TẠP CHÍ KHOA HỌC VÀ CÔNG NGHỆ NĂNG LƯỢNG - TRƯỜNG ĐẠI HỌC ĐIỆN LỰC
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DESIGN AND PERFORMANCE COMPARISON OF TWO WIRELESS POWER TRANSFER SYSTEMS BASED ON MAGNETIC INDUCTIVE COUPLING AND MAGNETIC RESONANCE COUPLING

THIẾT KẾ VÀ SO SÁNH HIỆU SUẤT HOẠT ĐỘNG CỦA HAI HỆ THỐNG TRUYỀN NĂNG LƯỢNG KHÔNG DÂY DỰA TRÊN CẢM ỨNG TỪ VÀ CỘNG HƯỞNG TỪ

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Abstract:

Wireless power transfer (WPT) is the technology that enables power transmission without the need for physical wires, such as electric wires typically used for power transmission. Near-field WPT is the most common for commercial devices that can be classified by two transmission methods: inductive coupling and magnetic resonance coupling. This paper provides a comparative analysis of the performance of two WPT systems that use two different configurations based on a transfer mechanism. The first system is a four-coil structure that utilizes the magnetic resonance coupling technique and operates at a frequency of 13.56 MHz. Conversely, the second WPT system is a two-coil structure that employs the inductive coupling method and operates at a frequency of 500 kHz. The results of this work demonstrate the superiority of magnetic resonant coupling WPT over inductive coupling WPT in terms of transmission distance. The results of this paper can serve as a reference for designing WPT systems in applications where simplicity, transmitted power, and transmission distance need to be considered.

Keywords:

Wireless Transfer Power, Inductive Coupling, Magnetic Resonance Coupling, four-coil Structure, two-coil Structure

Tóm tắt:

Truyền tải điện không dây (WPT) là công nghệ cho phép truyền tải điện mà không cần dây nối, chẳng hạn như dây điện thường được sử dụng để truyền tải điện. WPT trường gần là phổ biến nhất cho các thiết bị thương mại có thể được phân loại theo hai phương pháp truyền: ghép nối cảm ứng từ và ghép nối cộng hưởng từ. Bài viết này so sánh về hiệu suất của hai hệ thống WPT có kích thước tương đương sử dụng hai cơ chế truyền khác nhau. Hệ thống đầu tiên là hệ thống bốn cuộn dây sử dụng công nghệ ghép cộng hưởng từ và hoạt động ở tần số 13,56 MHz. Ngược lại, hệ thống WPT thứ hai là gồm hai cuộn dây sử dụng phương pháp ghép nối cảm ứng từ và hoạt động ở tần số 500 kHz. Kết quả của nghiên cứu này chứng minh tính ưu việt của kĩ thuật ghép cộng hưởng từ so với kĩ thuật ghép nối cảm ứng từ về khoảng cách truyền. Từ đó, chúng tôi có thể đưa ra lựa chọn việc sử dụng các hệ thống WPT cho các ứng dụng cụ thể.

Từ khóa:

Truyền năng lượng không dây, Ghép cặp cảm ứng từ, Ghép cặp cộng hưởng từ, Cấu trúc 4 cuộn dây, Cấu trúc 2 cuộn dây.

1. INTRODUCTION

Electricity is regarded as one of the four most significant innovations, alongside fire, wheels, and atomic energy. Presently, the predominant approach for power transmission remains the utilization of electrical wires. Nevertheless, this typically results in significant power losses due to resistance (ranging from 20% to 30%), thereby diminishing the transfer coefficient of power transmission. Currently, there is ongoing research in the field of power technology, which has made significant progress in developing wireless power transmission systems [1], [2]. This technology holds great importance for the future development of power systems [3], [4], as it has the potential to reduce the costs associated with constructing civil electricity infrastructure and make the process of using electricity more convenient. As the number of electrical devices increases, the electrical system does not need to connect intricate conductors. Wireless power transfer (WPT) devices will be an ideal solution for addressing this issue. Among the WPT technologies being researched and implemented, near-field WPT is the most widely used coupling technology, including inductive coupling and magnetic resonance coupling [5-8].

The inductive coupling is one of the most widely used and well-understood WPT methods. It operates on the principle of electromagnetic induction. A time-varying magnetic field is generated when an alternating current is passed through a primary coil. A current will be generated to supply power to the device if a secondary coil is positioned in this magnetic field, resulting in the appearance of an induced electromotive force in the secondary coil [9-11].

The magnetic resonant wireless power transfer (MR-WPT) system consists of four coils: a source coil, a transmitting resonant coil (Tx), a receiving resonant coil (Rx), and a load coil. Tx and Rx are two resonant structures that operate at the same frequency in order to improve the efficiency of the system. The magnetic coupling between the source coil and Tx, as well as between Rx and the load coil, is typically facilitated by the tiny distances between them. The system's effective transmission range is determined by the distance between Tx and Rx. A multi-turn spiral coil structure is frequently employed in Tx and Rx to enhance the transmission transfer coefficient of the MR-WPT system, thereby achieving a high quality factor (*Q*-factor) [12], [13].

In this paper, we will evaluate and design two WPT systems at the same distance and dimension to determine the most suitable system for specific applications. Two WPT systems are studied: a two-coil structure operating at a frequency of 500 kHz and a four-coil structure operating at 13.56 MHz. While the 500 kHz frequency has been widely utilized by many research groups to design two-coil WPT systems [14], the 13.56 MHz frequency falls within the ISM band (Industrial, Scientific, and Medical). The evaluation will focus on key technical factors such as transfer coefficient, energy performance, and system stability, allowing us to make an optimal selection for each targeted application.

2. METHODOLOGY

2.1. Two-coil structure

The model of the two-coil WPT system using magnetically coupled resonators is shown in Fig. 1. The resonant frequency of the Tx coil and Rx coil is the same. Through the magnetic field between two coils, electric power can be transmitted when the resonant frequency energizes the Tx coil. A high frequency magnetic field is created around the Tx coil by an RLC branch driven by an AC voltage source on the Tx side. After recovering energy from the field, the Rx coil powers a load (R_L). Additionally, the parasitic resistances R_{Tx} and R_{Rx} are present in both the Tx and Rx circuits [9].

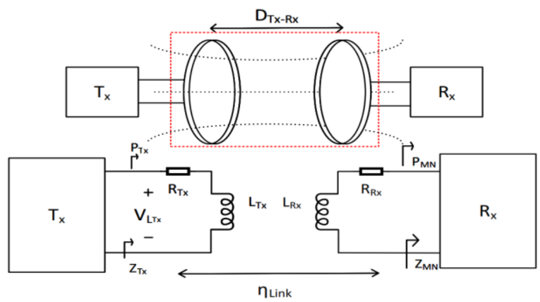

Figure 1. The schematic of the two-coil WPT system.

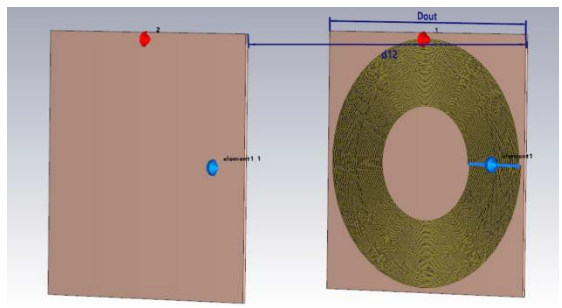

Figure 2. The design model of the two-coil WPT system.

Based on those theoretical foundations, we have proposed a design for a two-coil system operating at a frequency of 500 kHz, as shown in Fig. 2. The WPT system has been simulated by CST Studio Suite software [15]. Firstly, we designed a planar spiral coil. The shape of the spiral resonator can be structurally reduced compared to resonators of the same frequency. The geometrical parameters of Tx and Rx coils are listed in the following: D_{out} = 220 mm refers to the outer diameter of the coil, d indicates the inner diameter, w = 2 mm represents the spacing between the wires, the distance between loops is s = 1 mm, N = 30 is the total number of coil turns. We also added a capacitor with a value of 585 pF to adjust the resonant frequency. The parameters of the coils are selected with dimensions suitable for WPT applications. Furthermore, the values of w and s are chosen to minimize losses caused by the skin effect and proximity effect when the coils operate at high frequencies. The value of the external capacitor can be determined from the natural resonant frequency of the resonator. This explanation also applies to the four-coil WPT system later.

2.2. Four-coil structure.

A simplified block diagram of four-coil WPT, including a source loop, a transmitter coil, a receiver coil, and a load coil, is depicted in Fig. 3. In the four-coil structure, the system may include control circuits to adjust frequency and power, ensuring that the transmission process is stable and efficient [9], [12].

We have also designed a four-coil system operating at a frequency of 13.56 MHz, as shown in Fig. 4. The parameters of the MR-WPT system include: d = 220 mm denotes the outer diameter of the coil w = 1.5 mm, the wire spacing s = 3 mm, the distance between loops; and the number of coil N = 7. Additionally, we included $d_{12} = d_{34}$ = 4 cm, which are the distances between the source/load and the resonator coils.

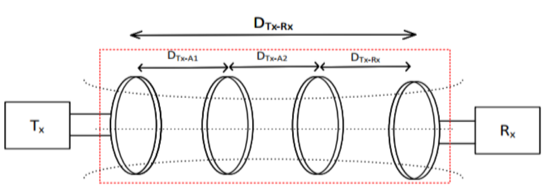

Figure 3. The schematic of four-coil WPT system.

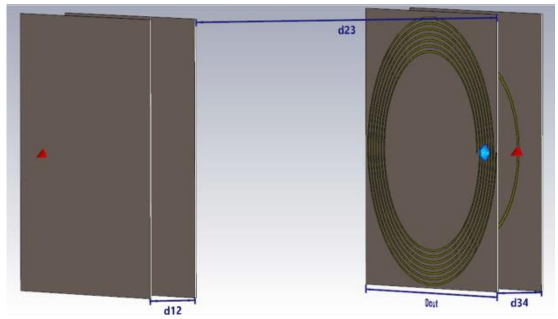

Figure 4. The design model of the MR-WPT system

3. RESULTS AND DISCUSSION

The simulation results for the structure of two coils operating at a frequency of 500 kHz, as shown in Fig. 5. At the same time, we also conducted a test with the two coils operating at different distances. First, we set the distance between the transmitter coil and the receiver coil at 30 cm, resulting in a transmission coefficient of 0.26. Next, we adjusted the distance to be closer, reducing it from 30 cm to 20 cm. The results show that the transmission coefficient of the two coils operating at a frequency of 500 kHz at a distance of 20 cm is 0.64 higher compared to when the distance is 30 cm.

For the four-coil WPT system operating at a frequency of 13.56 MHz, we also set up a similar configuration to assess its transmission coefficient. We selected two distances between the Tx coil and the Rx coil (d_{23}, as shown in Fig. 4) for the main survey of 20 cm and 30 cm. Fig. 6 shows that when the system was set at a distance of 30 cm, we obtained a transmission coefficient of 0.38. Next, when the distance was adjusted to 20 cm, the transmission coefficient increased to 0.72. The simulation results clearly showed a significant difference of 0.34 between the transmission coefficient at distances of 20 cm and 30 cm for the four-coil system operating at 13.56 MHz.

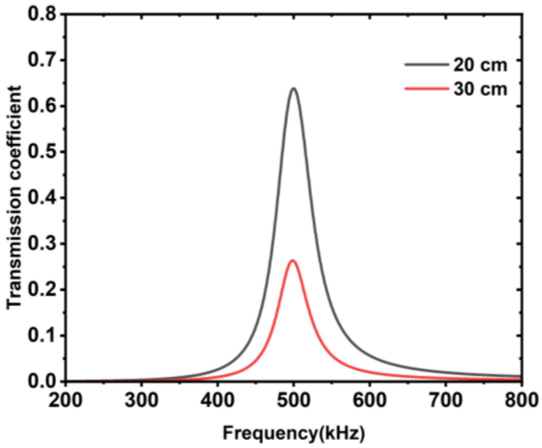

Figure 5. The transfer coefficient of two-coil system

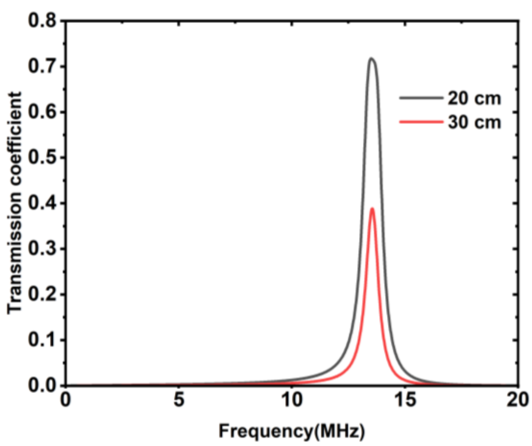

Figure 6. The transfer coefficient of four-coil WPT system

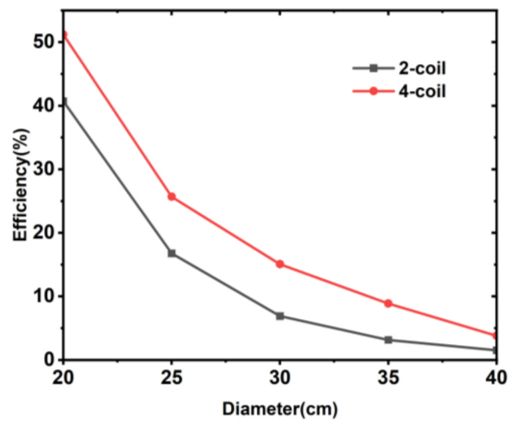

Figure 7. Comparison of Efficiency between the two-coil system and the four-coil system

Based on the results conducted from the simulation, we have obtained the transfer efficiency of two configurations by taking the square of the transmission coefficient ($|S_{21}|^2$), as presented in Fig. 7. It can be observed that the four-coil system operating at a frequency of 13.56 MHz consistently achieves higher efficiency compared to the two-coil system at 500 kHz when both are at the same distance and size. At a distance of 20 cm, the four-coil WPT system provides a transfer coefficient of 52%, which is over 11% higher than the 41% of the two-coil WPT system. In the case of a distance of 30 cm, the efficiency of the two-coil system is more than 10% lower than that of the four-coil system. When the distance between Tx and Rx is larger than 35 cm, at two far distances, the efficiencies of both two systems are smaller than 10%. However, the efficiency of the four-coil system is still greater than the two-coil system.

4. Conclusion

This paper has demonstrated the superiority of MR-WPT based on magnetic resonance coupling over WPT based on magnetic induction coupling in terms of transmission distance. Considering the condition that both coils have the same size and the same transfer distance, we have determined that the four-coil WPT system operating at 13.56 MHz frequency will have higher operating transfer coefficient than the two-coil WPT system operating at 500 kHz frequency. Therefore, our study provides analytical solutions for four-coil and two-coil WPT systems and suggests a solution to choose a reasonable set of wires. We have simulated the two systems on the same application with the hope that, in reality, they can operate similarly under the same conditions. However, the operation frequency of the system is also a factor that needs to be considered.

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