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Improving the Performance of Wireless Charging System for Electric Vehicles Using PS-SS Topology to Achieve High Power Transmission Efficiency

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Abstract

Highly efficient wireless power transfer system for charging electric vehicle batteries with high efficiency, based on a primary-series-secondary compensation (PS-SS) topology. The system is designed with a flat circular transmitter and receiver coil, a full-bridge inverter to convert DC to high-frequency AC, and a full-bridge rectifier on the receiving side to convert AC back to DC for battery charging. Resonant capacitors are used to adjust the frequency response and achieve resonant compatibility for the system . A working methodology based on accurate simulation using MATLAB was adopted to study the effect of several geometric variables on the efficiency of the system. The study included changes in the air gap, resonant capacitance, and load resistance . Four different operational cases were tested to evaluate the ultimate system efficiency and analyze its performance under realistic operating conditions. The results showed that optimizing, reducing the air gap , and precisely adjusting the capacitance values resulted in an efficiency exceeding 96% under optimal operating conditions. These results reinforce the importance of adopting the PS-SS topology with a well-thought-out engineering design to achieve reliable and highly efficient wireless charging systems suitable for modern electric vehicle applications .

Keywords: *Wireless Power Transfer, PS-SS Topology Electric Vehicle Charging, Resonant Capacitance, ,MATLAB Simulation*

1. Introduction

In recent times, the shift toward electric vehicles has grown significantly as a cleaner alternative to internal combustion engines, aiming to support environmental goals and lower harmful emissions [1]. One of the prominent advancements in electric vehicle technology is inductive wireless charging, which facilitates power transfer without physical connectors And

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improves both user experience and system dependability [2]. Key parameters affecting wireless power transfer efficiency include coil geometry, separation distance, tuning frequency, and resonant capacitance [3].

Figure (1) illustrates a contactless energy transfer system for charging electric car batteries .

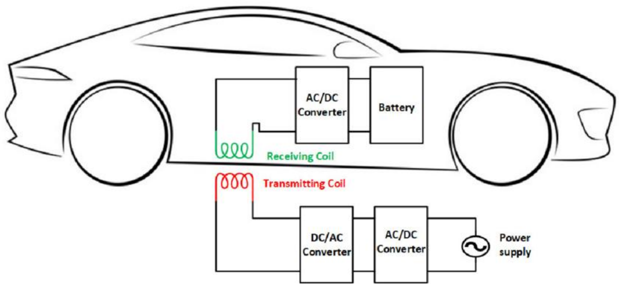

Fig. 1 Structureof the wireless charging system for electric vehicles

Ghazizadeh et al. (2023), designing the coils symmetrically and minimizing the air gap can significantly enhance the power transfer efficiency, with improvements reaching up to 15% [4]. WhileBenalia showed that (2024) Optimizing the resonance frequency can enhance system efficiency and lower energy dissipation during transmission [5]. Stankiewicz conducted et al. (2023) An experimental analysis of the effect of load resistance on the efficiency of a wireless power transmission system used in charging electric vehicle that As load resistance increases, efficiency improves up to a certain threshold, beyond which additional resistance results in performance decline.They also addressed the effects of leakage inductance and demonstrated that fine-tuning of circuit parameters such as load and capacitors plays a crucial role in achieving the highest possible efficiency [6]. Based on this background, this study aims to analyze the performance of a wireless power transmission system by modifying the values of the capacitance, and gap of the air coils, using accurate simulation to arrive at a design that achieves the highest possible efficiency with stable performance in an air environment .

2. Working Mechanism

A simulation model of wireless charging systems was developed using MATLAB The ,system consists of a flat circular transmitter coil, made of high-efficiency copper Litz wires connected to a high-speed MOSFET full-bridge inverter , which converts DC into sine wave with h igh frequency . The transmitting coil produces an oscillating magnetic field that is captured by a similar receiving coil mounted on the electric vehicle, which in turn converts .the captured energy into direct current, using a full bridge rectifier[7] Four operating conditions were tested, differing in coil dimensions and air gap between them, with two gaps

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of 80 mm and 120 mm being selected [8] , and the operating frequency was gradually changed ,between 10 to 250 kHz to observe the full response of the system for each operating condition with appropriate capacitors chosen to obtain resonance in each condition [9]. Figure)2(shows the topology of the main circuit of the wireless charging system.

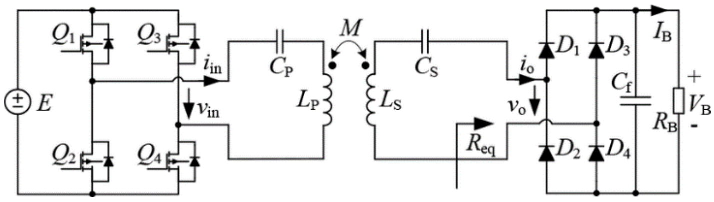

Fig. 2 Topologyof the main circuit of the wireless charging system

- ***Equivalent Circuit Contactless Charging System***

Figure (3) illustrates the simplified harmonic equivalent model of the proposed wireless charging circuit. This model is used to analyze the system performance at fundamental harmonic operation, focusing on the calculations of voltage and current at the fundamental frequency, which helps in understanding the dynamic behaviour of the circuit and improving efficiency. Figure (4) represents a helical coil for wireless power transmission

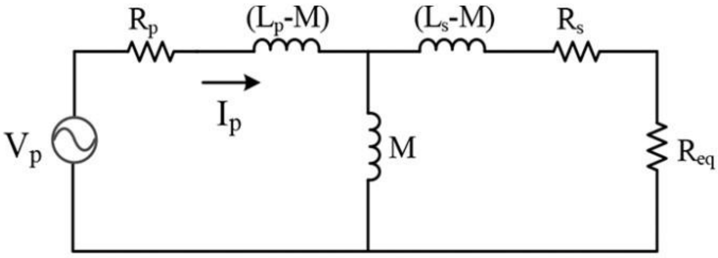

Fig. 3 Equivalent model of magnetic resonance wireless power transmission system

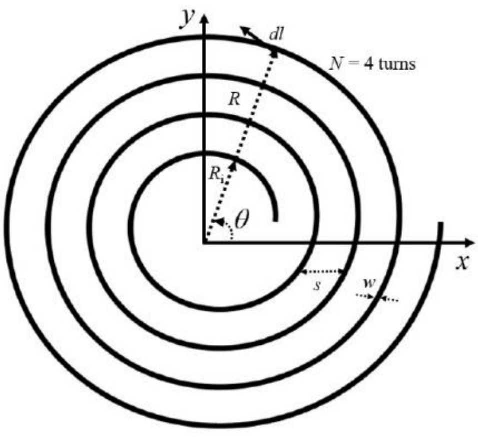

Fig. 4 Helical coil for wireless energy transfer

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$$L = \frac{\mu_0 N^2 (D_{out} + D_{in})}{20.3\ (15\ D_{out} - 7D_{in})} \quad (1)$$

$$M = \frac{\mu_0}{4\pi} \iint \frac{\overrightarrow{dl_1} \cdot \overrightarrow{dl_2}}{|\overrightarrow{r_1} - \overrightarrow{r_2}|} \quad (2)$$

$\overrightarrow{dl_1} \cdot \overrightarrow{dl_2}$ Where it represents linear vector differential elements along the paths of the first and second coils, and is used to calculate the magnetic differential between every two points on the current paths in both coils, and

$\overrightarrow{r_1} - \overrightarrow{r_2}$ presents the displacement vector between the positions of the differential elements in the first and second coils, and μ_0 is the permeability of the vacuum

$$\omega_o = \frac{1}{\sqrt{L_p C_p}} = \frac{1}{\sqrt{L_s C_s}} \quad (3)$$

Where: the resonant angular frequency

$$ip = \frac{4}{\pi}\frac{V_{dc}}{Z_r} \quad (4)$$

where ip :Primary coil current, V_{dc} : DC input voltage

$$V_{Cp} = \frac{4}{\pi}\frac{V_{dc}}{Z_r}\frac{1}{j\omega C_p} \quad (5)$$

Where V_{Cp}: Voltage across primary comensation on Capacitor

$$K = \frac{M}{\sqrt{L_p L_s}} \quad (6)$$

Impedance will be calculated based on the resistance, self inductance and mutual inductance btween the primary and secondary coils from equation)7(.

$$Z_e = Z_p + Z_m \,//\, Z_0 \quad (7)$$

Where Z_e It is the impedance of the primary the total impedance of the system (in ohms) Z_p coil (in ohms) and Z_m It is the connection impedance and Z_0it is the load impedance

$$P_{in} = |L_p|^2 Real(Z_e) \quad (8)$$

$$P_{out} = |i_s|^2 R_{ac} \quad (9)$$

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$$\eta_e = \frac{P_{out}}{P_{in}} = \frac{R_{ac}}{R_{ac}+r_s+r_p\frac{(R_{ac}+r_s)^2+(wL_s-1/wC_s)^2}{\omega^2 M^2}} \quad (10)$$

3. Results and Discussion

The theoretical and scientific study of all equations and curves presented in the paper was conducted using MATLAB. The program was used to simulate system behavior and analyze performance based on the mathematical relationships derived in the paper.

Table I: PARAMETERS VALUE OF COMPENSATION NETWORK.

Parameters	Symbol	Value
Equivalent load resistance (Ω)	R_L	10 ~ 80
Primary self-inductance (μH)	L_P	127
Secondary self inductance(μH)	L_S	127
Mutual inductance (μH)	M	35
Primary capacitance (nF)	C_P	8 ~ 40
Secondary capacitance (nF)	C_S	8 ~ 40
Operating frequency (KHZ)	f_s	0 ~ 250
Primary winding resistance (Ω)	r_p	0.2
Secondary winding resistance (Ω)	r_s	0.2
Number of turns of the transmitter coil	N_P	30
Number of turns of the receiver coil	N_s	30
Outer diameter of coil(mm)	d_{out}	300
Inner diameter of coil (mm)	d_{in}	40

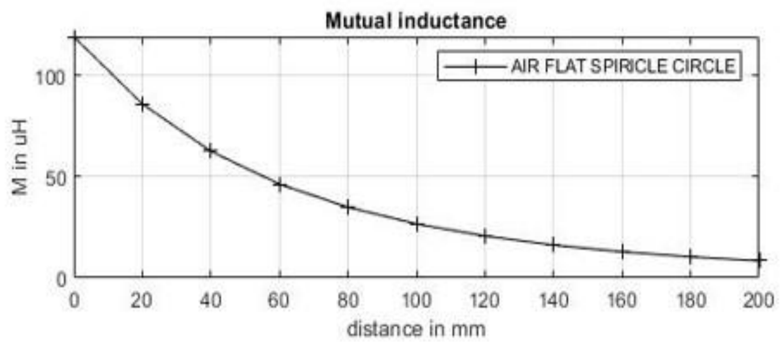

Fig. 5 : The relationship between mutual inductance as a variable for the air gap

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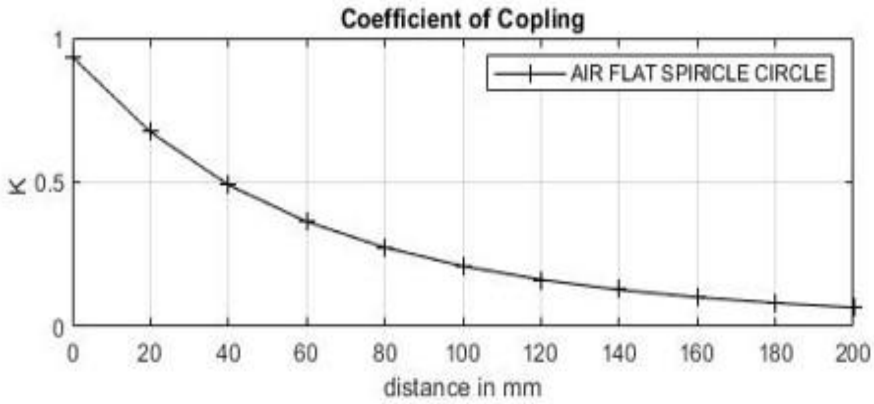

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Figure 6: The relationship between coupling coefficient as a variable for the air gap.

In Figure(5),(6) it appears that the mutual induction decreases nonlinearly with increasing distance, dropping sharply as the distance approaches 200 mm. In the lower curve, the ,coupling coefficient drops from a value close to 1.0 to less than 0.1 over the same range reflecting a sharp decline in magnetic transmission efficiency. These results represent significant design significance, as both coefficients are critical indicators of the efficiency of a wireless charging system. This analysis is typically used to determine the optimal operating distance for a system, as well as to determine the need for magnetic materials or coil shape .modifications to improve performance.

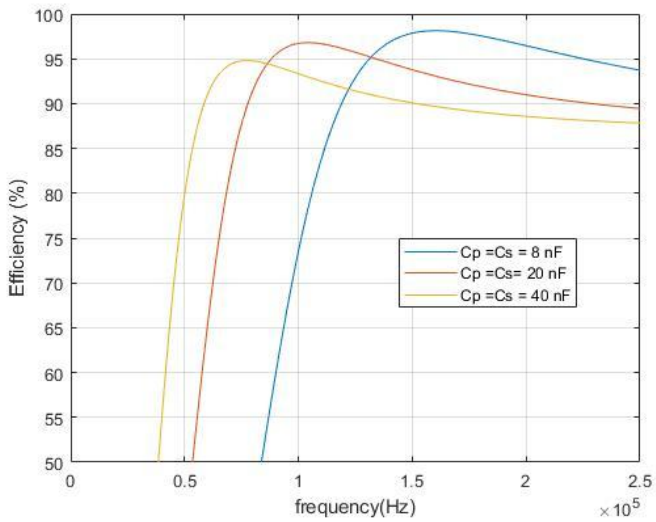

Figure 7: The effect of compensation capacity On the efficiency of wireless power transmission as a product of frequency change in an IPT system.

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Figure (7) shows the relationship between the operating frequency and the system efficiency in a wireless power transmission system operating with thePS-SS series compensation topology where the effect of changing the compensation capacitor capacitance values on both sides was analyzed , and the curve shows that each different value of capacitance leads to a different resonance point, which is the point where the maximum efficiency is achieved , and when the capacitance is 8 nanofarads , the maximum efficiency is at a frequency of about 150 kHz , exceeding 97% . At 20 nF , resonance is achieved at a lower frequency, but the maximum efficiency is less than 96% .

At 40 nF , the resonance frequency drops significantly, and the maximum efficiency decreases to approach 92%.

This figure indicates that there is an inverse relationship between the value of the compensating capacitor and the resonance frequency, and that efficiency is also affected by the nonlinear shape of this relationship. However, the system is operated at a frequency slightly above the resonance frequency to avoid high voltage spikes at the resonant frequency .

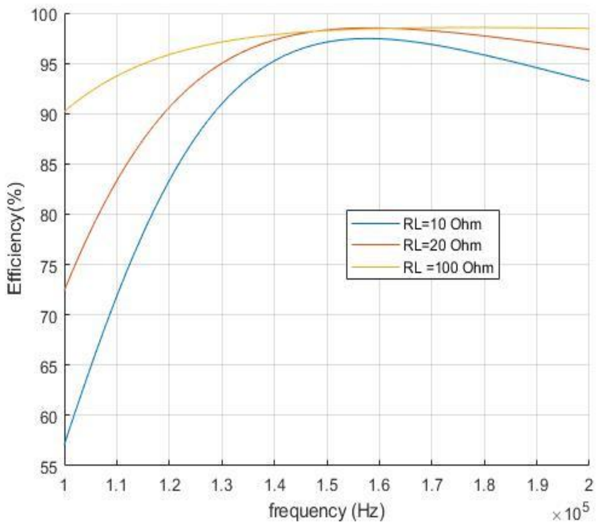

Figure 8:Compensation network efficiency as a function of operating frequency for different load resistances.

Figure (8) shows the dynamic response of the wireless power transmission system efficiency when using the PS-SS compensation topology, within an antenna medium with load resistance varying between 10 ohms, 20 ohms, and 100 ohms . It was observed that increasing the load resistance value led to a clear improvement in the overall system efficiency. In the case of RL = 100 ohms, a maximum efficiency of about 98% was achieved at the resonant frequency , reflecting a high compatibility between the load characteristics and the nature of

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electrical resonance. This is in line with the theoretical principles of resonant systems, where increasing the load resistance reduces circuit currents and thus reduces heat loss.

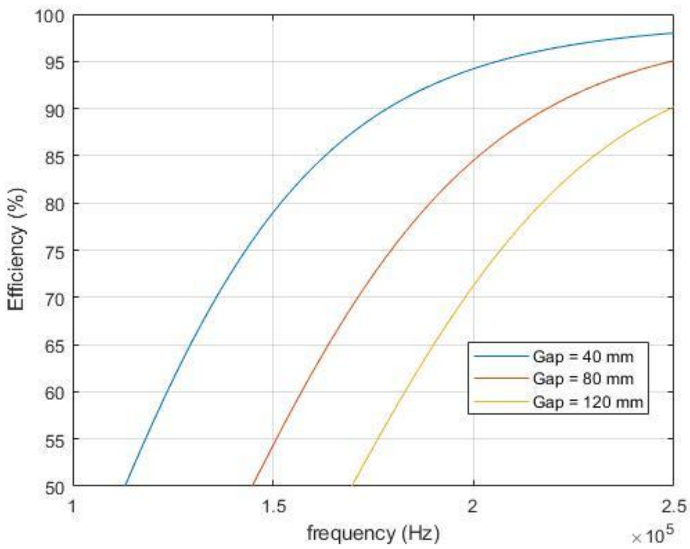

Figure 9: The effect of the air gap on the efficiency of the IPT wireless charging system.

Figure (9) shows the effect of three air gaps (40 mm, 80 mm, and 120 mm) on power transfer efficiency versus operating frequency. It is noted that reducing the air gap significantly improves efficiency, with a 40 mm gap achieving the best performance, reaching an efficiency ,of over 97%. This is due to the increased magnetic coupling coefficient at shorter distances .which reduces losses and increases the coupling effectiveness between the two coils Conversely, larger gaps reduce efficiency due to weaker coupling and increased magnetic leakage . In practical cases, the appropriate gap is selected based on the structural type of the vehicles to be charged.

4. Conclusion

Study demonstrated that the PS-SS topology provides an effective framework for building highly efficient wireless charging systems for electric vehicle batteries The analysis showed that reducing the air gap, tuning the resonant capacitance and taning the load resistance contribute to improving the ultimate system efficiency. A power transfer efficiency exceeding 96% was achieved under the best simulated operating conditions, enhancing the practical and widespread application of these technologies to support the development of wireless charging infrastructure for electric vehicles in the future

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