Wireless Power Transmission of plasma RF wave and the effects of the electromagnetic fields created by the inductive power transfer

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***Abstract*—Transferring energy from an RF plasma was once believed to be a challenging task. However, in this work, we demonstrate how the inductive power transfer created by the interaction of electromagnetic fields between primary and secondary inductors can impact and contribute to the harvesting of output DC voltage during the energy transmission process of RF plasma from the transmission circuit into the receiver circuit through air. Methodology: Two experiments were conducted to prove the feasibility of the interference of the electromagnetic field of the inductive power transfer in transmitting power as an RF plasma through air. Results: The study found that the efficiency of energy harvesting was highly dependent on the distance between the transmission and receiver circuits, as well as the angle between the primary and secondary inductive coils. In Experiment I, the transmission efficiency varied with the angle between the coils, indicating the electromagnetic field of the inductors influenced the RF plasma power transfer output. Experiment II showed the transmission efficiency was inversely proportional to the range beyond a certain distance, suggesting the inductive and RF plasma field interactions became more challenging at longer distances. Overall: The results of the two experiments demonstrate that the inductive power transfer created by the interaction of electromagnetic fields between the inductors can significantly influence the energy transmission of RF plasma through air, and this effect can be leveraged to improve the efficiency of the energy harvesting process.**

***Index Terms*—Wireless power transfer, air core inductor, inductive power transfer, RF plasma power transfer, power transfer efficiency.**

I. INTRODUCTION

Wireless power transmission has been an active area of research, as it offers the potential to deliver energy to remote or inaccessible locations without the need for physical wires or cables. This capability has significant implications for a wide range of applications, from powering sensors and devices in hard-to-reach areas to enabling new paradigms in energy distribution and management.

One promising approach to wireless power transmission is the use of radio frequency (RF) plasma waves propagating through the air. Unlike conductive mediums like metal wires, RF plasma waves can propagate along air-dielectric interfaces, such as the surface of the ground or buildings. This non-radiative propagation allows the energy to be coupled to the plasma wave and delivered to remote devices or sensors without the need for a physical connection. However, maintaining the air plasma over long distances and mitigating the impact of atmospheric effects, such as humidity, temperature, and wind, present significant challenges that have limited the practical deployment of RF plasma-based wireless power transmission.

Recent research has explored the integration of inductive power transfer (IPT) technology with RF surface plasma wave-based wireless energy transmission [1]. The IPT system can be used to efficiently couple electrical energy into a primary coil, which can then be converted into high-frequency electromagnetic fields to sustain the air plasma required for the RF surface plasma wave propagation. By combining these complementary technologies, researchers hope to leverage the strengths of each to address the limitations and improve the overall performance and viability of RF plasma-based wireless power transmission.

This paper investigates the potential synergistic effects and challenges of combining IPT and RF plasma wave technology for wireless power transmission. Through two experiments, the researchers examine how the interaction of electromagnetic fields between the primary and secondary inductors of the IPT system can influence the energy transmission and harvesting efficiency of the RF plasma wave. The results provide valuable insights into the complex interplay between these two technologies and offer guidance on how to optimize their integration for practical wireless power applications.

II. MATERIALS AND METHODS

A. Transmitting energy via RF surface plasma wave through air

The propagation of plasma waves is not limited to conductive water or metal wire mediums, as they can also occur in air when the air is transformed into a weakly ionized plasma. These atmospheric plasma waves, also known as RF plasma waves, can be leveraged for the wireless transmission of energy. To generate and sustain the necessary air plasma, high-frequency electromagnetic fields, such as those from RF or microwave sources, are typically employed. Unlike the plasma in water, the air plasma is more tenuous, with lower electron densities. In this case, the oscillating electric field of the plasma wave becomes the dominant factor, rather than the magnetic field [15]. The RF plasma wave can propagate along the air-ground interface or other air-dielectric boundaries, such as the surfaces of buildings or structures. The wave is guided and confined to the interface, with the electric field concentrated near the surface. This non-radiative propagation allows the energy to be coupled to the plasma wave and delivered to remote devices or sensors.

Maintaining the air plasma over long distances and mitigating the impact of atmospheric effects, such as humidity, temperature, and wind, present significant challenges. Additionally, safety and regulatory considerations must be addressed to ensure the safe operation of high-frequency plasma systems [18]. Despite these challenges, the transmission of energy via RF plasma waves through air is an active area of research, with potential applications in wireless power transfer, remote sensing, and communication systems. Careful design and innovative solutions are necessary to overcome the unique obstacles in the air-based plasma environment and unlock the full potential of this technology [19].

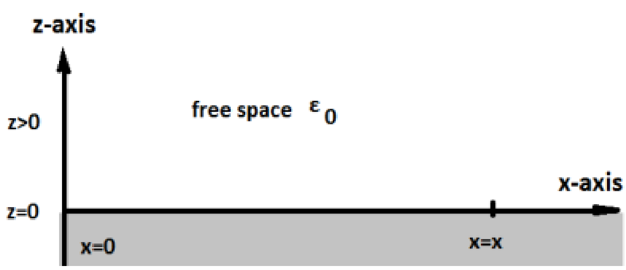

Fig. 1. transmission medium for air propagation of plasma wave

In (Fig. 1), at x = 0, the electric field in the time domain is

$$E(x=0,t) = A\exp(-i\omega t) \quad (1)$$

At x = x, the electric field in the time domain is

$$E(x=x,t) = E\left(0, t - \frac{x}{v_{\text{ph}}}\right) \quad (2)$$

$$= A\exp\left(-i\omega t - \frac{\omega x}{v_{\text{ph}}}\right) = A\exp(-i\omega t - k_x x) \quad (3)$$

where:

+ velocity of the plasma wave $v_{\text{ph}} = \omega/k_x$.
+ k_x is the wave number in the propagation direction.

Apply Maxwell's equations in closed form for differential equations to describe the electric fields in free space (air):

$$\nabla^2 E + \frac{\omega^2}{c^2}E = 0 \quad (4)$$

$$\frac{\partial^2 E_x}{\partial z^2} - (k^2 - \frac{\omega^2}{c^2})E_x = 0 \quad (5)$$

$$\frac{\partial^2 E_x}{\partial z^2} - \alpha^2 E_x = 0 \quad (6)$$

where

$$\alpha^2 = (k^2 - \frac{\omega^2}{c^2}) \quad (7)$$

The solution to Equation (5) is:

$$E_x = A_a \exp(\alpha z)\exp(-i(\omega t - k_x x)) \quad (8)$$

B. Effect of the inductive power transfer

Inductive Power Transfer (IPT) is a wireless charging technology that transfers energy between non-connected circuits via electromagnetic induction. The core IPT system has a power source, primary coil, secondary coil, and load. The source drives current through the primary coil, creating a magnetic field that induces voltage in the secondary coil to power the load [4]. Key IPT benefits are contactless charging and suitability for diverse applications like electronics, vehicles, and medical implants. Techniques like resonant coupling, field shaping, and impedance matching ensure efficient and reliable power transfer. Recent IPT advancements have improved efficiency, power, and range. Ongoing research addresses challenges to expanding IPT's widespread adoption for convenient, safe, and environmentally friendly wireless power.

The integration of inductive power transfer (IPT) technology with RF surface plasma wave-based wireless energy transmission through air can introduce both benefits and challenges. One potential benefit is the synergistic effect of combining these two wireless power transfer methods. The IPT system can be used to efficiently couple the electrical energy into the primary coil, which can then be converted into high-frequency electromagnetic fields to sustain the air plasma required for the RF surface plasma wave propagation [20]. However, the presence of the time-varying magnetic fields associated with the IPT system can also introduce potential interference and coupling issues with the RF plasma wave generation and propagation. The magnetic fields from the IPT coils may interact with the electric fields of the plasma wave, potentially affecting the plasma stability and the efficiency of energy transfer.

C. Circuit Design and Components

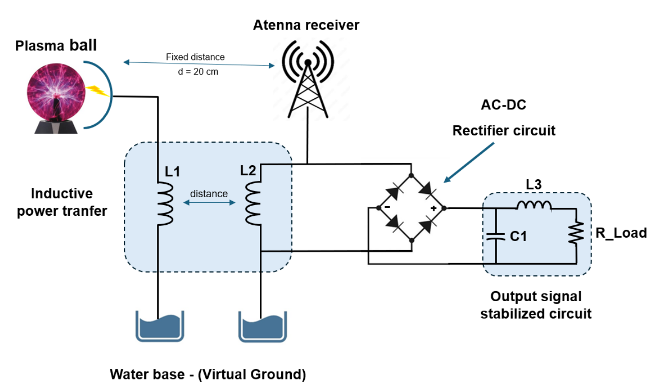

Fig. 2. Circuit system

1) Components:

- Primary and Secondary air core inductors are created by winding 60 and 80 rounds respectively of insulated copper wire around a PE plastic pipe with L1 = 8μH; L2 = 10μH.

Fig. 3. Air core inductor

- A plasma ball, also known as a plasma globe or plasma lamp, is a clear glass container filled with a mixture of noble gases, typically neon, krypton, and xenon. A plasma is formed within the container when a high-voltage, high-frequency (approximately 35kHz) alternating current is applied to the center electrode. The plasma filaments extend from the inner electrode to the outer glass insulator, creating the appearance of multiple constant beams of colored light, resulting from the corona discharge and electric glow discharge. The drive circuit for a plasma ball is a specialized power inverter, which steps up the voltage from a lower-voltage DC supply using a high-frequency, high-voltage transformer, such as a miniature Tesla coil or a flyback transformer.

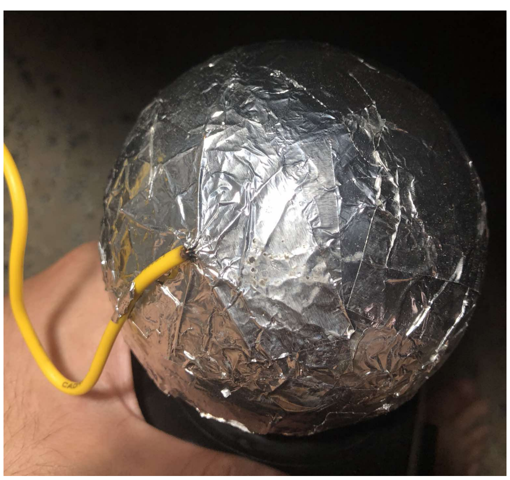

Fig. 4. Half surface covered by aluminum of the plasma ball

- Antenna receiver: A basic dipole antenna is a simple and effective way to receive airborne radio frequency (RF) signals. It consists of two equal-length metal rods, typically made of aluminum or copper, connected at one end. The rods are positioned in a line, with the connection point attached to a coaxial feed line that leads to the receiver. When the antenna is placed in an elevated, open location, the oscillating electric field of incoming RF waves causes electrons in the metal rods to move back and forth, inducing a small voltage in the feed line that can be detected by the receiver [6]. This type of omnidirectional antenna is inexpensive to construct and can effectively capture a wide range of airborne RF signals.

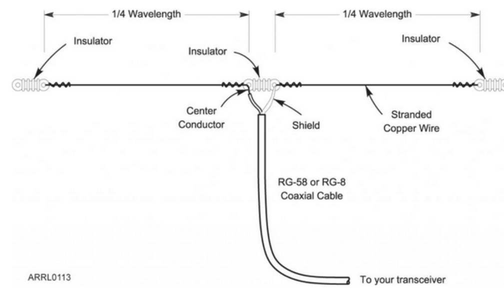

Fig. 5. Dipole antenna

- The AC-DC full-wave bridge rectifier circuit uses four 1N5399 diodes (2A, 1000V) to convert alternating current (AC) to direct current (DC). The input to the circuit is alternating current, and the output is direct current, which is then connected to a load resistor.
- Output signal stabilized circuit: using an LC filter circuit in which the inductor (L3 = 200mH) is connected in parallel with the capacitor (C1 = 100μF). This LC filter circuit is then connected in series with the 2MΩ load resistor.
  + Load Resistor: R_{Load} = 2MΩ.
  + Inductor: L3 = 200mH.
  + Capacitor: C1 = 100μF.

D. Circuit Operation

Distance between Plasma Ball and Antenna: 20cm (Fixed distance).

The circuit utilizes a plasma ball as the source of high-frequency current. The aluminum foil covering half the surface of the plasma ball acts as an electrode, allowing the high-frequency electricity to spark into a wire (transmission line) and go through a primary air-core conductor. Due to the high frequency of the current passing through the primary conductor, the inductive resistance becomes very high. The high current frequency couples with a quarter-wavelength (λ/4) design of the transmission line between the primary conductor and the water base resulting in very high input impedance at that point [8]. This creates a unique situation where the wire end connected to the salt-water base acts as a virtual ground [7].

Inductive resistance (Z_{L}) at the high frequencies used in this circuit, we can use the formula:

$$Z_{\text{L}} = 2\pi f L \tag{9}$$

where:

• f is the frequency of the high-frequency current.

• L is the inductance of the primary conductor.

Special Case: L = λ/4 at high frequencies:

$$\beta l = \frac{2\pi}{\lambda}\frac{\lambda}{4} = \frac{\pi}{2} \tag{10}$$

$$Z_{\text{in}} = Z_0 \left(\frac{Z_L + jZ_0 \tan(\pi/2)}{Z_0 + jZ_L \tan(\pi/2)} \right) = \frac{Z_0^2}{Z_L} \tag{11}$$

+ If the transmission line is open-circuited at the low, we have

$$Z_{\text{in}} = 0 \tag{12}$$

+ If the transmission line is short-circuited at the low, we have

$$Z_{\text{in}} = \infty \tag{13}$$

It is crucial to ensure the wire circuit connections between the various components are laid out in a straight, direct manner. This helps prevent the occurrence of signal reflections along the transmission line, which can significantly degrade the overall performance and reliability of the circuit [9]. Maintaining linear, unobstructed connections is an important design consideration to minimize the impact of reflections and optimize the signal integrity throughout the system. The reflection coefficient of a transmission line represents the ratio of the reflected voltage to the incident voltage. It can be expressed as the ratio of the difference between the load impedance (Z_L) and the characteristic impedance (Z_0) to the sum of the load impedance and the characteristic impedance.:

$$\Gamma = \frac{V^-}{V^+} = \frac{Z_L - Z_0}{Z_L + Z_0} \tag{14}$$

The high-frequency alternating current generated by the plasma ball passes through the primary inductor, creating an electromagnetic field that interacts with the secondary inductor, inducing a new alternating current in the receiver circuit [16] [17]. The induced current in the secondary circuit can then power the receiver circuit, which may include rectification, filtering, and regulation to provide the desired output. The efficiency of the inductive power transfer depends on the coupling coefficient and load impedance, with higher coupling and optimized impedance resulting in improved efficiency [**?**].

The induced voltage in the secondary circuit can be calculated using the formula:

$$V_s = V_p \cdot \left(\frac{N_s}{N_p} \right) \cdot k \tag{15}$$

where:

• Vs is the induced voltage.
• Vp is the primary voltage.
• Ns/Np is the turn ratio.
• K is the coupling coefficient between the inductors, which is affected by factors like distance and orientation.

The dipole antenna in this system is designed to capture the RF waves propagated by the plasma ball and convert them into a high-frequency alternating current. This current then will flow through a secondary air-core inductor and the virtual water base ground is the same as the operation of the transmission part where the input impedance draws out to be very high. During the inductive power transfer process, the electromagnetic field created by the primary inductor interacts with the secondary inductor, inducing a current in the receiver circuit. However, the presence of the RF plasma signal can affect this electromagnetic field, potentially influencing the inductive power transfer. Inversely, the inductive power transfer caused by the interaction of primary and secondary inductors could impact and manipulate the output DC voltage value. In this system, the two power transmission mechanisms (inductive power transfer and RF plasma signal) can affect each other, resulting in the creation of a new alternating signal before it reaches the half-bridge rectifier circuit.

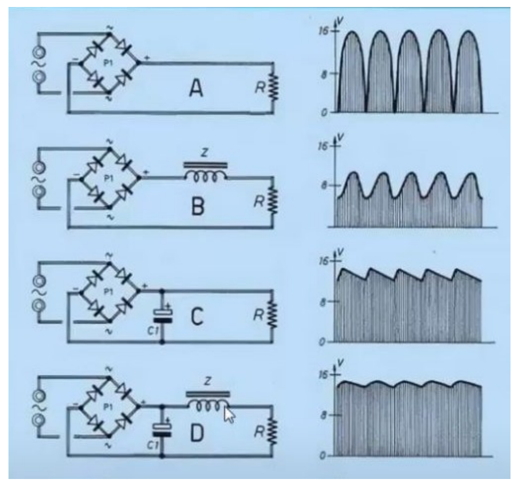

Fig. 6. Output signal stabilized situations

The output signal from the inductive power transfer and RF plasma signal transmission is fed into a full-wave rectifier circuit, and an LC filter is employed to stabilize the rectified output voltage. The inductor resists changes in current, helping to reduce ripple and voltage spikes, while the capacitor acts as a charge storage device, supplying current when the rectified waveform dips and absorbing excess current when it peaks, creating a resonant circuit that filters out high-frequency noise and stabilizes the output voltage; as the rectified signal passes through the LC filter, the inductor stores energy during the waveform peaks and releases it during the valleys, while the capacitor charges and discharges, effectively averaging out the fluctuations, resulting in a smooth, stable DC output voltage that can be used to power the downstream circuitry, with the specific component values of the inductor and capacitor carefully selected to optimize the filter's performance based on the characteristics of the rectified signal and the requirements of the load [10].

III. EXPERIMENT – TEST CASES

Two experiments were conducted to prove the feasibility of the interference of the electromagnetic fields of the inductive power transfer in transmitting power as an RF plasma through air. In Experiment I, the transmission efficiency varied with the angle between the coils, indicating the electromagnetic field of the inductors influenced the RF plasma power transfer output. Experiment II showed the transmission efficiency was inversely proportional to the range beyond a certain distance, suggesting the inductive and RF plasma field interactions became more challenging at longer distances. According to the manufacturer's datasheet, the plasma source in this system is a USB-compatible and battery-powered plasma ball that generates an RF plasma consuming no more than 1 watt of power, with a fundamental frequency of 26.55 kHz and a corresponding power level of -21.48 dB, as per the information provided [2]; given these specifications, the plasma ball generates a low-power, high-frequency RF signal that serves as the input to the inductive power transfer and signal transmission circuit.

A. Experiment I: Effects of changing angle degrees between primary and secondary inductors on the power transfer output.

- **Case 1:** Primary and secondary inductors are in parallel setup (Fig. 6).
- **Case 2:** Primary and secondary inductors are in 45 degrees angle difference setup (Fig. 7).
- **Case 3:** Primary and secondary inductors are in parallel setup (Fig. 8).

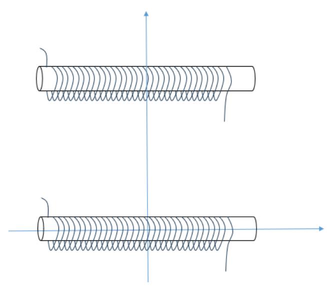

Fig. 7. Case 1: Parallel

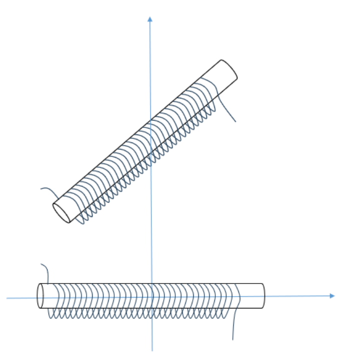

Fig. 8. Case 2: 45 degrees

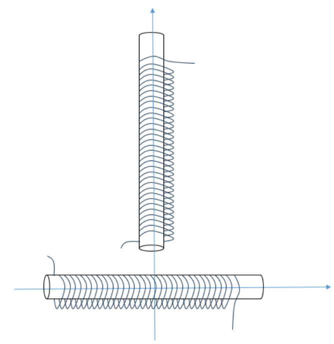

Fig. 9. Orthogonal

B. Experiment II: Effects of changing distances between primary and secondary inductors on the power transfer output.

- **Case 1:** 10cm distance between primary and secondary inductors (TABLE I).
- **Case 2:** 20cm distance between primary and secondary inductors (TABLE I).
- **Case 3:** 30cm distance between primary and secondary inductors (TABLE I).

C. Measurement Approach

The experiments involved carefully positioning the air core inductors to create different test cases. For each test case, the measurements were repeated 5 times, and the average value was calculated to ensure the reliability and consistency of the results. A voltmeter was used to measure the voltage across the load resistor connected to the secondary (receiver) circuit, and the averaged output voltage measurements for each test case were compiled and classified for easy analysis. This approach allowed the researchers to mitigate the impact of any potential variations or uncertainties in the experimental setup, providing more reliable and representative data to analyze the influence of the inductive power transfer on the RF plasma energy transmission.

IV. RESULT

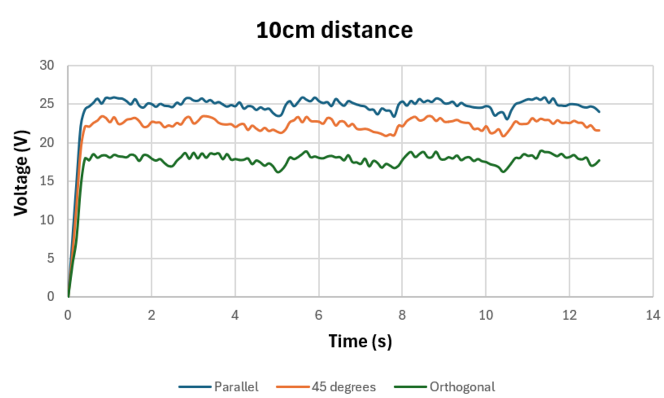

Fig. 10. 10cm distance between primary and secondary inductors

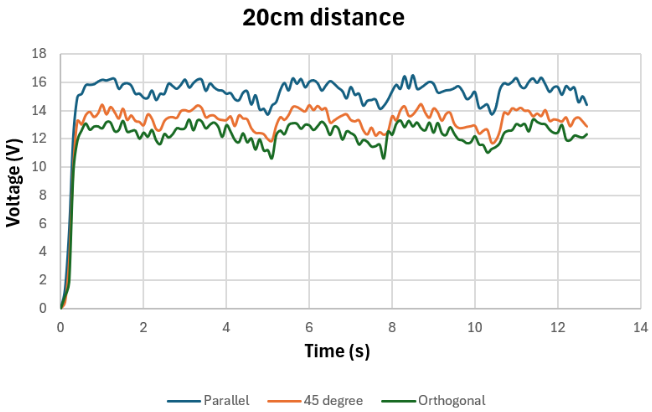

Fig. 11. 20cm distance between primary and secondary inductors

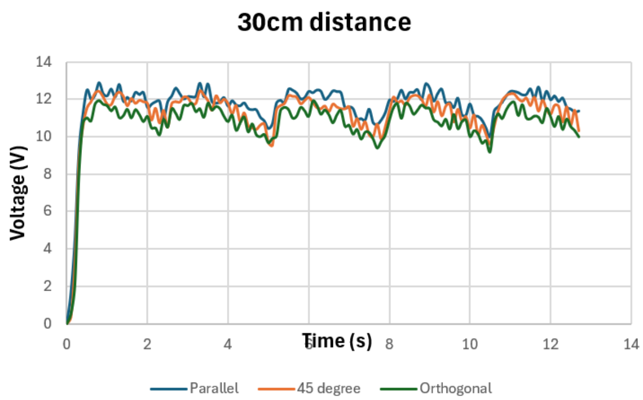

Fig. 12. 30cm distance between primary and secondary inductors

TABLE I
OUTPUT VOLTAGE (V)

Distance	Parallel	45 degree	Orthogonal
10 cm	24.91990849	22.41114333	17.92483404
20 cm	15.40783577	13.44162809	12.42779715
30 cm	11.92412926	11.4486584	10.92062577

$$P_{\text{out}} = \frac{V_{\text{out}}^2}{R_{\text{Load}}} \tag{16}$$

TABLE II
OUTPUT POWER (μW)

Distance	Parallel	45 degree	Orthogonal
10 cm	310.5009195	251.1296727	160.6498376
20 cm	118.7007015	90.33868284	77.22507094
30 cm	71.09242926	65.53588961	59.63003356

V. DISCUSSION

The results of the two experiments presented in this work demonstrate the significant influence that inductive power transfer (IPT) can have on the efficiency of wireless energy transmission using RF plasma waves through air.

In Experiment I, the researchers found that the transmission efficiency was highly dependent on the angle between the primary and secondary inductive coils. This indicates that the electromagnetic field interactions between the inductors play a critical role in determining the power transfer to the RF plasma. When the coils are aligned, the magnetic flux linkage is maximized, allowing more efficient coupling of energy into the plasma. As the angle between the coils deviates from the optimal alignment, the magnetic field coupling deteriorates, resulting in lower energy transfer to the plasma and reduced output power [5].

Experiment II further revealed that the transmission efficiency is inversely proportional to the distance between the transmitter and receiver circuits, beyond a certain range. This suggests that at longer distances, the inductive and RF plasma field interactions become more challenging to maintain. As the separation increases, the magnetic field strength decreases, leading to weaker inductive coupling and less efficient energy transfer into the plasma wave. Additionally, the propagation of the RF plasma wave may be affected by atmospheric factors such as humidity, temperature, and turbulence, which can become more pronounced at longer transmission distances.

The synergistic integration of inductive power transfer (IPT) and RF plasma-based wireless power transfer holds tremendous potential for future applications. The IPT system can efficiently couple electrical energy into the primary coil, which can then be converted into high-frequency electromagnetic fields to sustain the air plasma required for the RF surface plasma wave propagation. However, the time-varying magnetic fields associated with the IPT system may also introduce potential interference and coupling issues with the RF plasma wave generation and propagation. To fully harness the advantages of this hybrid approach, future research should focus on addressing the challenges related to the interactions between the inductive and plasma-based electromagnetic fields, such as optimizing coil design, implementing advanced field-shaping techniques, and developing robust control systems. By overcoming these challenges, the integration of IPT and RF plasma-based wireless power transfer could open up a wide range of futuristic applications, including wireless charging of autonomous vehicles and drones, powering IoT sensors and devices in harsh environments, delivering energy to remote or off-grid locations, and enabling wireless power for medical implants and wearables.

Based on the research presented in this paper, some potential real-life futuristic applications of the integration of inductive power transfer (IPT) and RF plasma-based wireless power transmission include:

1) Wireless Charging of Autonomous Vehicles and Drones: The combination of IPT and RF plasma-based wireless

power transfer could enable the seamless and efficient charging of autonomous vehicles and drones, even in remote or hard-to-reach locations. This could be particularly useful for applications such as transportation, logistics, and environmental monitoring, where the ability to wirelessly charge these mobile platforms without the need for physical docking or wired connections would be a significant advantage [11].

2) Wireless Power for IoT Sensors and Devices in Harsh Environments: The integration of these two wireless power transfer technologies could facilitate the deployment of wireless sensor networks and IoT devices in challenging environments, such as industrial facilities, agricultural settings, or disaster-affected areas. The ability to wirelessly power these devices, even in the presence of atmospheric disturbances or physical obstructions, would enable more robust and reliable monitoring and data collection [12].
3) Wireless Energy Delivery for Remote or Off-Grid Applications: The long-range wireless power transmission capabilities enabled by the combination of IPT and RF plasma-based methods could be utilized to deliver energy to remote or off-grid locations, such as rural communities, disaster relief camps, or temporary military outposts. This could help improve access to reliable and sustainable energy sources in areas without established infrastructure [13].
4) Wireless Power for Medical Implants and Wearables: The contactless nature of this hybrid wireless power transfer approach could be beneficial for powering medical implants and wearable devices, eliminating the need for invasive surgeries or frequent battery replacements. The ability to wirelessly charge these devices, even through the human body, could enhance patient comfort, convenience, and safety [14].

VI. CONCLUSION

The results of the two experiments described in this work demonstrate that the inductive power transfer created by the interaction of electromagnetic fields between the primary and secondary inductors can significantly influence the energy transmission of RF plasma through air. This effect can be leveraged to improve the efficiency of the energy harvesting process.

The study found that the efficiency of energy harvesting was highly dependent on the distance between the transmission and receiver circuits, as well as the angle between the primary and secondary inductive coils. Experiment I showed that the transmission efficiency varied with the angle between the coils, indicating the electromagnetic field of the inductors influenced the RF plasma power transfer output. Experiment II then revealed that the transmission efficiency was inversely proportional to the range beyond a certain distance, suggesting the inductive and RF plasma field interactions became more challenging at longer distances.

Overall, these findings highlight the importance of carefully considering the integration of inductive power transfer (IPT) technology with RF surface plasma wave-based wireless energy transmission. The synergistic effects of the two wireless power transfer methods can be leveraged to improve efficiency, but the potential for interference and coupling issues must also be addressed through proper circuit design and optimization. Further research and development in this area can help unlock the full potential of combined IPT and RF plasma wave systems for wireless power applications.

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