrays are required. At the same time, it also has high reliability and relatively high charging efficiency. It is not easily restricted by spatial position and has high flexibility.

2.1 IPT System Structure and Principle

The IPT system involves two subsystems: the transmitter system and the receiver system. The transmitter system includes input power, transmitting coil, and inverter circuit. It converts the input DC power into high-frequency AC power and then induces a magnetic field through coil. A receiving coil, rectifying circuit, compensation circuit, and a load make up receiver system. Its function is to induce alternating current from the magnetic field and output stable direct current after compensation and rectification. For the specific wireless charging system process, the high-frequency AC power at the transmitter is generated by the DC power input through the internal inverter circuit. When AC power is applied to the coil, a changing magnetic field is generated. This magnetic field induces an electromotive force in the coil at the receiving end and generates AC power. After being tuned, rectified by the compensation and rectifier network, it is output as DC power. The function of this part is to supply power to the load. The schematic diagram of the IPT principle is shown in Fig. 1.

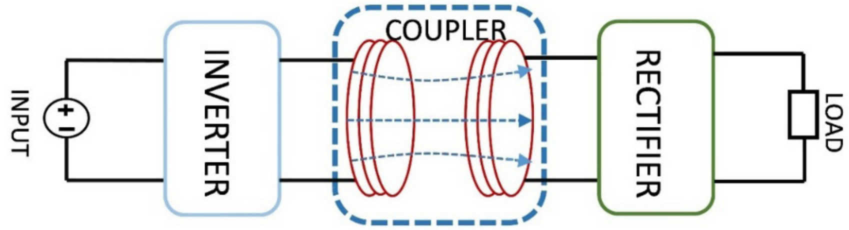

Fig. 1 Principle of IPT system [3]

1.2 Transmission efficiency of IPT system

According to the designed wireless energy transmission system, an equivalent circuit model as shown in Fig. 2 can be established. The parameters are as follows: R_1, R_2 are the internal resistances in the transmit and the receiver coil, respectively; C_1, C_2 correspond to the compensation capacitors on both sending and receiving sides. U_{in} is the alternating current integrated after the inverter, and its frequency is ω. Equivalent load resistance is denoted by R_L. M represents the mutual inductance of the coil. L_1, L_2 are the self-inductance coefficients of the transmitting coil, the receiving coil respectively.

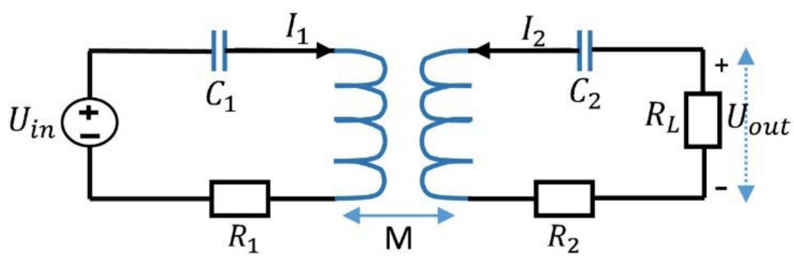

Fig. 2 Equivalent circuit of IPT system [4]

Kirchhoff's law can be used to write loop equations, and the following quantitative relationship is finally obtained. The coil transmission efficiency η is:

$$\eta = \frac{P_{out}}{P_{in}} = \frac{(\omega M)^2 R_L}{(R_2+R_L)^2 (R_1 + \frac{\omega^2 M^2}{R_2+R_L})} = \frac{R_L}{(R_2+R_1)[\frac{R_1(R_2+R_L)}{(\omega M^2)}+1]} \tag{1}$$

It can be seen that η is related to the coil equivalent internal resistance R_1, R_2, power supply frequency ω, load resistance R_L and mutual inductance coefficient M.

3. Impact of coil structure characteristics on WPT efficiency

3.1 Analysis of Typical Coil Structure

In the IPT system, the coil is the core element of energy coupling, and its structural design directly determines the power transmission efficiency and stability. Under high-frequency conditions (ω>100 kHz), the copper loss of a coil increases exponentially as a result of the skin effect and proximity effect. Simply increasing the power supply frequency can no longer effectively optimize the efficiency. Therefore, the coordinated optimization of coil structure and materials has become a key technical path. Current research focuses on improving the coupling coefficient, enhancing the offset tolerance and miniaturizing the system design through geometric parameter adjustment, magnetic material matching and topological innovation.

Table 1 lists five mainstream coil structures in near-field charging scenarios, including: Circular Pad (CP), Rectangular Pad (RP), Double-D Pad (DDP), Double-D Quadrature Pad (DDQ), and Bipolar Pad (BPP). The performance differences are mainly reflected in three aspects: magnetic field distribution, offset sensitivity, and engineering applicability.

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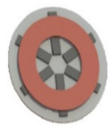
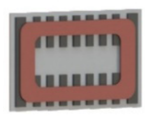
Table 1. Summary of five common coil characteristics ((a)-(e)) [3, 5, 6]

	CP	RP	DDP	DDQ	BPP
	 (a)	 (b)	 (c)	 (d)	 (e)
Range of use	Most common	More common	Commonly used in primary coils	Commonly used in secondary coils	Versatile
Usage scenarios	Static transmission	Charge in-vehicle	Medium distance transmission(20-50cm)	Dynamic charge	Low power transmission
efficiency	95% and above (after optimization)	95% and above (high frequency)	89%	85% and above	
Efficiency retention rate at misalignment conditions	68%(30cm)	89.67% (7.5cm)	Transmission distance 30cm 32%(20cm)		

3.2 Establishment of the Relationship Between Coupling Coefficient and Efficiency

In the study by Rizelioğlu et al., it was mentioned that:

$$k = \frac{M}{\sqrt{L_1 L_2}} \tag{2}$$

Among them, coupling coefficient is denoted by k. [7]. Formula (2) displays relationship between L_1, L_2 and M. k varies from 0 to 1 according to the air gap characteristics. The effect of k on η can be expressed as:

$$\eta = \frac{P_{out}}{P_{in}} = \frac{R_L}{\left(R_2 + R_1\right)\left[\frac{R_1\left(R_2 + R_L\right)}{\left(\omega k^2 L_1 L_2\right)} + 1\right]} \tag{3}$$

While changes in the number of turns and coil size affect the coil's self-inductance, changes of coil spacing, direction and material characteristics have a great impact on M. Take the square coil as an example. Through theoretical deduction and simulation methods, it was proposed and verified that k have to do with the number of coil turns n, coil spacing d, magnetic permeability μ of the material and inner radius around two coils. Therefore, plans for optimizing the coil structure can be developed in the direction of improving these parameters.

4. Structural Optimization Plan

Kim et al. proposed an efficiency optimization scheme for rectangular pads. Through finding the optimal solution for the number of coil turns n and increasing the material magnetic permeability μ, the coupling coefficient k is improved. A range of magnetic properties can be obtained by varying the number of coil layers. The maximum mutual inductance can reach 3.369. By comparing the data in Table 2, as n rises, k increases. This shows that an increase in the transmitting coil inductance L_p significantly enhances the magnetic coupling with the receiving coil, thereby improving the mutual inductance M and the energy transfer capability of the system. According to the formula (3), the increase of k will lead to an improve in efficiency η. The research successfully illustrated that when the number of coil layers is 4, the design can achieve a mutual inductance of up to 2.145($k = 0.034$). Compared with the unoptimized design, k has increased by 25%. However, further investigation by Kim found the minimal M reached 9.46 in S-S topology This suggests that this coil design does not perform well in the S-S topology. Applying it to LCC-S and DS-LCC topologies, achievable M can be up to 61.9 µH and 458.9 µH, respectively. This design should be considered in combination with other compensation circuits [8]. Fig. 3 shows the relationship between the inductance of the transmitter board, the resistance and the number of coil layers. The horizontal axis in Fig. 3 is the number of coil layers, and the vertical axis is the inductance M (μH) and the AC resistance value ($m\Omega$). With the increase in the quantity of coil layers, inductance and AC resistance show an upward trend. M reaches its maximum at 6 layers. However, the AC resistance also reaches a peak and is roughly the same as the M value.

This greatly increases the coil resistance loss. When the number of coil layers is moderate (3-4 layers), it can be observed that M is in a high state. The AC resistance is also appropriate. The coil is designed to achieve a maximum k in a limited volume, so coil resistance loss needs to be considered.

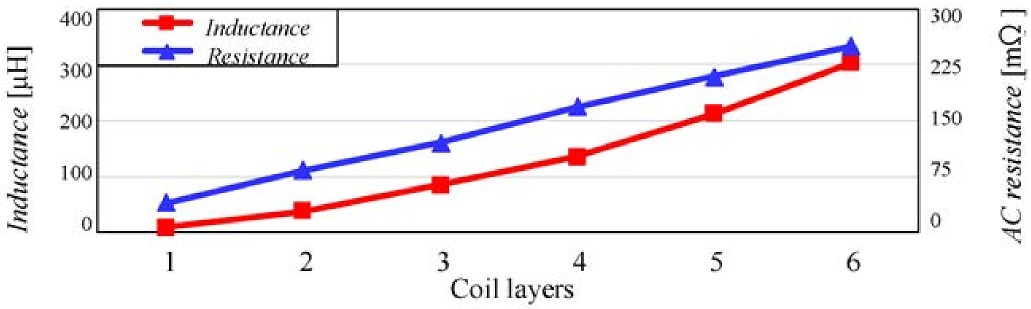


Fig. 3 Relationship between inductance, AC resistance as and coil layers [8]

Table 2. Magnetic characteristics of various transmit coil layers [8]

Tx Layer:	1 Layer	2 Layers	4 Layers	6 Layers
L_p [**μH**]	8.482	37.23	135.35	303.36
L_s [**μH**]	29.792	30.115	30.110	30.034
k	0.028	0.033	0.034	0.035
M [**μH**]	0.443	1.003	2.145	3.369

Jaafari et al. proposed a circular coil structure design based on ferrite core, which optimizes transmission efficiency by improving the magnetic permeability μ and determining optimal n [6]. The low conductivity of ferrite materials can significantly suppress eddy current losses. It also effectively reduce energy dissipation, meanwhile, improve η. Fig. 4 demonstrates how n affects k and Electromagnetic field (EMF) strength. The results in Fig. 4 (a) show that the k varies between 0.25 (15 turns) and 0.57 (65 turns). It shows that the k is proportional to n. k continues to rises as n increases. EMF generated by primary coil (Fig. 4 (b)) shows that its strength is also proportional to n. When n is 15 or less, the EMF strength is 0.000,085 T, while when n is 65 or more, the EMF strength is 0.000,23 T [6].

The research results show that changing the coil parameters has a significant impact on the coupling coefficient. Increasing the number of coil turns to 65 significantly increases the coupling coefficient k (from 0.25 to 0.57). Although improving the inner radius parameter increases k, it reduces the EMF strength. The overall effect is not good. After comparison, an inner radius of 75 mm was selected to balance performance and cost. On this basis, ferrite boxes as well as ferrite planar cores were brought in for further improvement. After the ferrite plate is introduced, k is increased by 49% and EMF is enhanced by 82% at an air gap of 140mm, but the misalignment tolerance is only improved within the range of ±300mm. Further replacing it with a ferrite box structure, k increased slightly to 0.583 (+0.012 compared to planar), and the EMF distribution was more concentrated (central intensity +0.01T). By comparison, the coil with an inner radius of 75 mm has a better coupling effect after the ferrite box is introduced, and the equivalent design achieves the efficiency target of 95%. [6]. In general, this study is based on a circular coil and explores effect of n on k. While choosing the optimal n to find a suitable k, a ferrite core is introduced to further optimize the coil performance. It effectively combines two optimization methods and provides a design reference for the subsequent coordinated optimization of coil coupling coefficients.

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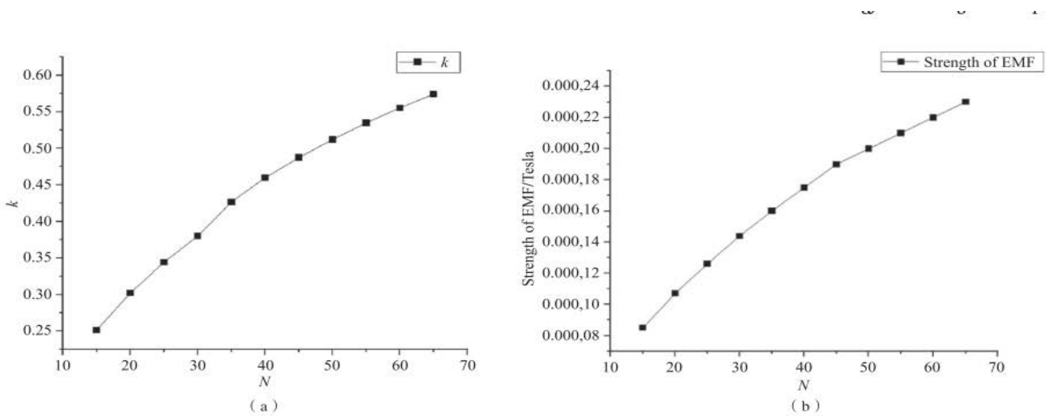

Fig. 4 Relationship between n and coil characteristics; (a) k; (b) strength of EMF [6]

5. Conclusion

This study found that η of the IPT system depends on many factors. Through the establishment and derivation of the model, it can be known that k is one of the key factors affecting the efficiency. The larger the k, the higher the η. Therefore, when studying efficiency improvement plan, researchers should try to find a solution with a higher k. The coil characteristics , like inner diameter, n etc., will have different effects on k. Research shows that if choosing a circular pad with inner radius of 75 mm and 65 turns, k can be increased to even 0.57, achieving the 95% efficiency target. The cost is relatively appropriate. In a square coil, the maximum k can be achieved within a limited volume. The number of coil layers is fixed to 4, and the coupling coefficient k reaches 0.034. However, it performs poorly in the S-S compensation circuit. So it should be considered to conFig. other compensation circuits for improvement

Although IPT technology has made remarkable progress, there are still some limitations. For example, power loss, limitations of coil materials, relative misalignment of coils, safety issues, and inherent complexity of system design may restrict its scale-up process. Overcoming these challenges must be a top priority for future study. Simultaneously, it is crucial to discover a novel approach to enhance the system's functionality and performance.It includes researching cutting-edge coil plans and establishing robust security systems to enhance user trust in it.

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