The Relationship Between Charging Distance and Efficiency in Wireless Charging for Unmanned Aerial Vehicle

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Abstract. The short endurance of unmanned aerial vehicles and the need to frequently interrupt missions to recharge them severely limit their ability to operate continuously in areas such as logistics, inspection and rescue. Wireless charging technology, especially electromagnetic induction power transfer, provides a viable solution for unmanned aerial vehicles to achieve continuous power supply in the air, but the sharp decrease of its transmission efficiency with increasing distance is the key challenge. This paper focuses on the bottleneck of unmanned aerial vehicle endurance and studies the in-air charging efficiency of the electromagnetic induction wireless power transmission system, with an emphasis on exploring the impact of charging distance (represented by the coupling coefficient k) on the transmission efficiency. This paper sorts out the classification of wireless power transmission technology, analyzes the structure and working principle of electromagnetic induction systems, and discusses the key factors affecting efficiency. An initial baseline was established using a simplified simulation model that omitted resonant compensation. As anticipated, both output voltage and efficiency were observed to decline markedly as the distance increased (and the coupling coefficient k decreased), even over short ranges. These baseline outcomes highlight a fundamental limitation of inductive coupling and reinforce the necessity of resonant compensation networks in real-world applications, as will be elaborated in the subsequent section. This research provides an important basis for the optimal design of the wireless charging system for unmanned aerial vehicles.

Keywords: unmanned aerial vehicle; wireless charging; electromagnetic induction; coupling coefficient; transfer efficiency.

1. Introduction

The earliest origin of wireless charging technology, or wireless power transmission (WPT), can be traced back to the 20th century. In 1903, the world-renowned engineer Nikola Tesla built the Tesla Tower and attempted to conduct an experiment on transatlantic wireless energy transmission on Long Island, New York. However, due to the imperfection of the theory at that time and the lack of technical strength, the experiment was not successful. Although the Tesla Tower experiment was not successful, its forward-looking ideas have inspired more scholars to devote themselves to the research of radio power transmission.

Wireless charging technology has developed rapidly in recent years. This technology is reflected in all aspects of people's lives and has emerged as a viable alternative to the traditional wire-linked transmission method, becoming a key technology in fields such as electric vehicles, industrial robots, and smart devices. Among the various WPT approaches, resonant compensation technology has proven to be a critical means of overcoming transmission distance limitations and improving efficiency. As WPT will extend to more fields in the future, scientists are paying more and more attention to the exploration of this technology. The American magazine Technology Review once selected WPT technology as one of the top ten future energy researches [1]. This can highlight that WPT technology is of great research value.

In the field of science and technology, unmanned aerial vehicles (UAVs) are unmanned aircraft that are operated and controlled by radio remote control and autonomous programs [2-3]. Drones have undergone significant development over the past decade. Due to their advantages such as simple structure, flexible flight, convenient operation and no pollution, they are often applied in rescue operations, intelligent transportation, unmanned transportation and environmental monitoring, etc.

[4-5]. Because of the continuous improvement of the precision, sensor capabilities and automation levels of the Global Positioning System (GPS), the application of UAVs in multiple fields is expected to experience significant growth [6].

However, despite these technological breakthroughs, UAVs still face many limitations. This is mainly because the main power systems of UAVs all come from their batteries, and the capacity of the batteries is limited, which limits their range. Nowadays, most of the UAVs on the market cannot operate for more than an hour. When the battery power is too low, they need to land at a designated location and be charged manually. Such operations are time-consuming and laborious, affecting work efficiency. To address these limitations, WPT technology has developed into a feasible solution [7-8]. It has the potential to significantly enhance the flight time and operational range of UAVs by achieving dynamic flight charging.

Although resonant technology has been widely studied, the quantitative benchmarks for its performance improvement often lack comparison. This study first establishes a baseline model without resonant compensation to quantitatively analyze the impact of distance on efficiency, thereby providing a clear comparison benchmark and theoretical basis for the subsequent demonstration of the superiority of resonant networks and their optimized design.

2. Classification and Basic Theory of WPT for UAVs

2.1. Classification of WPT

With the gradual maturation and development of technology and theory nowadays, the WPT technologies that have been extensively studied by domestic and foreign research institutions can be classified into four major categories. They will be introduced one by one in the following text.

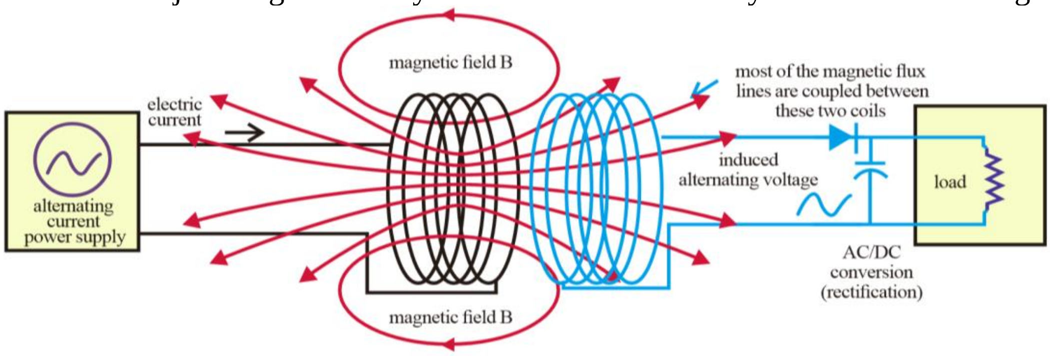

Fig. 1 Schematic diagram of magnetic induction wireless charging

Magnetic induction wireless charging is based on Faraday's law of electromagnetic induction and transfers energy through the transmitting coil and the receiving coil, as shown in Figure 1. In our daily life, low-power devices such as mobile phones and sweeping robots all adopt this technology. With the development of technology, electromagnetic induction wireless charging can achieve power transmission of several hundred watts. At the same time, the Wireless Power Consortium has also established the Qi standardization to ensure its safety and reliability.

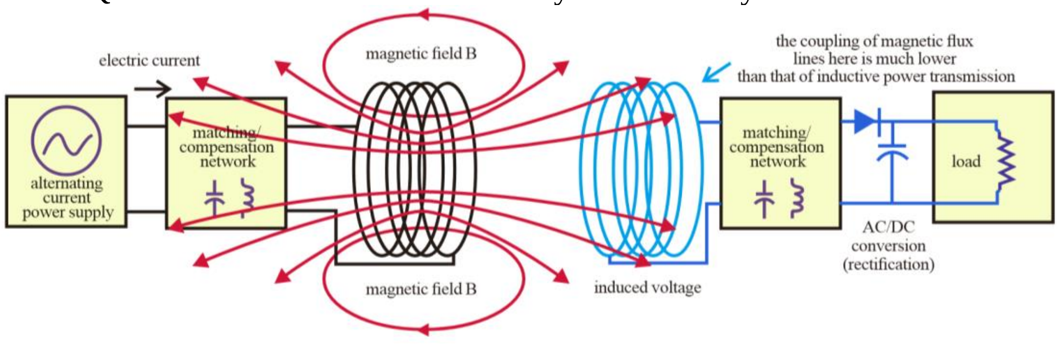

Fig. 2 Schematic diagram of magnetic resonance wireless charging

Magnetic resonance wireless charging use the principle of resonance. When the resonant frequencies of the transmitting end and the receiving end are the same, efficient energy transmission can be achieved, as shown in Figure 2. Compared with magnetic induction wireless charging, magnetic resonance wireless charging has lower requirements for coil placement, but its efficiency can also change due to distance. The transmission distance of this technology is also much longer, which can be extended to several meters, and the power can reach several kilowatts. It can be applied to medium and high power scenarios such as electric vehicles.

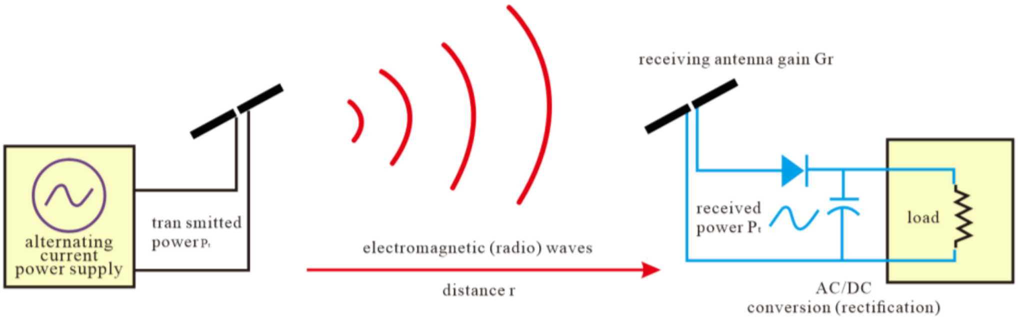

Fig. 3 Schematic diagram of radio wave wireless charging

Radio wave wireless charging uses microwaves as the medium and radiates energy directional through an antenna, as shown in Figure 3. Its application is also very common in daily life, often seen in televisions, wireless networks and Bluetooth, etc. However, this technology has extremely high requirements for directed and the transmitting end must be aligned with the receiving end. However, due to the fact that radio waves cannot penetrate obstacles and electromagnetic waves propagate seriously in space, the transmission efficiency is not ideal. Constrained by the Ferris equation, the propagation efficiency decays with the square of the distance. The Ferris equation is given below:

$$P_r = G_t G_r P_t \left(\frac{\lambda}{4\pi r} \right)^2 \tag{1}$$

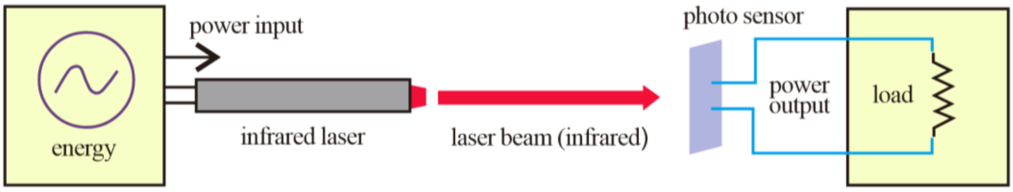

Fig. 4 Schematic diagram of laser wireless charging

Laser wireless charging converts electrical energy into laser beams, which are then received and converted back into electrical energy by photovoltaic cells, as shown in Figure 4. This technology can reach a distance of over a kilometer and a power of over a kilowatt, but once there is an obstruction, it will block the transmission. This technology is not yet mature at present, but it can be used for mobile electrical devices such as space station satellites. For UAVs, laser charging could enable long-range, high-power energy supply in open environments, making it suitable for missions involving aerial inspection or continuous flight.

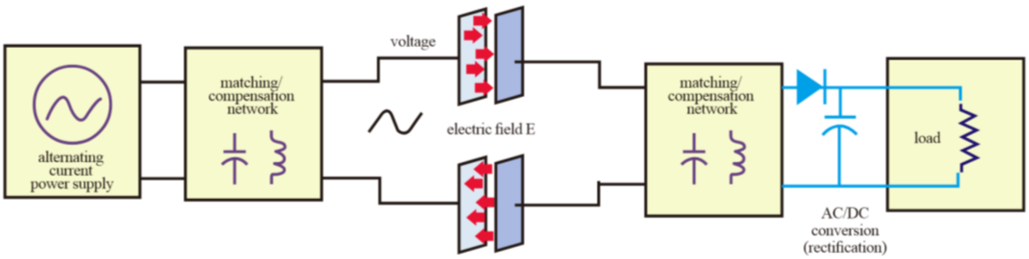

Fig. 5 Schematic diagram of electric field-coupled wireless charging

Electric field-coupled wireless charging transmits energy by coupling metal plates with high-frequency alternating electric fields, as shown in Figure 5. At present, it is mostly applied to millimeter-level energy transmission, with power ranging from milliwatts to kilowatts. However, due to its relatively small transmission distance, even minor deviations can affect the transmission efficiency. It has a low sensitivity to metals, so it can penetrate metal materials. This makes it a potential fit for UAV landing and charging platforms where precise docking are required.

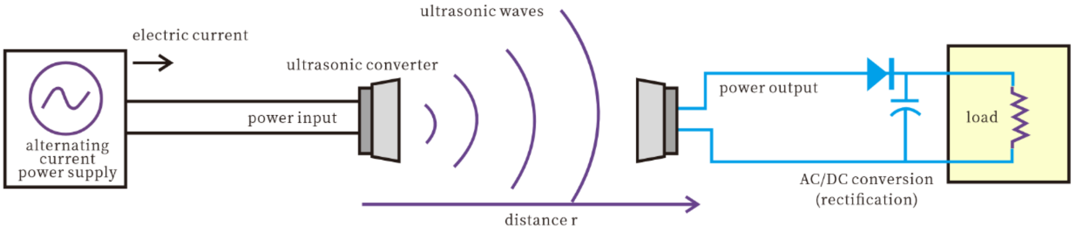

Fig. 6 Schematic diagram of Ultrasonic wireless charging

Ultrasonic wireless charging utilizes the vibration of sound waves to transfer energy in a medium, as shown in Figure 6. It has strong anti-electromagnetic interference ability, but its transmission power is limited, ranging from milliwatts to kilowatts. This technology is still in its infancy. In conclusion, based on the understanding of various wireless charging methods, they are compared here as shown in Table 1.

Table 1 Comparison of various wireless charging methods

Wireless charging method	Mechanism	Typical range	Transmission power	Frequency band
Magnetic induction	Near-zone magnetic field	Short (mm-cm)	mW-hundreds of kW	20kHz-10Mhz
Magnetic resonance	Near-zone magnetic field	Medium (cm-m)	W-kW	20kHz-10Mhz
Radio wave	electromagnetic wave	Long (m-km)	kW	5.8GHz
Laser	electromagnetic wave	Long (hundreds of m-km)	kW	384.6THz-789.5THz
Electric field-coupled	Near-zone electric field	Short (cm)	mW-kW	100kHz-1MHz
Ultrasonic	sound wave	Short-Medium (m)	mW-kW	40KHz-1MHz

2.2. Electromagnetic Field Theory

In classical electromagnetism theory, a changing electric field leads to a corresponding changing magnetic field, and a changing magnetic field, in turn, can also generate a changing electric field. This alternating change of electric field and magnetic field thus constitutes the electromagnetic field. When wavelength is taken as the unit, electromagnetic fields can be divided into near-field and far-field based on the length of the wavelength. The physical properties of these two regions are different, and so are the electromagnetic characteristics they exhibit.

Specifically, the area centered on the field source where the distance is less than one wavelength is called the near-field, or it can also be referred to as the induced field; The area where the distance exceeds one wavelength range is called the far field. Electromagnetic resonance wireless charging technology precisely utilizes the electromagnetic coupling characteristics of the near-field to achieve energy transmission. During this process, electromagnetic energy flows periodically between the space around the radiation source and within the radiation source itself. Since the energy of the electric field is mainly confined within the capacitor, a non-radiating alternating magnetic field is formed around the transmitting coil, and this magnetic field is relied upon for the wireless transmission of energy.

3. Structural Analysis of Electromagnetic Induction WPT System

3.1. Basic Structure of the Electromagnetic Induction WPT System

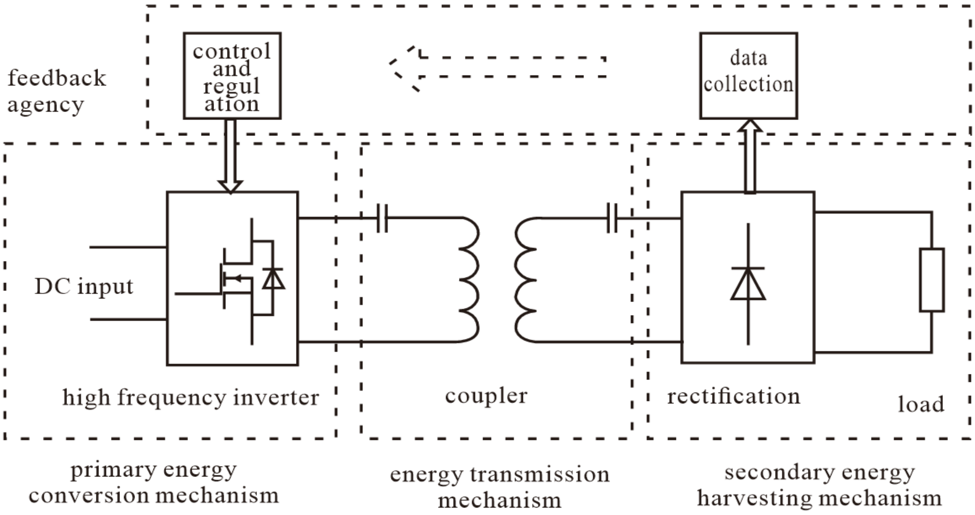

Fig. 7 Schematic diagram of the magnetic induction wireless charging structure

As shown in Figure 7, the electromagnetic induction wireless charging system mainly consists of four core parts. The first part is the primary energy conversion mechanism, whose core function is to convert the input direct current into the high-frequency alternating current required for system operation through a high-frequency inverter circuit. The second part is the energy transmission mechanism, which is composed of the primary coil, the secondary coil and the compensation capacitors respectively connected to them. Its function is equivalent to that of a loosely coupled transformer; Wireless power transfer is achieved when an alternating electromagnetic field from a transmitting coil couples through the air to a receiving coil. The system performs optimally when both the primary and secondary sides are tuned to the same resonant frequency. The third part is the secondary energy reception mechanism, mainly including the rectifier filter circuit and the load.

It is responsible for rectifying, filtering and other processing the alternating current induced by the receiving coil, and converting it into direct current energy that can be used by the load. The fourth part is the feedback mechanism, which continuously monitors the load status through sensors and feeds back the detection data to the controller; Based on these real-time sampling results, the controller dynamically adjusts the output frequency of the inverter, ultimately forming an accurate closed-loop control system to ensure the stability and efficiency of the entire charging process.

3.2. The Transmission Efficiency of the Electromagnetic Induction Radio Power Transmission System

The transmission efficiency of a wireless charging system is one of the key indicators for measuring its performance. During the process of energy transmission, electrical energy is inevitably lost among various components. At the same time, certain energy losses will also occur in the energy conversion and transmission from electrical energy to field energy and then to electrical energy. Compared with the traditional wired charging method, the overall efficiency of wireless charging is relatively low, and for this reason, it has long received widespread doubts and attention. Therefore, improving the transmission efficiency of wireless charging should become one of the important goals that need to be focused on in its circuit design. The efficiency of wireless charging is mainly influenced by three factors: transmitting end loss, coil induction efficiency and receiving end loss. Among them, the transmitting end loss mainly stems from the conduction loss of the MOSFET during the energy transmission process. Generally speaking, the on-resistance of a MOSFET is controlled within 50mΩ. Considering that a full-bridge circuit will have two MOSFETs on in one cycle, when transmitting a current of 2A, the power loss generated by the two is approximately 400mW.

Combined with the losses of other chips at the transmitting end, the overall energy efficiency of the transmitting end can usually be maintained at over 95%. At the receiving end, the main loss is concentrated in the rectifier module. After taking into account the losses of other functional modules, the efficiency of the receiving end can also be maintained at over 95%. As for the induction efficiency of the coil, it mainly depends on the combined effect of multiple factors such as the mutual inductance coefficient between the primary and secondary side coils, the operating frequency, and the load resistance.

In a wireless charging system, the inductance values of the primary and secondary side coils are usually fixed parameters, while the coupling coefficient is mainly affected by the relative spatial positions of the two coils. In practical applications, the relative positions between the receiving end and the transmitting end are not fixed, resulting in dynamic changes in the coupling coefficient during the system operation. To study the approximate variation range of the mutual inductance coefficient during the charging process, the open-circuit and short-circuit methods and the coil coupling method will be adopted respectively to test the coupling coefficient, thereby determining the value range of the coupling coefficient *k*. The basic theories of the two calculation methods will be explained in the following text. When testing the loose coupling situation (i.e., when the coupling coefficient *k* is low), the open-circuit and short-circuit method needs to measure three key inductance parameters: When the secondary side is open-circuitedL_{open1}, the inductance of the primary side and the coupling coefficient of the primary side are usually higher than their actual values. However, by adopting a higher measurement frequency, the measurement error caused by this can be reduced to a certain extent.

$$M = \sqrt{\left(L_{open1} - L_{sht}\right) L_{open2}} \tag{2}$$

$$k = \sqrt{\frac{L_{open1} - L_{sht}}{L_{open1}}} \tag{3}$$

In the series coupling method, the inductance L_s of the two coils when they are connected in series in the forward direction and the inductance L_f when they are connected in series in the reverse direction need to be measured respectively. These two inductances can be derived and calculated from the self-inductances L_1 and L_2 of their respective coils. The specific calculation principles are as follows:

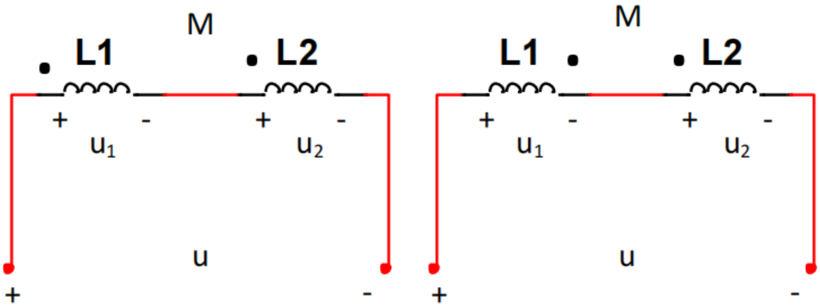

Fig. 8 Schematic diagram of the series coupling method

As shown in Figure 8, Figure a shows two coils connected in series in the forward direction, and Figure b shows two coils connected in series in the reverse direction. When in forward series connection:

$$\begin{aligned} \dot{U} &= \dot{U}_1 - \dot{U}_2 \\ &= j\omega L_1 \dot{I} + j\omega M \dot{I} + j\omega L_2 \dot{I} + j\omega M \dot{I} \\ &= j\omega \left(L_1 + L_2 + 2M\right) \dot{I} \\ &= j\omega L_s \dot{I} \end{aligned} \tag{4}$$

When connected in reverse series:

$$\begin{aligned}\dot{U} &= \dot{U}_1 - \dot{U}_2 \\ &= j\omega L_1\dot{I} + j\omega M\dot{I} + j\omega L_2\dot{I} + j\omega M\dot{I} \\ &= j\omega\left(L_1 + L_2 + 2M\right)\dot{I} \\ &= j\omega L_s\dot{I}\end{aligned} \tag{5}$$

From the above two formulas, mutual inductance M can be obtained:

$$M = \frac{L_s - L_f}{4} \tag{6}$$

The coupling coefficient *k* can be calculated through mutual inductance:

$$k = \frac{M}{\sqrt{L_1 L_2}} \tag{7}$$

4. Simulation and Results Analysis

4.1. Simulation Circuit Construction and Parameter Design

To investigate the relationship between charging efficiency and distance in the electromagnetic induction wireless charging system. This simulation circuit is mainly composed of an AC power supply and a primary side coil, a mutual inductance model, a rectifier and filter circuit, as well as a voltage stabilizing and load section. Its structure is shown in Figure 9.

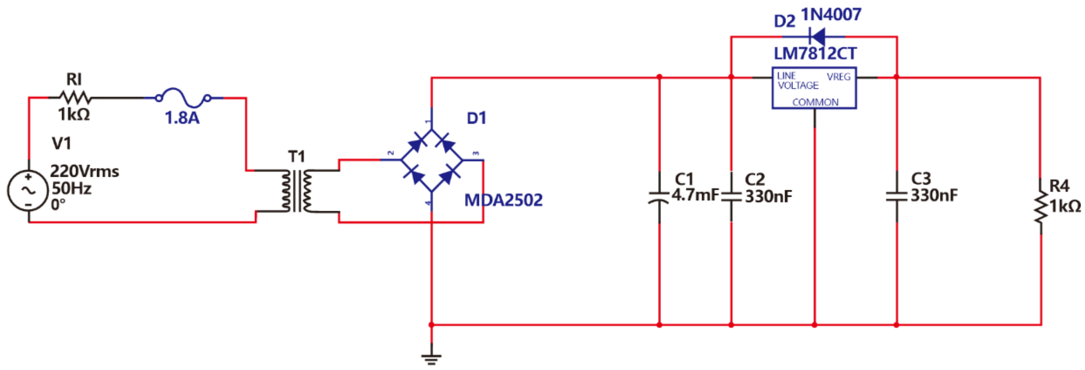

Fig. 9 Electromagnetic induction wireless charging model

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4.1.1Primary side power supply and coil modeling

The primary power supply uses an AC power source (V1), with parameters set at 220V, 50Hz, phase 0°, and a rated current of 1.8A. The primary side coil is modeled using the primary winding T1 (transformer element) of the mutual inductance model at a scale of 1:1 to study the variation of energy transfer efficiency under different coupling coefficients *k*.

In Multisim, by changing the coupling coefficient *k* of T1, different charging distances can be equivalently simulated. The lower the coupling coefficient, the farther the distance between the primary side and the secondary side coils, which affects the transmission efficiency.

4.1.2 Design of Rectifier and Filter Circuits

The induced voltage on the secondary side is rectified by the D1 of the bridge rectifier, and the output is a DC signal. To suppress voltage ripple and enhance the stability of the output voltage, a large-capacity filter capacitor C1 (4.7mF) was added after rectification and used in parallel with a small-capacity high-speed filter capacitor C2 (330nF). Among them, C1 is responsible for filtering out the ripple of low-frequency components, while C2 is used to absorb high-frequency spikes, thereby improving the quality of the output waveform.

4.1.3 Voltage Stabilization and Load Section

The filtered DC voltage is stabilized and output through the voltage stabilizing chip LM7812 to ensure that the voltage at the load terminal is stable at 12V. A freewheeling diode D2 is connected in series at the front end of the voltage stabilizer to prevent damage to the voltage stabilizer chip when it is turned off or the load is recharged with current.

A filter capacitor C3 (330 nF) is connected in parallel at the output end of the voltage stabilizer to further suppress high-frequency currents, and a resistive load R4 (1 kΩ) is connected to simulate actual electrical equipment.

4.2. Equivalent Distance Simulation Experiment

To analyze the impact of charging distance on transmission efficiency in electromagnetic induction wireless charging systems, this section, based on a simulation model, equivalently replaces the changes in physical distance by adjusting the transformer coupling coefficient k, thereby establishing the relationship between distance and efficiency. The core parameter of the electromagnetic coupling system, the coupling coefficient k, represents the ability of energy transmission between coils, and it has a significant negative correlation characteristic with the distance d. According to the formula of coupling coefficient and distance, the coupling coefficient decreases exponentially with the increase of distance:

$$k \approx k_0 e^{-\alpha d} \tag{8}$$

Here is the maximum coupling coefficient when the coil is in close contact, and α is the attenuation constant, which is determined by parameters such as the coil radius and the number of turns. This formula indicates that when the distance d increases, the proportion of leakage flux rises, causing a sharp drop in the k value. This phenomenon constitutes the theoretical basis of the simulation experiment.

The transmission efficiency η is defined as the ratio of the output power at the receiving end to the input power at the transmitting end:

$$\eta = \frac{P_{out}}{P_{in}} \times 100\% = \frac{V_{load} \times I_{load}}{V_{in} \times I_{in}} \times 100\% \tag{9}$$

In the simulation experiment, the input voltage of 220Vrms/50Hz and the load current of 1.8A were kept constant. The voltage and current at the receiving end and the transmitting end are directly collected through the probe. The coupling coefficient k can be adjusted within the range of 0.1 to 1, covering from tight bonding to long-distance separation.

A key conclusion can be drawn from the simulation: The output voltage of the system decays severely - even when the coupling coefficient is relatively high (k=0.8), the output voltage is still only at the millivolt level. This result profoundly reveals that the simple inductive coupling system without resonant compensation has fundamental limitations. The core reason for this poor performance lies in the inherent high leakage inductance characteristic of the loosely coupled coil itself. If a resonant capacitor is not equipped to counteract this capacitive impedance, the current in the primary coil will be severely restricted, which in turn leads to a weakened magnetic field strength and extremely low power transmission efficiency. Moreover, as the distance increases (i.e., the coupling coefficient k decreases), this attenuation effect intensifies exponentially, which also confirms the high sensitivity of non-resonant induction systems to the alignment accuracy of the coil and the transmission distance. This discovery fully demonstrates that in the actual radio power transmission system of UAVs, resonant compensation networks (such as series-string and series-parallel topologies) are indispensable. Such networks can effectively alleviate the negative impact of leakage inductance and significantly enhance the power transmission capacity and efficiency of the system by constructing high-quality factor resonant circuits.

5. Conclusion

This study systematically demonstrates the severe efficiency degradation with distance in basic inductive WPT systems, highlighting the impracticality of using such simple systems for UAV applications. The findings strongly suggest that future work must focus on integrating resonant topologies (e.g., Series-Series compensation), frequency tracking algorithms, and optimized coil designs to achieve viable in-air charging performance. This research provides a theoretical and simulation-based benchmark for evaluating the effectiveness of such advanced compensation strategies.

This research has important implications for the practical design of wireless charging systems for UAVs. The results clearly indicate that in practical applications, if only relying on the basic electromagnetic induction structure, it is difficult to achieve efficient medium and long-distance power transmission. Therefore, to enhance system performance, strategies such as resonant topology, frequency tracking, coil optimization or adaptive control must be introduced to suppress the efficiency attenuation caused by the increase in distance. This study also provides a theoretical basis for the collaborative design of positioning accuracy and energy transmission in the subsequent dynamic charging system of UAVs.

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