

Analysis on Distance Optimization Method of Magnetic Coupling Resonant Wireless Charging Coil for Unmanned Aerial Vehicle

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Abstract. The development of UAVs has led to a surge in demand for wireless charging of drones. Among these, magnetically coupled resonant wireless charging serves as an effective solution to this problem, with transmission distance being one of the critical factors influencing its wireless charging efficiency. To optimize the coil distance for magnetically coupled resonant wireless charging in UAVs, this paper begins with the basic principle of this technology. It analyzes the working mechanism and transmission characteristics of the system in detail. The fundamental principle is illustrated by both theoretical analysis and simulation experiments. Also, this study explores how coil distance affects charging efficiency. On this basis, an optimal design for coil distance is carried out. Two improved schemes are proposed, including parameter optimization of the original circuit and optimization using an L-type impedance matching network. A comparative analysis between the optimized schemes and the original design is conducted to verify the optimization effect. The research results can provide theoretical reference and technical support for the practical engineering application of UAV wireless charging technology.

Keywords: Unmanned aerial vehicle (UAV), magnetically coupled resonance, wireless charging, coil distance ,optimization method

1. Introduction

In recent years, with the development of technology, unmanned aerial vehicles (UAVs) have been increasingly widely used in various fields. However, most UAVs have a small body, so the battery capacity they can carry is limited. This results in poor endurance, making them unable to fly continuously for a long time. They need to land frequently for manual battery replacement, which seriously affects daily operational efficiency. In response to this problem, there is currently a relatively mature Wireless Power Transfer (WPT) technology, which can effectively solve the cumbersome problem of wired charging for UAVs [1-3]. Currently, there have been studies on the design of magnetically coupled resonant UAV wireless power supply systems [2]. Among them, the transmission distance of the coils directly affects the flexibility of UAV charging. Therefore, optimizing the coil distance plays an important role in the improvement of this technology. Although discussions on distance characteristics have been conducted, no effective optimization scheme has

been proposed for it [4]. This paper takes the magnetically coupled resonant charging of UAVs as the research object. It sorts out the basic principles of magnetically coupled resonant charging and designs optimization schemes. Two optimization schemes are adopted: parameter optimization of the original circuit and optimization of the L-type impedance matching network. These optimized schemes are compared with the basic magnetically coupled type to optimize the transmission distance of UAV magnetically coupled resonant wireless charging. The research provides a reference for the practical application of this technology [5].

2. Construct the circuit structure for simulation

The daily household power supply is 220 V / 50 Hz alternating current. To protect the UAV battery, the AC source U adopts a high-frequency equivalent AC power obtained by rectification and inversion of the mains supply, with an amplitude of 36 V and a frequency of 100 kHz, which meets the charging requirements of the UAV battery. The parameters of the transmitting resonant circuit are designed as follows: coil inductance $L_1=149\mu\text{H}$, equivalent internal resistance $R_1=0.8\Omega$, and resonant capacitance $C_1=17\text{nF}$. The receiving side adopts identical parameters: $L_2=149\mu\text{H}$, $R_2=0.8\Omega$, $C_2=17\text{nF}$, and the load resistance R_L is set to 20Ω . Based on the above conditions, the quality factor can be calculated. $Q = Q_1 = Q_2 = \frac{\omega_0 L}{R} = \frac{1}{\omega_0 RC} = \frac{1}{R} \sqrt{\frac{L}{C}} \approx 117$. Let $\lambda = \frac{RL}{R_2^2}$. Combined with the aforementioned formulas, it can be deduced that:

$$\eta = \frac{Q_1 Q_2 \lambda K^2}{Q_1 Q_2 (1+\lambda) K^2 + Q_2 (1+\lambda)^2} \times 100 \% \quad (1)$$

By substituting the above formulas for calculation, the numerical relationships among k, d and η are obtained, as presented in Table 1 [4, 6, 7].

Table 1. Relationship among d, k and η

d (cm)	K	η
8	0.9766	78.0
10	0.5000	50.9
12	0.2894	26.3
15	0.1481	8.6
18	0.0823	2.85
20	0.0625	1.66
25	0.0320	0.43
30	0.0185	0.13

The circuit simulation model established in Multisim is illustrated in Fig 1.

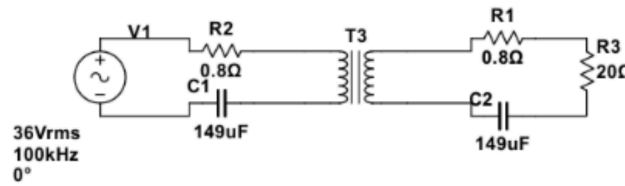


Figure 1. Constructed simulation circuit diagram (picture credit: original)

3. Research on transmission distance optimization

3.1. Design of the scheme

3.1.1. Scheme 1: parameter optimization of the original circuit

Combined with the correlation between coil inductance and average radius in the magnetically coupled resonant wireless charging system, the ratio of inductance of the transmitting and receiving coils is set equal to the square of the ratio of their average radii, and the calculated result is $L_2 \approx 9.31\mu\text{H}$.

With the reduction in the length of the receiving coil, its internal resistance decreases to 0.25 times the original value, and R_2 is reduced to 0.2Ω . According to $\omega_0 = \frac{1}{\sqrt{L_2 C_2}}$, $C_2 \approx 272\text{nF}$. The optimized values are $Q_2=29.2$ and $\lambda=100$. The efficiency η_1 of Scheme 1 is calculated through the efficiency formula, and the relationships among d , k and η_1 are shown in Table 2 [4, 8].

Table 2. Relationship among d , k and η_1

d (cm)	K	η_1
8	0.9766	98.55
10	0.5000	81.53
12	0.2894	53.67
15	0.1481	36.54
18	0.0823	11.06
20	0.0625	6.94
25	0.0320	1.85
30	0.0185	0.63

3.1.2. Scheme 2: optimization of L-type impedance matching network

In the original scheme, the receiving end adopts a direct series connection of coil internal resistance R_2 and the fixed load R_L of the UAV. The total impedance is 20.8Ω , which differs greatly from the transmitting end internal resistance $R_1=0.8\Omega$. Severe impedance mismatch between the transmitting and receiving ends causes massive reflection loss during magnetic energy transmission and greatly reduces the energy transfer efficiency. Meanwhile, considering that $R_L=20\Omega$ on the UAV side is an inherent load of the battery terminal and its resistance cannot be directly adjusted, this scheme adopts an L-type passive impedance matching network optimization strategy. An L-type matching network composed of inductors and capacitors is added between the receiving coil and the 20Ω

fixed load. Optimal matching between the equivalent impedance of the receiving end and the internal resistance of the transmitting end is realized through impedance transformation, without modifying the geometric structure and original electrical parameters of the coil [9, 10]. An L-type passive impedance matching network is added between the receiving coil and the 20 Ω load. Impedance transformation is adopted to realize the optimal matching between Rref and R1, as shown in Fig2 below.

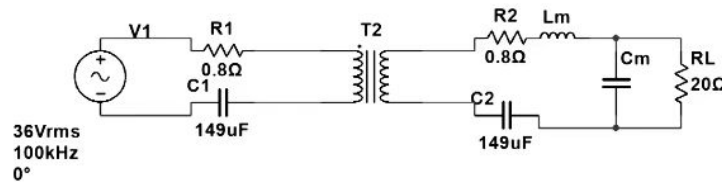


Figure 2. Constructed L-type impedance matching network

The implementation principle is expressed as: $R_{ref} = \frac{k^2 \omega^2 L_1 L_2}{R_2 + R_L'}$ (where R_L' denotes the equivalent load resistance converted by the matching network). Under the resonant purely resistive condition, the transmission efficiency reaches the maximum when $R_{ref} = R_1$. The relevant parameters are calculated as: $R_{ref} = R_1 = 0.8\Omega$, $R_L' = \frac{k^2 \omega^2 L_1 L_2}{R_1} - R_2$, $Q_m = \sqrt{\frac{R_L'}{R_L} - 1}$, $L_m = \frac{Q_m R_L}{\omega}$, $C_m = \frac{Q_m}{\omega R_L'}$, The efficiency formula of Scheme 2 is obtained as follows:

$$\eta_2 = \frac{Q_1 Q_2 \frac{R_L'}{R_2} K^2}{Q_1 Q_2 \left(1 + \frac{R_L'}{R_2}\right) K^2 + Q_2 \left(1 + \frac{R_L'}{R_2}\right)^2} \times 100 \quad (2)$$

The efficiency η_2 of Scheme 2 is calculated by the efficiency formula. The relationship among d, k and η_2 is presented in Table 3.

Table 3. Relationship among d, k and η_2

d (cm)	K	η_2
8	0.9766	92.50
10	0.5000	86.30
12	0.2894	68.70
15	0.1481	45.20
18	0.0823	22.70
20	0.0625	16.64
25	0.0320	6.37
30	0.0185	1.97

3.2. Efficiency comparison with variable transmission distance

To verify the practical improvement effect of the coil distance optimization scheme, this section conducts a comparative analysis of the original scheme, Scheme 1 with receiving circuit parameter optimization, and Scheme 2 with L-type impedance matching network optimization in terms of coil transmission distance. Table 4 below shows the efficiency comparison of the three schemes.

Table 4. Relationship among d , η , η_1 and η_2

d (cm)	η (%)	η_1 (%)	η_2 (%)	$\eta_1 - \eta$ (%)	$\eta_2 - \eta$ (%)
8	78.0	98.55	92.50	20.55	14.50
10	50.9	81.53	86.30	30.63	35.40
12	26.3	53.67	68.70	27.37	42.40
15	8.6	36.54	45.20	27.94	36.60
18	2.85	11.06	22.70	8.21	19.85
20	1.66	6.94	16.64	5.28	14.98
25	0.43	1.85	6.37	1.42	5.94
30	0.13	0.63	1.97	0.50	1.84

Based on the obtained data, a MATLAB model is established to derive the relationship between efficiency and transmission distance d for the three schemes, as shown in Fig 3.

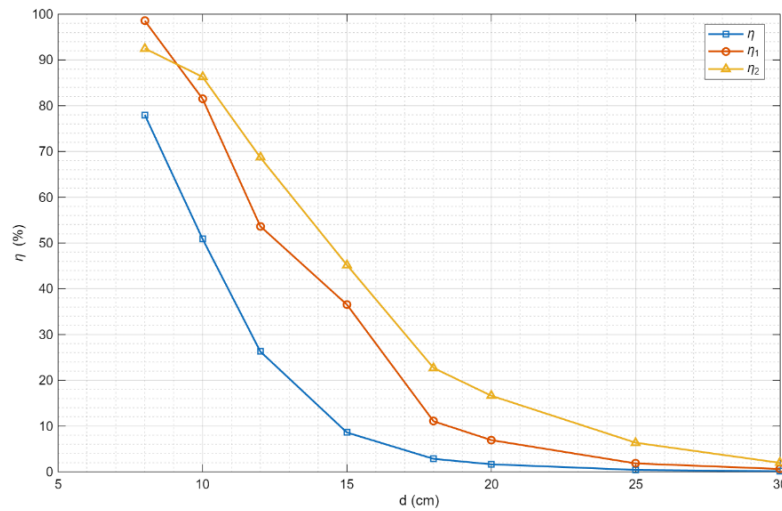


Figure 3. Relationship among d , η , η_1 and η_2 (picture credit: original)

Now, the entire transmission distance is divided into three sections for analysis: the short-distance section (0–8 cm), the medium-distance section (10–15 cm), and the long-distance section (18–30 cm). According to the above figure, in the short-distance range (0–8 cm), Scheme 1 achieves the highest efficiency of 98.55 %, realizing extremely low loss in short-distance energy transmission. When the distance falls within the medium-distance range (10–15 cm), Scheme 2 surpasses Scheme 1 and becomes the optimal solution in terms of efficiency. The maximum improvement reaches 42.4% at 12 cm, which is the peak enhancement across the whole distance range [11]. In the long-distance range (18–30 cm), the efficiency of the original scheme approaches zero, while Scheme 2 still maintains a relatively high transmission efficiency. At 20 cm, its efficiency reaches 16.64%, which is much higher than the 6.94% of Scheme 1, showing a remarkable advantage [10, 12].

The efficiency difference between the optimized schemes and the original scheme presents a trend of "first increasing and then decreasing" as the distance rises. The medium-distance section (10 cm–15 cm) is the interval with the most prominent optimization effect. The gentle attenuation characteristic of Scheme 2 extends its effective transmission distance to 20 cm, which greatly improves the position fault tolerance of UAV wireless charging. It adapts well to minor position

deviations that inevitably occur during actual UAV landing [13, 14]. Although Scheme 1 has a high peak efficiency at short distances, it attenuates rapidly with distance, with an effective transmission distance limited to only 18 cm. By contrast, the original scheme possesses little practical engineering application value for effective energy transmission.

3.3. Discussion

As the basic scheme of magnetically coupled resonant wireless charging, the original scheme can only provide references for theoretical research. It suffers from short transmission distance and rapid efficiency attenuation, resulting in limited practical engineering application value [14]. By reconstructing the parameters of the receiving circuit, Scheme 1 maximizes the efficiency at short distances. However, it is accompanied by drawbacks such as high implementation difficulty, rapid efficiency attenuation at medium and long distances, and elevated cost. This scheme is only applicable to niche scenarios that require extremely high charging efficiency and allow precise fixed-point landing of UAVs [7]. By adding an L-type passive impedance matching network, Scheme 2 achieves triple optimization in efficiency, transmission distance and implementation feasibility. This scheme maintains satisfactory charging efficiency across the entire distance range, and features low implementation difficulty, low cost and excellent compatibility. Its effective transmission distance is extended to 20 cm, which greatly improves the position fault tolerance of UAV charging. Therefore, it is the most suitable optimization scheme for the practical engineering promotion of magnetically coupled resonant wireless charging for UAVs [9, 10, 15]. In terms of application fields, the proposed optimization scheme can be widely used in many key industries. First, in the field of power inspection. UAVs can rely on this technology to automatically dock in the nest of transmission towers for energy replenishment, solving the difficulty of manual battery replacement. Second, in the smart logistics industry, delivery UAVs can achieve high-frequency automatic turnover at logistics hubs, greatly improving distribution efficiency.

4. Conclusion

This paper addresses the range limitation in magnetically coupled resonant wireless charging for drones by establishing a correlation model between efficiency and distance. Simulation results reveal that while receiver circuit parameter optimization achieves an ultra-high efficiency of 98.55% at close range (8 cm), it suffers from a short effective transmission distance and high modification costs. In contrast, the L-type impedance matching network optimization significantly improves transmission efficiency at medium-to-long ranges (10–20 cm) with a gentle attenuation rate, all without altering the physical coil structure. Consequently, the L-type impedance matching scheme is identified as the optimal solution due to its superior position tolerance and engineering feasibility. However, given that this study relies primarily on simulation, future work will focus on constructing a physical platform to further validate the proposed approach.

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