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Research Article

Adaptive Frequency Control in a Wireless Power Transfer System Using RF Modules

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Abstract: This paper presents an adaptive frequency control method for wireless power transfer systems, which monitors the resonant frequency variations caused by changing operating conditions and guarantees optimal system performance. The system is evaluated both at fixed frequency and with the proposed adaptive control approach in a simulation environment. It is then physically designed and tested. The simulation results show that the system automatically adapts to the resonance condition at different winding distances with adaptive frequency control, and higher output power is obtained compared to the fixed frequency structure. In the tests performed on the physical prototype, lower power transfer was observed compared to the simulation due to the low voltage components and application-specific mounting, alignment, and environmental effects. The developed system is also capable of wireless control of a door lock mechanism through a radio frequency communication based, battery-free portable controller. The results show that adaptive frequency control provides significant advantages in terms of energy efficiency and power transfer in wireless power transfer systems.

Keywords: *Wireless power transfer, Ansys Maxwell, RF communication*

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I. INTRODUCTION

Wireless Power Transfer (WPT) is a technology used in recent years to transfer electrical power without any physical contact between the source and the load. This technology is used in charging electric vehicles (Aydin et al., 2018; Babaki et al., 2021; Bai et al., 2022), low-power devices attached to the human body for medical purposes (Bao et al., 2022; Iqbal et al., 2022; le-Huu et al., 2023), and many other areas that require contactless charging (Kopar et al., 2022). This system, which was pioneered by Nikola Tesla, is nowadays realized with different methods such as laser, microwave, magnetic induction, and magnetic resonance. In magnetic resonance power transmission, the capacitors used in the primary and secondary circuits are placed according to different compensation topologies. This arrangement ensures maximum efficiency by operating the system at the resonant frequency (Ozdemir, 2017). To achieve maximum efficiency in WPT systems, it is critical to operate the system at a resonant frequency. However, the resonant frequency may change due to load variations, distance variations, and tolerances of circuit elements. At this point, adaptive frequency control keeps the system at the resonant frequency dynamically. This minimizes power losses during energy transmission and increases the stability of the system. This approach makes a significant contribution to making WPT systems more efficient and reliable in real-time applications.

The use of RF modules in adaptive frequency control is one of the innovative aspects of this work. The RF module collects voltage and current information in the receiving circuit in real time and transmits this data to the RF module in the transmitting circuit. This communication allows the source frequency in the transmitting circuit to be dynamically adjusted to ensure that the system operates at a resonant frequency. Changes in load conditions in the receiving circuit are detected in real time by the RF modules, and the source frequency is optimized based on this information. This process guarantees that the system operates continuously at a resonant frequency, enabling both maximum efficiency in energy transfer and stable operating performance. In addition, frequency tracking in the WPT system not only helps to increase power transfer but also increases the system's tolerance to misalignment, as investigated in multi-frequency phase-shift control studies (Zhang et al., 2021; Drici et al., 2022; Al-Saadi et al., 2019).

There have been many recent studies on WPT. Chen et al. developed a modular four-channel wireless power transmission system with a capacity of 50 kW for fast electric vehicle charging. The study utilizes a non-interacting winding design that increases channel independence and improves the stability of the system. With the proposed system, they were able to transfer approximately 50 kW of power in a 200 mm air gap (Chen et al., 2021). Kamalapathi et al. designed and implemented a dual-source charging system combining WPT and solar energy for charging electric vehicle batteries. In the study, dual input converters were analyzed, and an efficient controller was designed (Kamalapathi et al., 2021). Meng et al. designed a WPT system for biomedical implants. The system designed in the study was able to transfer power with 65% efficiency at 3 cm under a source frequency of 1.1 MHz (Meng et al., 2017). Guan et al. designed a

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repetitive WPT system. In this system, multiple receiver and transmitter windings transferred power through each other. Thus, power transfer was realized using the WPT system at 1.5 meters. According to the results obtained, the designed system transmitted 1.5 W of energy under different loads with 34-42% efficiency (Guan et al., 2022). They realized a versatile coil design for the WPT system. It was observed that the proposed design increased the system efficiency by approximately 18% (Cha et al., 2021). They investigated the influence of the quality factor on power transfer efficiency, critical air gap, and capacitor voltage in a high-power WPT system operating at 85 kHz and 20 kW. Through both experimental and simulation-based analyses, they demonstrated that the quality factor plays a crucial role in determining optimal transfer efficiency and system stability (Aslan et al., 2024). They conducted a comprehensive analysis of a magnetically resonant coupled WPT system, emphasizing the effect of the Q factor and key system parameters on transmission performance. Their findings highlighted that adaptive frequency tuning significantly enhances system efficiency and ensures stable operation under varying coupling conditions (Ozupak et al., 2024). In addition, RF communication technologies have been intensively investigated to increase efficiency and optimize control mechanisms in wireless power transmission systems. Some studies have investigated the impact of RF-based systems in providing remote control and communication in security and automation applications (Housman et al., 2018; Ayir et at., 2020). In addition, RF power supplies and software-defined radio technologies have demonstrated significant contributions to enhancing energy efficiency and overall system performance in wireless power transmission applications.

In this study, an efficient and stable WPT system is proposed by using adaptive frequency control and RF communication technology together. Using the ANSYS Maxwell-Twin Builder package program, the transceiver winding structure and compensation circuits of the system are modeled and analyzed in a simulation environment. According to the results obtained, the proposed WPT system is physically designed. The designed system enables the control of a door lock mechanism via RF communication with a portable controller. Thanks to the proposed adaptive frequency control, the resonant frequency is automatically detected and maximum power transfer is achieved. This method improves the reliability and stability of the system while increasing energy efficiency. The proposed WPT system provides an innovative and practical solution for smart home applications and security systems.

II. MATERIAL AND METHOD

A. *Wireless Power Transfer Technology*

The WPT system consists of coils that act as transmitter and receiver, respectively. In this system, there is usually a rectifier circuit on the receiving coil side. This is to convert the alternating current induced on the receiving coil into the desired direct current (Lee et al., 2017). The basic representation of the WPT system is shown in Figure 1.

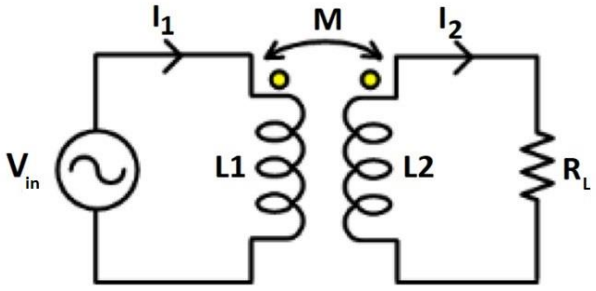


Figure 1. Basic Demonstration of the WPT System

Where V_{in} is the source voltage, I_1 is the source current, L_1 is the transmitter winding inductance, M is the mutual inductance, L_2 is the receiver winding inductance, I_2 is the load current and R_L is the load resistance. If no compensation is realized for the windings in the WPT system, the capacity of the power transferred from the transmitting winding to the receiving winding is divided between inductive and active power. Therefore, power transfer cannot be realized at maximum efficiency. For this, compensation topologies should be used in the WPT system. To transfer the active power capacity in the compensated system, the circuit is made resonant and the capacitive reactive power generated by the capacitor and the inductive reactive power drawn by the coil are balanced. In this way, the active power is equal to the apparent power and power transfer is realized with maximum efficiency (Kisseleff et al., 2017).

Compensation is realized with different topologies in the WPT system. Some of these topologies are parallel-parallel (Li et al., 2024), series-series, parallel-series, series-parallel, series-LCC (Wang et al., 2023), CLC/N (Yang et al., 2023), and LCL (Bertoluzzo et al., 2023). In topology selection, parallel compensation is preferred to obtain a constant voltage at the load side and series compensation is preferred to obtain constant current (Ozdemir, 2017).

A.1. Targeted WPT Application

In this study, the WPT system is used for contactless control of the lock mechanism with a portable control system that does not require batteries. In this system, there are a transceiver winding, a transceiver RF module, a microprocessor, a motor driver, and a motor. Thus, when a control circuit without a battery is brought close to the transmitter circuit, it is energized to open the lock mechanism on the transmitter circuit. Parallel-parallel compensation circuit is preferred for this targeted system. The block diagram of the targeted application is shown in Figure 2.

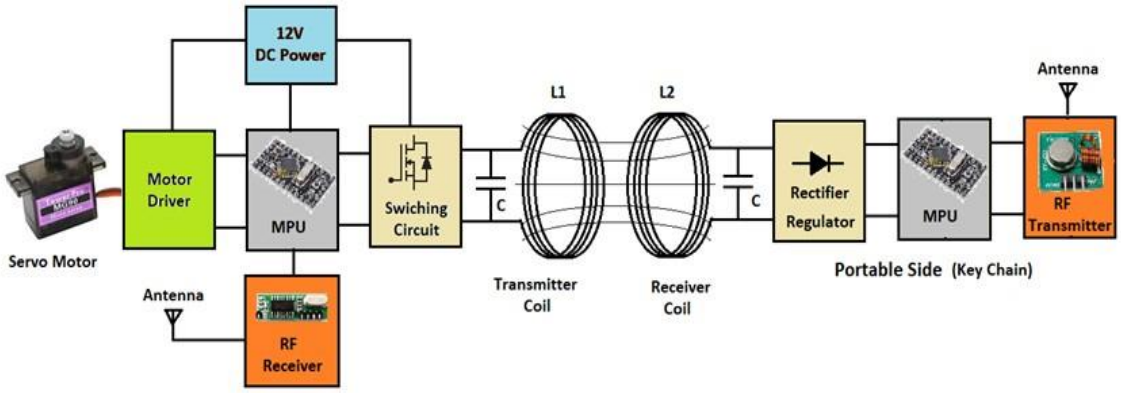


Figure 2. Targeted WPT System

As can be seen in Figure 2, a parallel capacitance is connected to the transmitter and receiver circuit for compensation in the WPT system. The value of this capacity, resonant frequency, and optimum load resistance are determined according to the following equations (1-3).

$$f_r = \frac{1}{2\pi\sqrt{L_1 C_1}} = \frac{1}{2\pi\sqrt{L_2 C_2}} \tag{1}$$

$$C_{1,2} = \frac{1}{(2\pi f)^2 L_{1,2}} \tag{2}$$

$$R_{eq} = R_{load} = \sqrt{\frac{L_2}{C_2}} \tag{3}$$

Where f_r is the resonant frequency, L_1 is the transmitter winding inductance, L_2 is the receiver winding inductance, C_1 is the capacitance used in the transmitter circuit, C_2 is the capacitance used in the receiver circuit, and R_L is the load resistance in the receiver circuit. For the targeted WPT system to operate at maximum efficiency, it is of great importance that the system operates at a resonant frequency. However, shifts in the resonant frequency may occur due to changes in the mutual inductance value depending on the distance between the windings. Therefore, an adaptive frequency control mechanism is used to adapt the operating frequency of the system to the resonant frequency in real time. The flow diagram for adaptive frequency control is shown in Figure 3.

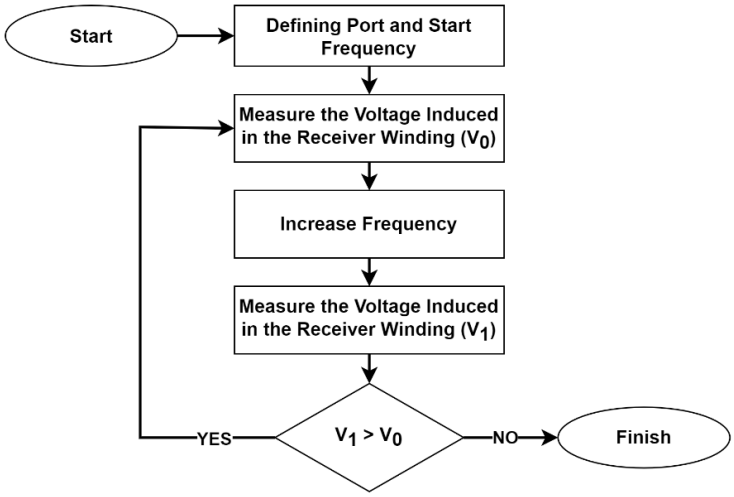


Figure 3. Flow Diagram of Adaptive Frequency Control

A.1.1. Dynamic Frequency Control in Wireless Power Transmission

There are many effects that can change the resonant frequency of the WPT system, such as variation of L and C elements, variation of the distance between the windings, load variation, parasitic magnetic effect, and environmental effects. To maintain high efficiency and stability of the WPT system, adaptive frequency control is required against the changing resonant frequency. With adaptive frequency control, the frequency of the source in the WPT system is always at the resonant frequency. Thus, the efficiency and stability of the system increase. For this purpose, frequency optimization was performed in the WPT system using the Adaptive Single-Objective (ASO) algorithm. The ASO algorithm is used to dynamically adjust the source frequency to ensure the WPT system continuously operates in resonance. During this optimization process, the algorithm changes the frequency based on the induced voltage on the receiver winding. The objective function is defined to maximize the induced voltage, as expressed in Equation 4. The algorithm starts with a low frequency and gradually increases the frequency through successive iterations until the highest voltage level is found. It maintains the current frequency at the highest voltage level.

$$F(f_{Source}) = Vout\ (f) \tag{4}$$

A.1.2. RF Communication Module Integration into the System

Radio Frequency (RF) communication refers to the wireless transmission of information using electromagnetic waves in the radio frequency spectrum. This technology underpins various wireless communication systems such as mobile networks, Wi-Fi, and Bluetooth. In the targeted WPT system, adaptive frequency control was implemented to increase efficiency and stability. To realize this, the input and output powers on the transceiver circuit must be known. This problem is solved by integrating an RF communication module into the WPT system. The RF module integrated into the system transfers the output power information on the receiver circuit to the microprocessor via the RF module on the transmitter circuit. Here, according to the input and output power information, the ASO algorithm optimizes the frequency of the source. Thus, the system provides high efficiency and high stability by continuously operating at the resonant frequency value. Figure 3 shows the RF communication module used in the application.



Figure 4. RF Communication Module Used in WPT System

B. Design Of the WPT System

In this study, the design of the WPT system consists of three parts. In the first part, the receiver and transmitter windings are designed using the ANSYS Maxwell package program. Inductance values of the windings are obtained by magnetic static analysis. In the second section, the compensation topology circuits are modeled on Twin Builder, and the operation of the system at resonant frequency is simulated. In the third part, the simulation results are evaluated, and the physical design of the targeted WPT system is realized.

B.1. Design Of WPT Windings

Many types of winding structures such as solenoid, spiral, rectangular, or circular windings are used in WPT systems (Tran et al., 2018; Yang et al., 2019; Luo et al., 2018; Bouanou et al., 2021). In this study, the spiral winding structure is preferred. The main reason for this is that the spiral winding structure can distribute the magnetic field intensity more homogeneously and thus improve the system performance. In addition, the spiral winding offers a compact design and provides a size advantage in the WPT system. Figure 5 shows the designed transmitter and receiver winding structure.

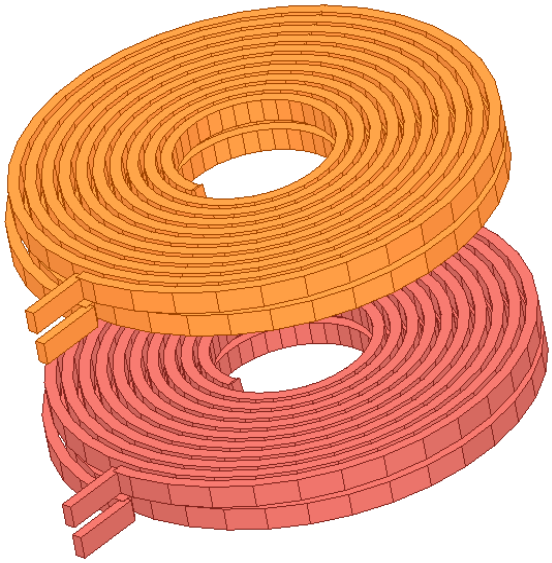


Figure 5. Designed Receiver and Transmitter Windings

The transmitter and receiver windings in the WPT system can be designed differently and equally. In this study, number of turns and sizes of the transmitter winding and receiver winding are designed to be equal to harmonize their natural frequencies. The characteristics of the designed windings are shown in Table 1.

Table 1. *Characteristics of the Designed Windings*

Parameters	**Values**
Total coil turns	20
Coil's inner diameter (mm)	20
Coil's outer diameter (mm)	60
Measured inductance (μH)	14

B.2. Design Of WPT System Compensation Topology

Compensation topologies are critical in WPT systems to increase energy transfer efficiency and to ensure operation at the desired power level. To achieve resonant frequency operation, the parallel-parallel compensation structure has been chosen in this study. This topology ensures stable operation of the system at the resonant frequency with the help of capacitors connected in parallel to both transmitter and receiver windings. In the compensation circuit design, the resonant frequency has been determined using Equation 1, the capacitance value using Equation 2, and the optimum load value using Equation 3. The compensation circuit parameters are shown in Table 2. The resonant frequency of the system has been determined as 40.9 kHz, and although the inductance of each winding is 14 µH, the total inductance value has been measured as 22.3 µH with the contribution of the mutual inductance factor. This value has been achieved with 680 nF compensation capacitors, which ensures the resonance condition.

Table 2. Compensation Circuit Parameters

Parameters	**Values**
Inductance (μH)	22.3
Resonant Frequency (kHz)	40.9
Capacitance (nF)	680
R_L (Ω)	5

The compensation circuit in Figure 6 has been created using the values of the compensation circuit elements in Table 2. Since the transmitter and receiver windings are designed with equal parameters, the same capacitance value is used for C1 and C2 capacitors.

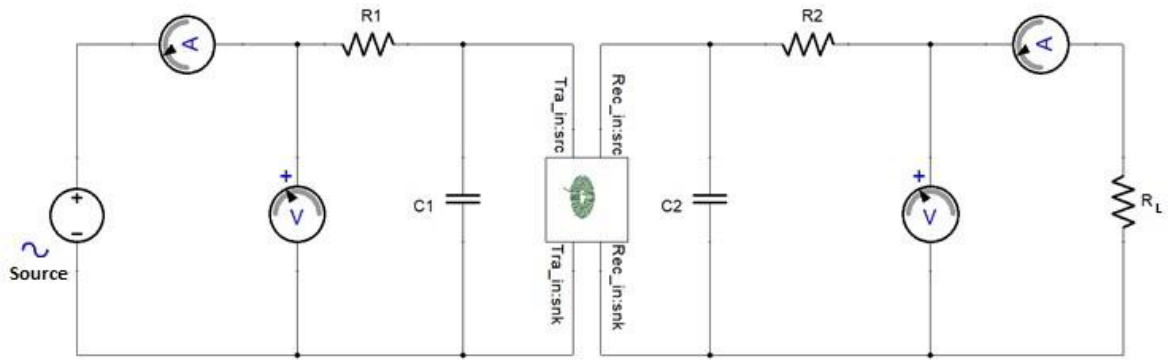


Figure 6. Equivalent Circuit of the Targeted WPT System

B.3. Experimental Setup of the WPT System

In this part of the study, the setup used for WPT experiments is introduced. Prior to the hardware design phase, the receiver and transmitter windings, compensation circuit elements, and other required components have been determined based on the simulation results. According to the determined circuit elements, both the receiver and transmitter circuits of the WPT system have been implemented in hardware. Figure 7 shows the designed receiver and transmitter card module. Thanks to the receiver winding of the WPT system, energy is induced in the board structure without any energy source. In addition, thanks to an integrated RF communication module, current and voltage values are transmitted to the transmitting circuit.

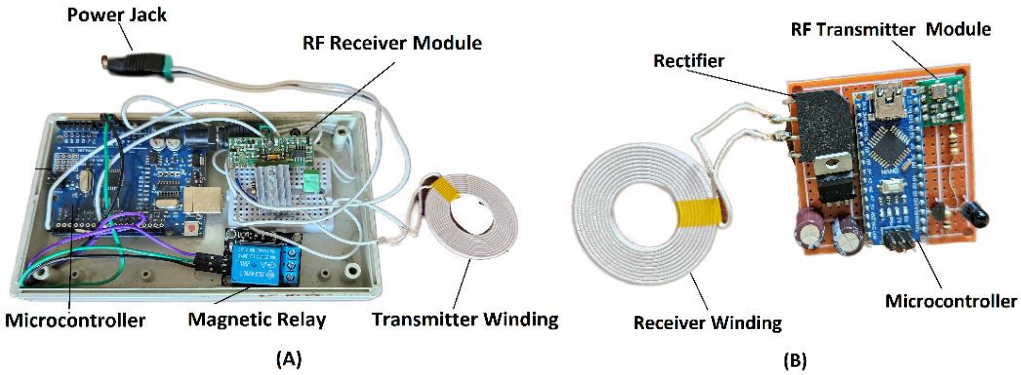


Figure 7. Designed Transmitter (A) and Receiver (B) Modules

Power is transferred from the transmitting winding of the WPT system to the receiving winding. In this module, capacitors designed in accordance with the parallel-parallel compensation topology are placed to increase energy transfer efficiency. In addition, the transmitter circuit includes a microcontroller-based control unit to track the operation of the system and intervene when necessary. This control unit receives current and voltage information from the receiving circuit via RF communication module and adjusts the system parameters to optimize energy transfer through adaptive frequency control. In the design, 433 MHz RF receiver and transmitter modules, Arduino Pro Mini microcontroller, SG90 servo motor, DRV8833 DC motor driver, and voltage regulators have been used. These elements enabled the system to successfully realize wireless energy transfer, RF-based communication, and control of the lock mechanism.

III. PERFORMANCE OF THE WPT SYSTEM

In this section, the performance of the designed WPT system is first evaluated in a simulation-based analysis using both constant resonant frequency and adaptive frequency control. The analyses are performed using ANSYS Maxwell and Twin Builder software packages. Then, the WPT system has been tested after being implemented in hardware. In the first stage, the system has been operated with a fixed resonant frequency of 40.9 kHz, and the distance between the transceiver coils has been varied from 1 cm to 5 cm, increasing by 1 cm each time. At each distance, the voltage induced on the receiver coil and the output power values have been obtained. In the second stage, the source frequency of the WPT system has been optimized by adaptive frequency control. In this method, the performance of the system is improved by updating the resonant frequency at different distances. At the final stage, the hardware-implemented WPT system has been tested by applying both constant frequency and adaptive frequency control. The flow diagram in Figure 3 is followed for adaptive frequency control.

A. *Performance of the WPT System at Constant Frequency*

First, the system has been tested in the simulation with a constant resonant frequency of 40.9 kHz. The induced voltage and output power values have been obtained by varying the distance between the transmitter and receiver windings. The results are shown in Table 3.

Table 3. Output Values of the WPT System at 40.9 kHz for Different Distances

Windings Distance (cm)	Induced Voltage (V)	Output Power (W)
1	15.25	25.48
2	8.12	7.36
3	3.73	1.56
4	2.24	0.47
5	1.50	0.16

When a constant resonant frequency is used in the WPT system, a significant decrease in system performance is observed as the distance increases. These results show that constant frequency has a limited adaptability to distance variations. This is due to the fact that the mutual inductance between transmitting and receiving coils decreases with distance. The mutual inductance is an indicator of the magnetic flux linkage between the coils and depends on the distance and alignment between the two coils (Zhang et al., 2019).

B. *Performance of the WPT System with Adaptive Frequency Control*

In the simulation, the performance of the WPT system with adaptive frequency control at different transmitter-receiver distances is analyzed. As the mutual inductance value decreases as the distance increases, the resonant frequency also changes accordingly. Therefore, the resonant frequency for each distance is determined separately, and the output power of the system at these frequencies is evaluated. To more clearly demonstrate the effect of different distances on energy transfer, the output power obtained in each case has been normalized to the output power at 1 cm. The normalized output power-frequency curves of the designed WPT system according to the distance between the transmitter and receiver windings are shown in Figure 8.

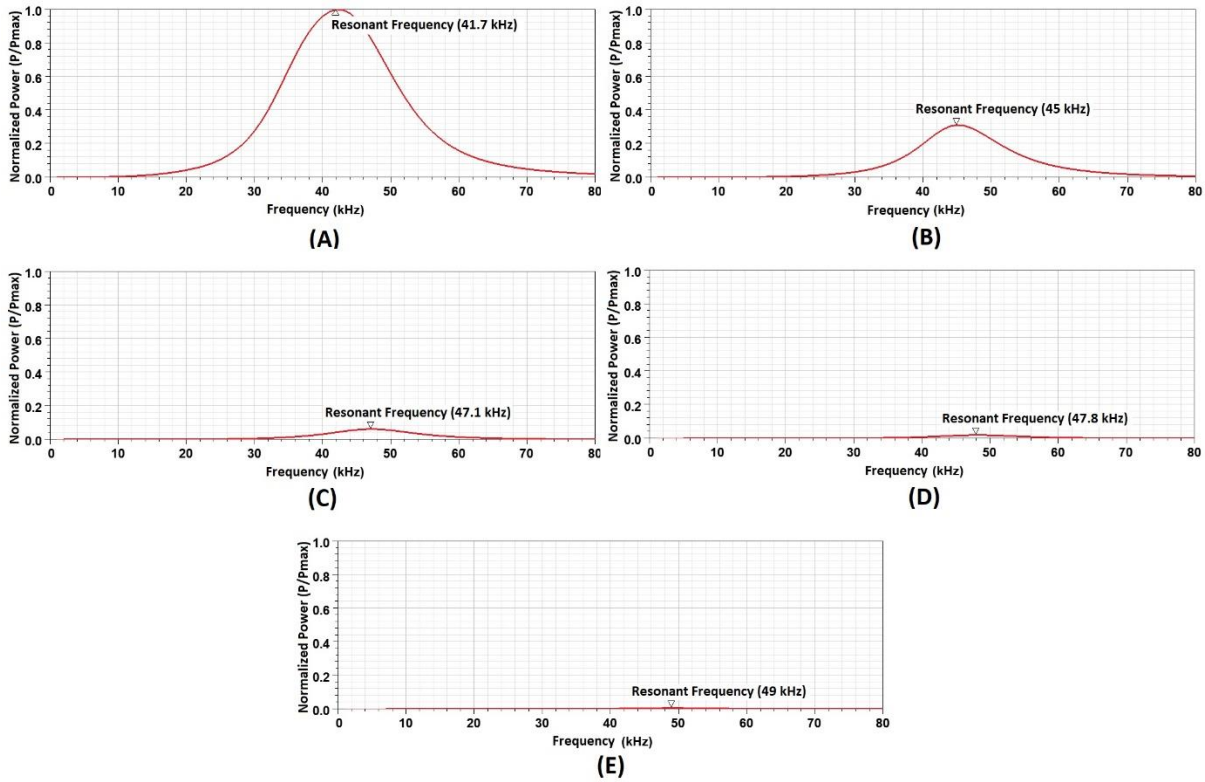


Figure 8. Normalized Power-Frequency Curves of the WPT System for Different Distances. A) 1 cm. B) 2 cm. C) 3 cm. D) 4 cm. E) 5 cm.

In this WPT system using adaptive frequency control, the resonant frequency at each distance is dynamically optimized. Thus, higher efficiency and output power values are obtained in adaptive frequency control compared to fixed frequency. The resonant frequency, induced voltage, and output power of the WPT system with adaptive frequency control according to the distance between the windings are shown in Table 4.

Table 4. Output Values of Adaptive Frequency Controlled WPT System According to Different Distances

Windings Distance (cm)	Resonant Frequency (kHz)	Induced Voltage (V)	Output Power (W)
1	41.7	16.6	29.16
2	45	10.4	13.12
3	47.1	4.64	2.64
4	47.8	2.60	0.63
5	49	1.74	0.21

Table 4 shows that the WPT system with adaptive frequency control provides an improvement in output power compared to the use of constant frequency. This situation arises from the adaptive frequency control mechanism effectively compensating for changes in the coupling coefficient and mutual inductance as the coils move.

C. *Performance of the Experimental WPT System*

After the analysis stage in simulation, the behavior of the system on real hardware has been tested experimentally. The receiver and transmitter circuits of the designed WPT system have been installed and tested in the laboratory environment. In the system operated at a constant frequency of 40.9 kHz, the distance between the windings has been gradually changed from 1 cm to 5 cm, and the required values have been collected in each case. The setup for the coil positioning used during the test is shown in Figure 9. With this setup, the effect of distance variation on energy transfer performance has been analyzed systematically.

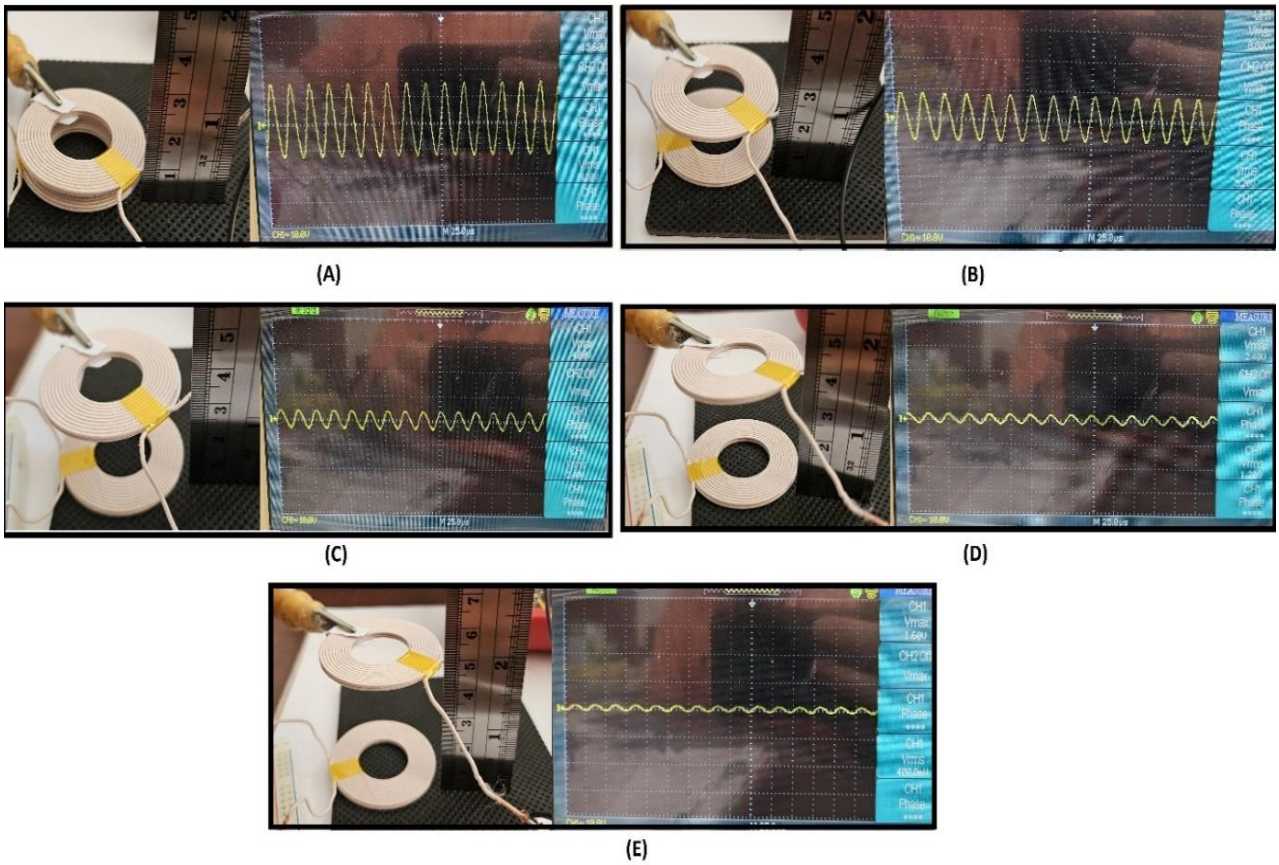


Figure 9. Experimental Test Setup and Oscilloscope Display of the WPT System at Various Distances: A) 1 cm, B) 2 cm, C) 3 cm, D) 4 cm, E) 5 cm

As seen in Figure 9, as the distance between the transmitter winding and receiver winding increases, the voltage induced in the receiver winding decreases. Hence, there is a significant decrease in the transmitted power. The experimental measurements were performed using a digital multimeter with a voltage measurement accuracy of ±0.1 V and a current measurement accuracy of ±0.02 A. Considering these instrument tolerances, the uncertainty in calculated output power is estimated to be within ±2%. All experiments were repeated three times at each distance, and the average values were used to minimize random error effects. Table 5 shows the results of the experimental tests performed at a constant frequency of 40.9 kHz, and Table 6 shows the results of the experimental tests performed with adaptive frequency control.

Table 5. Results of the Experimental WPT System at 40.9 kHz for Different Distances

Windings Distance (cm)	Induced Voltage (V)	Output Power (W)
1	15.60	22.17
2	8.80	6.91
3	4	1.44
4	2.4	0.37
5	1.6	0.06

Table 6. Results of the Experimental WPT System with Adaptive Frequency Control for Different Distances

Windings Distance (cm)	Resonant Frequency (kHz)	Induced Voltage (V)	Output Power (W)
1	40.5	16.98	25.37
2	44.8	11.27	12.31
3	47	4.97	2.43
4	47.4	2.78	0.49
5	48.2	1.85	0.08

When the experimental test results are examined in Tables 5 and 6, it is observed that lower output power is obtained in the experimental test results compared to the simulation test results. The main reason for this difference is that the sine waveforms obtained in the experimental system are more distorted, and the RMS values are lower. Since the RMS value directly affects the output power, it caused the power values in the experimental measurements to be lower than the simulation results. This is thought to be due to a variety of practical factors such as incomplete alignment of the winding centers, interactions between cables, or minor setup errors in the system.

D. *Comparison of the Results*

In this section, the simulation results of the system with constant resonant frequency and adaptive frequency control are compared with the experimental test results. In each case, the performance of the system depending on the transmitter-receiver winding distance is evaluated and the differences between them in terms of energy transfer capacity are revealed. Comparing the constant frequency and adaptive frequency control, it is seen that the adaptive structure provides a significant performance advantage, especially for increasing winding distances. Adaptive frequency control provides the resonant frequency for each distance, ensuring maximum power transfer of the system continuously. Table 7 shows the results obtained from the simulation and experimental test setup and the percentage increase.

Table 7. Comparative Performance Table

Distance (cm)	Simulation								
	Constant Frequency			Adaptive Frequency			Relative Increase		
	Voltage (V)	Power (W)	Efficiency (%)	Voltage (V)	Power (W)	Efficiency (%)	Voltage (%)	Power (%)	Efficiency (%)
1	15.25	25.48	91.20	16.6	29.16	92.08	8.85	14.45	0.88
2	8.12	7.36	25.38	10.4	13.12	41.00	28.08	78.26	15.62
3	3.73	1.56	5.20	4.64	2.64	8.41	24.40	69.23	3.21
4	2.24	0.47	1.74	2.60	0.63	1.85	16.07	34.04	0.11
5	1.50	0.16	0.06	1.74	0.21	0.09	16.00	31.25	0.03
Distance (cm)	Experimental Setup								
	Constant Frequency			Adaptive Frequency			Relative Increase		
	Voltage (V)	Power (W)	Efficiency (%)	Voltage (V)	Power (W)	Efficiency (%)	Voltage (%)	Power (%)	Efficiency (%)
1	15.60	22.17	89.20	16.98	25.37	89.52	8.85	14.44	0.32
2	8.80	6.91	27.64	11.27	12.31	42.45	28.07	78.14	14.81
3	4	1.44	5.54	4.97	2.43	8.17	24.25	68.75	3.2
4	2.4	0.37	1.37	2.78	0.49	1.58	15.83	32.43	0.21
5	1.6	0.06	0.02	1.85	0.08	0.03	15.63	33.33	0.01

As shown in Table 7, the induced voltage and output power obtained from the simulation are higher than the corresponding experimental values due to the idealized conditions of the simulation environment. Although the peak amplitudes of the waveforms are similar in both cases, the RMS voltage of the transmitter coil output in the experimental setup decreased by approximately 6–8% compared to the simulation, directly reducing the transmitted power. In addition, a peak noise level of 50–80 mV has been observed on the receiver coil side, slightly distorting the waveform and lowering its effective value. Misalignment between the coils, magnetic flux deviations caused by mechanical placement, parasitic effects, and ±10% component tolerances also contributed to these discrepancies, leading to a resonance frequency shift of approximately 0.5–0.7 kHz. These combined effects explain the reduction in overall energy transfer efficiency and the deviation from theoretical predictions. Nevertheless, the adaptive frequency control provided a measurable improvement of efficiency, reaching up to about 15% at medium distances, while smaller improvements have been observed at short and long distances. This confirms that adaptive operation increases efficiency by maintaining performance close to resonance and minimizing reactive power losses. An uncertainty and deviation analysis has been performed to measure the agreement between simulation and experiment for both fixed-frequency and adaptive-frequency operation. The analysis results are shown in Table 8.

Table 8. Deviation and Uncertainty Analysis Between Simulation and Experimental Results

Windings Distance (cm)	Constant Frequency		Adaptive Frequency		Uncertainty (%)
	Voltage Deviation (%)	Power Deviation (%)	Voltage Deviation (%)	Power Deviation (%)	
1	2.30	12.99	2.29	13.04	±2.0
2	8.38	6.11	8.37	6.20	±2.0
3	7.24	7.69	7.33	7.95	±2.0
4	7.14	21.28	6.92	22.22	±2.0
5	6.67	62.50	6.32	61.90	±2.0

As shown in Table 8, while the voltage deviations between the simulation and the experiment remain relatively low, the power deviations are larger and increase significantly at greater distances. These high deviations are thought to arise due to weak coupling, misalignment, and component tolerances.

IV. CONCLUSION

In this study, an adaptive frequency control approach for compensating resonant frequency variations in wireless power transmission (WPT) systems was presented. The performance of the proposed system was validated through both simulation and experimental analyses. The adaptive control maintained the resonant condition for each transmission distance, resulting in higher induced voltage, output power, and energy transfer efficiency compared to the constant-frequency structure. The experimental results demonstrated an average improvement up to 70–80% in transmitted power at larger winding distances, confirming the effectiveness of the ASO-based adaptive frequency optimization. In addition, the designed system successfully implemented wireless control of a door lock mechanism via RF communication using a battery-free portable controller, highlighting its practical applicability.

However, the proposed system also presents several limitations. The experimental setup employed low-voltage components and manual winding alignment, which restricted the maximum transferable power and prevented testing under high-power conditions. Furthermore, thermal characterization has not been performed, and temperature-dependent variations in winding resistance or component tolerances have not been analyzed. These factors may influence overall efficiency and long-term stability, particularly under high-power or continuous operation.

In conclusion, the results clearly demonstrate that adaptive frequency control enhances resonance tracking, improves energy transfer efficiency, and enables stable operation under varying coupling conditions, making it a promising approach for future high-performance and self-tuning WPT applications.

DECLARATIONS

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