Dielectric Resonant Antenna Technology for Wireless Transfer in Electric Vehicles

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Abstract. Exploring Dielectric Resonator Antennas (DRAs) in Electric Vehicles (EVs) Wireless Power Transfer (WPT) systems is the focus of this study. DRA technology has gained prominence for its unique advantages, offering high efficiency and compact form factors in comparison to conventional antennas. In the context of EVs, the integration of DRAs in WPT systems has shown promising results in addressing challenges related to charging efficiency and spatial constraints. The resonant properties of DRAs enhance power transfer efficiency by mitigating impedance mismatches and reducing energy losses during transmission. Furthermore, the dielectric material properties of DRAs contribute to minimizing electromagnetic interference and enhancing the reliability of WPT in EV applications. This highlights the potential benefits of employing DRAs in achieving robust and efficient wireless charging solutions for electric vehicles. The study encompasses theoretical analysis, simulation studies, and practical implementations to validate the performance of DRAs in WPT systems. The findings suggest that DRA-based WPT systems present a compelling avenue for advancing the state-of-the-art in EV charging technology with efficiency of 84%, providing a more streamlined and effective approach to meet the growing demands of electric mobility in scooters.

1 Introduction

Wireless Power Transfer (WPT) in electric scooters revolutionizes charging by eliminating the need for physical connectors. This innovative technology enables electric scooters to charge wirelessly, offering enhanced convenience and ease of use for riders. By employing resonant coupling or other WPT techniques, electric scooters can seamlessly recharge their batteries simply by being positioned over a charging pad or within a designated charging area [1-3]. This advancement not only simplifies the charging process but also contributes to a cleaner and more efficient urban mobility landscape, aligning with the growing demand for sustainable and user-friendly transportation solutions.

Magnetic resonant coupling in electric scooters involves wireless power transfer through resonant coils, eliminating the need for physical connectors during charging. This technology enhances user convenience and contributes to cleaner urban mobility. Recent developments

focus on extending operating distances, improving efficiency through advanced coil designs, exploring multi-resonant systems, and implementing adaptive control strategies [4-6]. Integration into wireless charging infrastructure for electric vehicles is progressing, fostering standardized solutions for enhanced compatibility and efficiency in urban electric scooter fleets. It has become competitive for air gaps less than 2 m, demonstrating efficacy in the kHz and MHz frequency bands. To achieve wider air gaps exceeding 8 m, however, has trade-offs due to electromagnetic interference. Thus, the standardization is required to avoid electromagnetic interference. Accepted as the standard for electric vehicles, SAE J2954 delineates regulations and the frequency band to ensure safe and efficient Wireless Power Transfer (WPT) operation. The main frequency band for WPT in electric vehicles, as designated by SAE J2954, is 79–90 kHz, with a central frequency of 85 kHz [7]. The LC resonant circuit is highlighted as an effective approach for high-power WPT in large air gaps, achieving efficiency comparable to magnetic induction. Various combinations of charging patters are depicted in Fig 1. Parallel topology is considered advantageous for heavy loads in the LC resonant circuit [8], particularly in the context of SAE J2954 specifications.

This paper proposes the innovative antenna design for WPT systems, similar to magnetic resonant coupling technology. Dielectric Resonator Antenna (DRA) technology, traditionally associated with wireless communication, has emerged as a potential candidate for magnetic coupler designs in EVs [9-10]. DRAs leverage resonance phenomena in dielectric materials to achieve efficient wireless power transfer. This technology offers the advantage of miniaturization, enabling compact and lightweight designs suitable for the limited space within EVs [11].

2 Design & Engineering

The resonance characteristics of DRAs can be harnessed to achieve high-efficiency power transfer within specific frequency ranges [12]. This inherent efficiency makes DRA technology promising for EVs, where the need for rapid and reliable charging is paramount. However, challenges exist in terms of flexibility and customization, as DRAs may have limitations in adapting to diverse EV architectures [13]. Basic model of proposed system is shown in Fig 2.

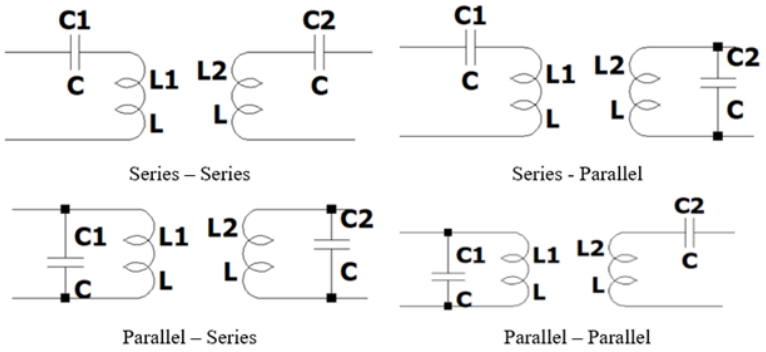

Fig. 1. LC Resonant Circuits.

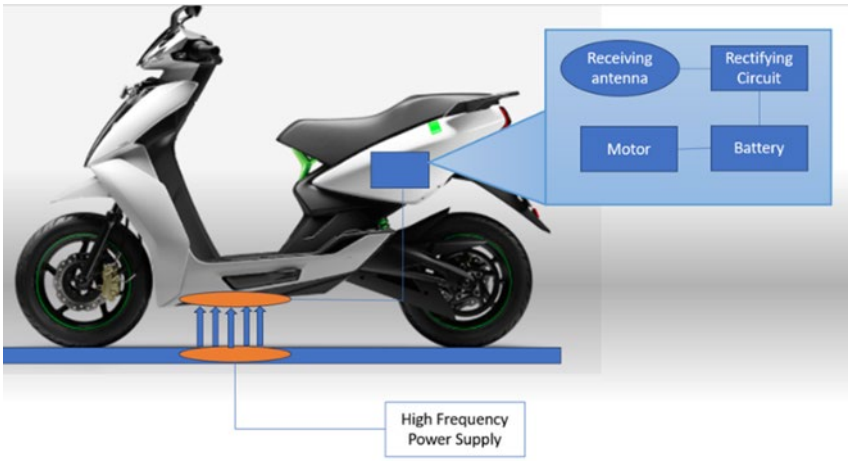

Fig. 2. Proposed System Model.

The design of a magnetic coupler based on Dielectric Resonator Antenna (DRA) technology involves leveraging the resonant properties of dielectric materials. The schematic of the technology proposed is given in Fig 3.

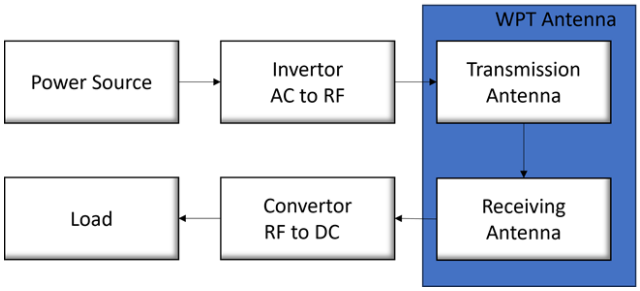

Fig. 3. Block diagram of Dielectric Resonator Antenna (DRA).

2.1 Design Parameters affecting Electrical Characteristics

The Critical design considerations include:

2.1.1 Dielectric Resonator Selection

Choosing the appropriate dielectric material with resonant properties that match the desired frequency for efficient power transfer.

Dielectric Constant (ε): The dielectric constant of the resonator material affects the resonant frequency. It is a unitless constant that characterizes a material's capacity to store electrical energy within an electric field.

Dielectric Loss Tangent ($\tan\delta$): Denotes the energy loss in the dielectric material. A lower loss tangent is desirable for achieving high-efficiency power transfer.

2.1.2 Resonator Shape and Size

Determining the optimal shape and size of the dielectric resonator to achieve resonance at the desired frequency range.

2.1.3 Coil Arrangement

Designing the arrangement of coils to maximize the coupling efficiency with the dielectric resonator.

Number of turns (N): Similar to PCB design, the coil wounding's around the dielectric resonator affects the inductance and, consequently, the efficiency of power transfer.

2.1.4 Mutual Inductance and Coupling Coefficient

Mutual Inductance (M): Crucial for efficient power transfer is the mutual inductance between the dielectric resonator and the coil. It is influenced by the geometric arrangement of the coil and resonator. Mutual Inductance is given by Eq. 1.

$$M = \frac{k.\sqrt{L_1.L_2}}{\omega} \quad (1)$$

Coupling Coefficient (k): By dividing the square root of the product of self-inductances, the mutual inductance is determined through evaluation, as specified in Eq 2.

$$k = \frac{M}{\sqrt{L_1.L_2}} \quad (2)$$

2.1.5 Resonant Frequency and Quality Factor

Resonant Frequency (f_o): The frequency at which the dielectric resonator exhibits maximum energy absorption. It's calculated as given by Eq. 3.

$$f_o = \frac{1}{2\pi\sqrt{LC}} \quad (3)$$

Quality Factor (Q): A measure of the sharpness of the resonance. It's calculated as given by Eq. 4.

$$Q = \frac{f_o}{\Delta f} \quad (4)$$

2.1.6 Efficiency and Power Transfer

Power Transfer Efficiency (η): Efficiency is a critical parameter indicating how much power from the source is successfully transferred to the load and is calculated as given in Eq. 5. It is influenced by factors such as coil and resonator losses.

$$\eta = \frac{P_{received}}{P_{transmitted}} \quad (5)$$

To develop a high-power antenna operating at 13MHz was selected for this experiment. The spiral coil is used to design the magnetic coupler. The block diagram in the Fig 4 explains the overall view of wireless power transmission systems.

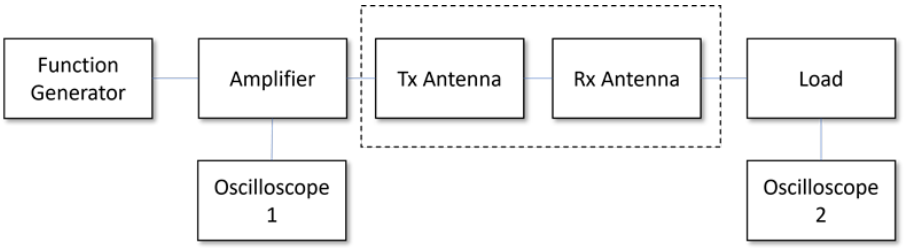

Fig. 4. Block diagram of wireless transmission system using DRA.

The proposed wireless power transfer (WPT) system's charging scenarios are illustrated in depicting the relevant circuit as shown in Fig 4. The main circuit in Fig 5 utilizes power electronics like MOSFET or IGBT for frequency switching, forming an 85 kHz sinusoidal oscillator in a parallel-parallel structure. Notably, this approach triggers self-oscillation without an external function generator, enhancing convenience and cost-effectiveness. As per SAE J2954, with an oscillation frequency of 85 kHz, conventional AC-to-DC converters are unsuitable, presenting a challenge in receiving and charging magnetic energy to the battery. Current directions in the converters as shown in Fig 6.

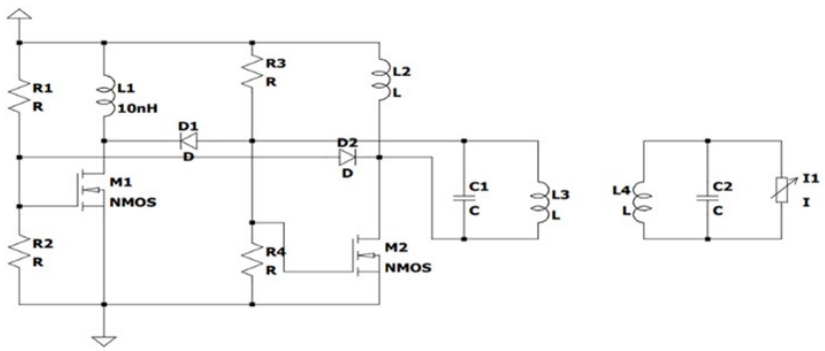

Fig. 5. Main circuit of AC-DC converter.

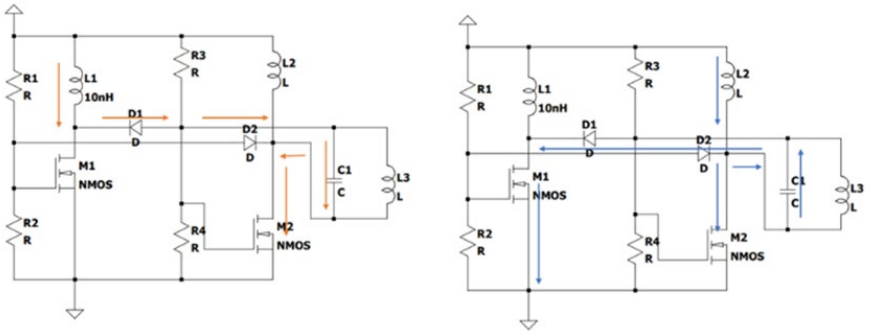

Fig. 6. Current Directions of AC-DC converter.

Parametric values of the antenna are given in the Table 1.

Table 1. Antenna Parameters.

Parameters	
Transmitting distance	250 mm
Diameter of the coil	500 mm
Diameter of the wire	3 mm
Pitch of the coil	12 mm
Number of turns	4
Width of the antenna	3 mm
Material used	Acrylic frame

2.2 Design Parameters affecting Electrical Characteristics

This paper involves the analysis of electrical characteristics of antenna impacted by below parameters.

1. Pitch of the coil
2. Material permittivity.

Pitch of the coil: The pitch of a coil in an antenna, referring to the spacing between adjacent turns, plays a crucial role in determining its resonant frequency. Frequency at which the antenna efficiently absorbs and emits electromagnetic waves is the resonant frequency. The impact of pitch on resonant frequency is a result of the coil's inductance, capacitance, and the distributed capacitance between turns. The observational outcomes are given in Fig 7 and 8. In general, as the pitch increases, meaning the turns are spaced farther apart, the inductance of the coil decreases. This is because there is less magnetic coupling between adjacent turns, leading to reduced inductive reactance. At the same time, the distributed capacitance between turns increases due to the larger separation. The combined effect is a shift in the resonant frequency to a lower value. Conversely, when the pitch decreases and turns are closely spaced, the inductance increases, resulting in higher inductive reactance. The distributed capacitance between turns decreases, pushing the resonant frequency to a higher value. Optimizing the pitch is crucial for achieving resonance at the desired frequency for efficient antenna performance. Designers carefully consider pitch alongside other parameters to tailor antennas for specific frequency bands and applications.

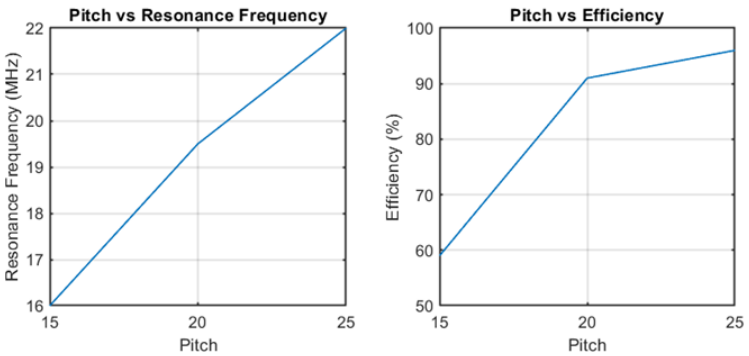

Fig. 7. (a) Pitch vs Resonance Frequency (b) Pitch vs Efficiency.

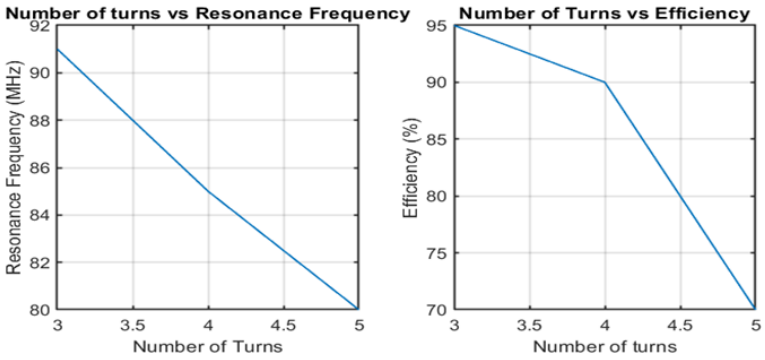

Fig. 8. (a) Number of turns vs Resonance frequency (b) Number of turns vs Efficiency.

Material Permittivity: The material permittivity of the coil significantly influences the resonant frequency of an antenna. Permittivity is a measure of how a material interacts with electric fields, affecting the speed of electromagnetic wave propagation through the material. In the context of antennas, the material permittivity contributes to the overall capacitance of the system, impacting the resonant frequency.

For example, consider a coil wound on a wooden framework with relatively low permittivity. Wood has a lower permittivity compared to other materials like metals or certain plastic. In this scenario, the reduced permittivity lowers the overall capacitance of the coil, shifting the resonant frequency to a higher value. The antenna's performance would be optimized for higher frequency bands. On the other hand, if the same coil is wound on an acrylic framework with higher permittivity, the increased capacitance due to higher permittivity would result in a lower resonant frequency. This makes the antenna more suitable for lower frequency bands. The outcomes are depicted in the Fig 9.

The material permittivity of the coil and its framework directly influences the antenna's capacitance and, consequently, its resonant frequency. Designers choose materials based on the targeted frequency bands, adjusting permittivity to achieve optimal resonance for specific applications.

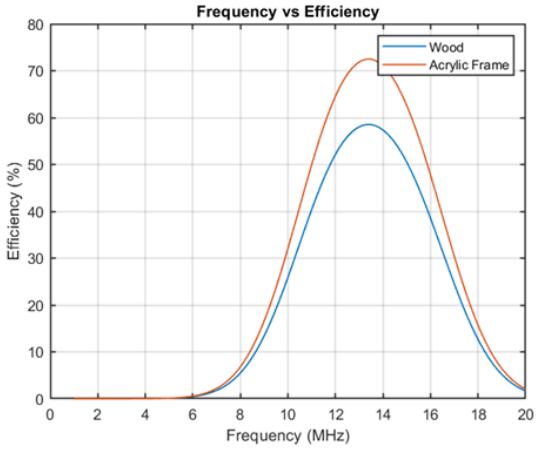

Fig. 9. Frequency vs Efficiency using Wood and Acrylic frame.

3 Results and Discussions

To illustrate the performance of antenna Vector Network Analyzer (VNA) is employed. Series of measurements are made to analyse the various parameters such as reflection coefficients (S11) and radiation patterns. To calculate the antenna efficiency, measure reflection coefficient (S11) by connecting the antenna to VNA. Across a spectrum of frequencies, the S11 measurement indicates the fraction of incoming power that is reflected. Calculate the Return Loss (RL) using the formula in Eq. 6.

$$RL = -20\, log_{10}(S11) \tag{6}$$

Higher Return Loss values indicate lower reflection and better matching. Determine Radiation Efficiency (η_{rad}) given in Eq. 7. It indicates the fraction of the power that is radiated into free space.

$$\eta_{rad} = 1 - 10^{\frac{-RL}{20}} \tag{7}$$

Total Efficiency (η_{total}) considers both radiation efficiency and losses in the system. It is given by Eq. 8.

$$\eta_{total} = \eta_{rad} \times other\ losses \tag{8}$$

The other losses can include losses in connectors, cables, and other components in the system. It is also noted to validate efficiency measurements by examining the directional patterns of antenna's radiation at various frequencies.

The efficiency measurements for the proposed basic antenna model shown in the Fig 10 depicts that the efficiency of antenna to be 85% at 13.5 MHz during power transmission.

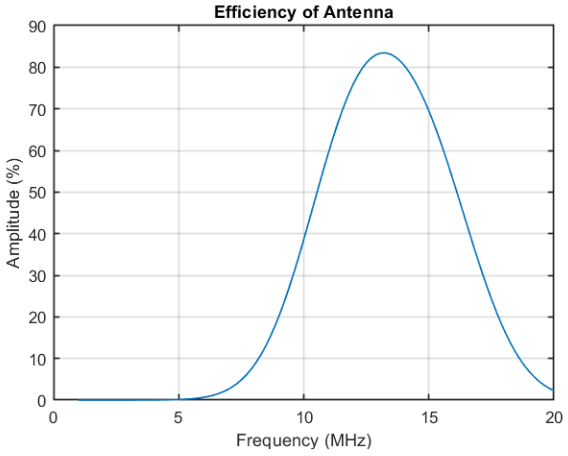

Fig. 10. Efficiency of Antenna.

High Power Transmission Efficiency: In high-power transmission systems, the efficiency of an antenna at a specific frequency, such as 13.5 MHz with a power input of 2500 W, is a critical parameter. Antenna efficiency gauges the effectiveness of transforming input power into emitted electromagnetic energy. The efficiency of the antenna at 13.5 MHz and 2500 W power input is determined to be 84% as shown in Fig 11 Antenna efficiency represents the

ratio of radiated power to the total input power. An efficiency of 84% indicates that 84% of the input power is effectively radiated as electromagnetic energy. High antenna efficiency is desirable in high-power applications to minimize power losses and ensure effective transmission of electromagnetic signals. It contributes to overall system performance and reduces energy dissipation in the form of heat.

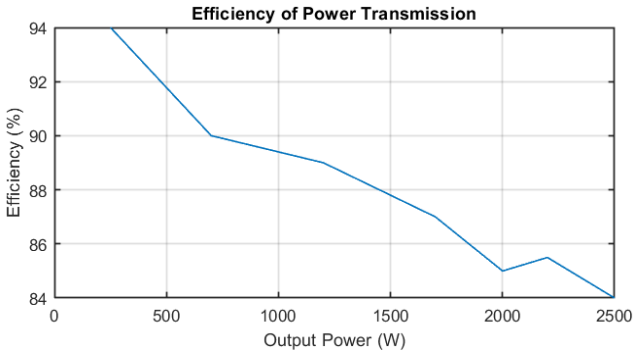

Fig. 11. Efficiency of Power Transmission.

Comparison with radiation efficiency of proposed DRA with Microstrip Patch Antennas (MPA) from previous research is shown in Table 2. The designed system provides efficiency of 84%.

Table 2. Efficiency comparison with previous studies.

	Radiation Efficiency	Rectifier Efficiency
MPA [14]	$70<\eta<90$	$60<\eta<70$
DRA [15]	$90<\eta<100$	$60<\eta<70$

4 Conclusion

In conclusion, the integration of directional resonant antennas in electric scooters for Wireless Power Transfer (WPT) represents a promising technological advancement. The proposed system, as depicted in the provided figures, demonstrates efficient charging scenarios within a practical air gap range of 10 to 15 cm. The circuit design, featuring an 85 kHz sinusoidal oscillator in a parallel-parallel structure, offers a self-oscillation capability without the need for external function generators, enhancing convenience and cost-effectiveness. Notably, the inductor value for the transmitter can be minimized, simplifying impedance matching requirements. The receiver design, crucial for overall efficiency and air gap considerations, employs solutions, addressing challenges posed by the specified oscillation frequency of 13 MHz according to SAE J2954 standards. Overall, the directional resonant antennas contribute to an efficient and convenient wireless charging solution for electric scooters, showcasing potential advancements in urban mobility technology. It is evident that the proposed solution offers efficiency 84%.

For the future development of electric scooters utilizing directional resonant antennas, a key recommendation is to further enhance impedance matching techniques to optimize power transfer efficiency. Exploring advanced algorithms and adaptive control strategies can dynamically adjust impedance matching in real-time, ensuring optimal charging efficiency

under varying conditions. Additionally, research efforts should focus on integrating dynamic charging capabilities, allowing electric scooters to charge wirelessly while in motion. This innovation would significantly extend the range and usability of electric scooters, fostering sustainable urban mobility solutions. Continuous exploration of impedance matching, and dynamic charging technologies will propel the evolution of wireless charging systems in the electric scooter industry.

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