A Simulation-Based Driven Method to Design and Analysis of Wireless Power Transfer for Electric Vehicle Systems

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Abstract---In this research, we designed and optimized the wireless power transfer (WPT) systems for electric vehicles (EVs) through an extensive simulation approach. We focused on three major factors: the distance between the transmission coils and receiver coils, the review of the configuration of these coils and compensation topologies in both coils. We discovered that power transfer efficiency was maximum when the coils were placed close together, confirming numerical analysis. The best performance was achieved with 1.5cm airgap between the coils, by reducing distance beyond this point yielded only marginal improvements. Furthermore, our simulations showed that by using Series-Series capacitor in both the transmitter and receiver coils helped achieve resonance eliminating reactance, enhanced the coupling coefficient and the power transfer efficiency. These results offer practical insights into optimizing WPT systems, suggesting that both minimizing distance, carefully designing coil configurations and configuring the capacitors in both coils are pivotal in improving power transfer efficiency.

Index Terms---Electric Vehicle (EVs), Wireless Power Transfer (WPT), Compensation Networks, Series-Series Resonant Inductive Power Transfer (SS-RIPT)

I. INTRODUCTION & BACKGROUND

Wireless Power Transfer (WPT) technology was very first introduced by Nikola Tesla in the late 19th century, has now evolved from experimental analysis to an important component of modern energy applications, particularly in the area of electric vehicles (EVs)[1]. As the global shift in electrifying transportation sector induced, traditional wired charging methods present some limitations, including physical wear, safety risks, and user inconvenience. WPT setup supports different charging levels: Level 1 (120V AC), Level 2 (240V AC), and Level 3 (DC fast charging), each level offers varying rates of EVs. Level 1 is suitable for charging at home with slow charging rate, Level 2 provides faster charging rate suitable for residential and commercial usage, and Level 3, or DC fast charging, delivers rapid charging ideal for public charging stations[2]. WPT systems offer a transformative alternative by enabling contactless charging, which not only enhances user experience but also mitigates risks associated with physical connectors and mechanical wear. This technology is crucial for accommodating the high-power demands of fast charging while integrating seamlessly into various environments such as parking spaces and roadways. Key parameters in WPT design include the coupling coefficient, which measures the effectiveness of power transfer between the transmitter and receiver coils, and resonant frequency, which is tuned to compensate the reactance of both the coils. Power transfer efficiency, a critical performance metric, represents the ratio of the power received by the load to the power transmitted by the source. In the figure 1 a transmitter coil is installed in the road side and one receiver coil is installed in the chassis of EV and the batter is getting charged. Through this prototype we will be explaining each term in advance.

Among the various WPT techniques, inductive and capacitive methods are prominent. Inductive wireless power transfer (IPT) operates through magnetic fields

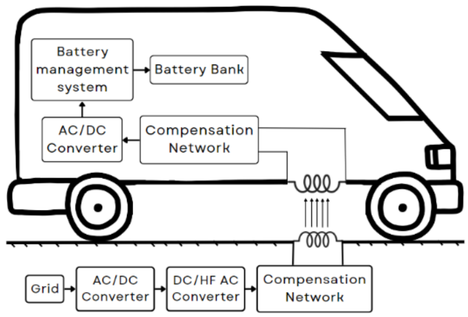


***Figure 1**:* The Schematic of WPTS

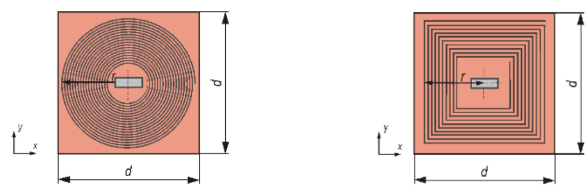
generated by alternating current in coils, while capacitive wireless power transfer (CWPT) uses electric fields between capacitive plates. In the context of EVs, the inductive method is particularly prevalent due to its efficiency and ease of integration[3]. Typically, inductive WPT systems consist of a transmitter coil installed in the ground and a receiver coil mounted under the vehicle. The EV's receiver coil aligns with the ground transmitter coil, enabling power to be transmitted without physical connectors.

WPT systems however have several limitations. They include maintaining high efficiency, alignment precision and managing thermal effects. Inductive Power Transfer can be grouped into three types: Static, Quasi-Static and Dynamic. Static IPT has fixed transmitter and receiver coils which are mainly used for stationary charging applications. Quasi-static IPT allows some movement between both coils thereby giving more flexibility in different charging scenarios. Dynamic IPT ensures continuous charging while a vehicle is moving properly hence representing the most advanced solution of overcoming charging problems[4]. All types have their own advantages and disadvantages that determine their applicability across various sectors. Therefore, addressing these challenges as well as optimizing such systems is essential in popularizing wireless charging technologies that strive to ensure convenience and better efficiency in EV charger infrastructure.

This paper article will be conducting investigations into the design and optimization of WPT systems for EVs using simulation-based approach, concentrating on how variations in coil distance, using compensation topologies and configuration of coils affect performance. The aim is to provide valuable insights into enhancing WPT system efficiency and practicality through exploration of these factors through simulations, leading to more effective and reliable solutions in EV charging.

II. Types of Coils Used in WPT System for EVs

Coils are an integral part of these systems known as Wireless Power Transfer (WPT) circuits in EVs, their design and configuration play a key role to improve performance for the best possible efficiency. Different coils are used, each providing distinct benefits depending on the application. Static WPT systems used in home or public charging stations use planar coils mainly circular, squared which are placed parallel to each other and aligned flatly. If the transmitter and receiver Coils are well-aligned, their parallel alignment works better resulting in maximizing power transfer Efficiency.



(a) (b)

Figure 2: Circular Planar Coil (b) Square Planar Coil

Solenoid Coils are a type of coil having helical wire wound to generate an intense magnetic field for high power or dynamic applications, where focused magnetic fields are preferred [6]. These coils are placed perpendicularly to the vehicle's direction of travel in order to provide optimal high-power transfer with coupling.

Figure 3: Copper Solenoid Coils

Circular coils are also known for their symmetrical magnetic field distribution and they can be arranged both in parallel or perpendicular fashions depending on the application. In stationary settings, circular coils aligned in parallel to optimize the coupling when the vehicle is parked. For dynamic situations, such as on-road charging where the vehicle is in motion, these smaller circular coils are employed perpendicularly to adapt to varying distances and alignments.

The size and configuration of these coils highly impact their performance; larger coils offer better coupling and efficiency in static systems but require more space, while smaller coils are arranged perpendicularly and can provide greater flexibility in dynamic systems[7]. Selecting the appropriate coil type, size, and orientation is important for achieving nominal wireless power transfer, as advancements in coil design and materials must continue to enhance the practicality and efficiency to solve EV charging.

III. WIRELESS POWER TRANSFER IN EV:

Power is supplied through the ac source 240V and then a rectifier converts this ac current in the dc with power factor correction (PFC). This dc current is then converted back to a high frequency (30KHz) ac current using HF inverter. There are two types of IPT closely and loosely coupled. The loosely coupled coils then creates a mutual inductance with a factor of coupling coefficient (k) and the power is then transferred to the secondary coil (EV side).

$$k = \frac{M}{\sqrt{L_1 L_2}}$$

This power is again converted to the dc current and then the battery of EV is charged. The efficiency before the power transfer is ~95% and after the power transferred it is ~90%. The overall efficiency remains above 90%. In the next sections first, we will discuss the compensation networks then will discuss the design on actual parameters and in the third section we will prove through simulations and will verify the coupling coefficient and the mutual inductance dynamically by varying distance between the coils.

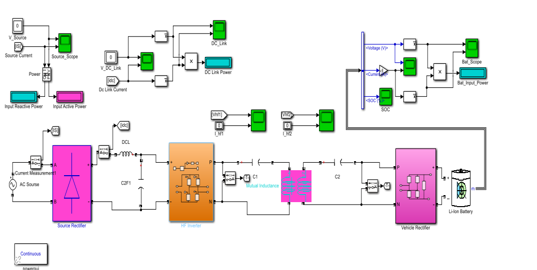


Figure 4: Circuit Configuration in MATLAB/Simulink

IV. Compensation Networks IN EV:

Compensation networks are essential in Wireless Inductive Power Transfer (IPT) systems in maximizing the power transfer efficiency from the primary to the secondary coil by achieving and maintaining resonance. Resonance only occurs when the inductive reactance and capacitive reactance in the coils cancel out each other, resulting in the pure resistive circuit that allows the maximum power transfer. Primary and secondary compensation networks, such as Series-Series (SS), Series-Parallel (SP), Parallel-Series (PS), and Parallel-Parallel (PP) topologies, are used to configure the system to the resonant frequency, thereby enhancing efficiency and effectiveness[8]. For instance, the primary capacitor neutralizes the overall reactance, while the secondary capacitor maximizes power transfer to the load. Notably, PS and PP topologies include protective features that prevent the source coil from operating without the receiver coil, thus safeguarding the system. Misalignment between coils and load variations can disrupt resonance, so adaptive compensation networks are often employed to dynamically adjust the capacitors, ensuring consistent performance and efficient power transfer.

IV. Design of EV charger:

We aim to design an 8KW WPT, the electrical parameters are calculated as the charger supply voltage is 240V rms voltage and after rectification it is converted to 30KHz high frequency signal by ac-dc and dc-ac using Rectifiers and HF inverter demonstrated as:

The inductance for first coil is 266.16 (µH) and second coil inductance is 256.79 (µH). And for the instance the value of mutual inductance is taken as 85.46 (µH) and further the effect of varying distance on mutual inductance will be later verified. The high frequency ac current then passes through the magnetic linkage with the coupling coefficient:

$$k = \frac{85.46}{\sqrt{266.16 \times 256.76}}$$

The value of coupling coefficient was found to be k=0.3269. And the power transferred will be the multiple of this factor. The series capacitor on the both primary and secondary coils is introduced to create a resonant effect. The primary capacitor value is 105.79nF and secondary capacitor value is 109.69nF.

$$f = \frac{1}{2\pi\sqrt{LC}}$$

Using above equation, f1= 29.993kHz and f2= 29.993Hz and the resonance will be achieved and reactance will be cancelled out and only resistive opposition is left that leads to maximum power transfer. Once the power has been transferred then it is converted back to dc current using rectifier circuit and the battery is the charged having the nominal voltage 360V and the size of 100Ah.

Table 1: Circuit parameters

Parameters	Values (except battery all are peak values)
V_{source}	$325V$
I_{source}	$34A$
$V_{Road\ side}$	$400V$
$I_{Road\ side}$	$24A$
$V_{Vehicle\ side}$	$350V$
$I_{Vehicle\ side}$	$20A$
$V_{Battery}$	$360V$
$I_{Battery}$	$13A$

V. SIMULATIONS:

Simulations were done on the MATLAB Simulink Version 10.1 (R2020a) and FEMM and are perfectly aligned with the expected values. The figure shows the waveforms of source currents and voltages:

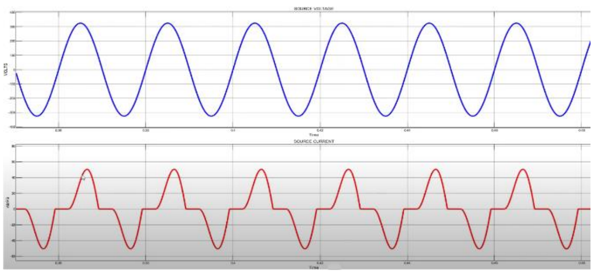


Figure 5: Source Voltage and Current

after the power has been converted into high frequency ac using HF inverter has been shown below:

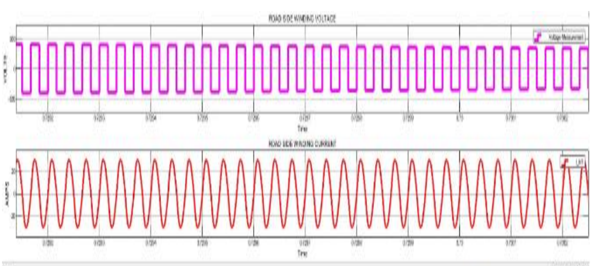


Figure 6: Current and voltages after HF Inverter

The current reaches the secondary coil through magnetic flux and has been shown below:

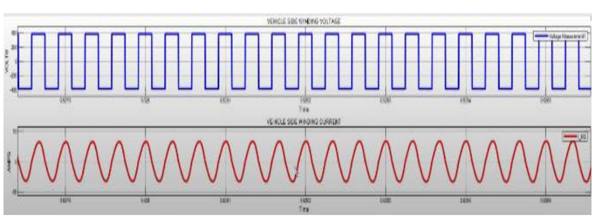


Figure 7: Parameters at secondary Coil

after passing through the rectifiers again it is converted to the dc to charge the battery. The battery has shown the following voltages and currents:

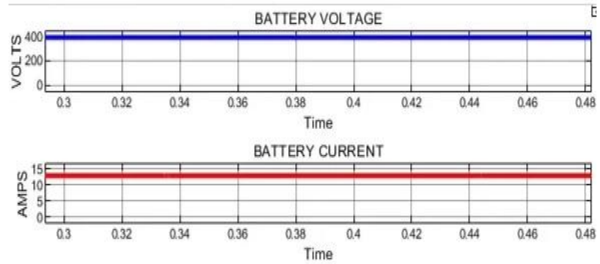


Figure 8: Battery Voltage and Current

VI. Varying airgap between coils:

We used FEMM 4.2 to simulate the mutual inductance for this IPT. Below is the Table that shows the mutual inductance between both coils with the varying air gap and the figure shows the graphical trend of changing mutual inductance and the black dotted line represents the trend of change with respect to the air gap distance

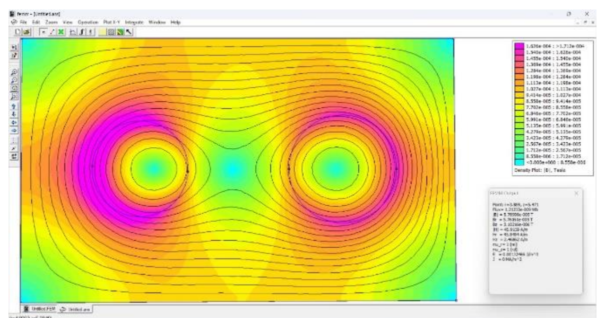


Figure 9:Graphical Trend of changing Mutual inductance

Table II: Mutual inductance between both coils with the varying air gap

No.	Airgap Distance (cm)	Mutual Inductance (µH)
1	1.5	286.466
2	3.0	135.317
3	4.5	63.919
4	6.0	30.193
5	7.5	14.262
6	9.0	6.737
7	10.5	3.182

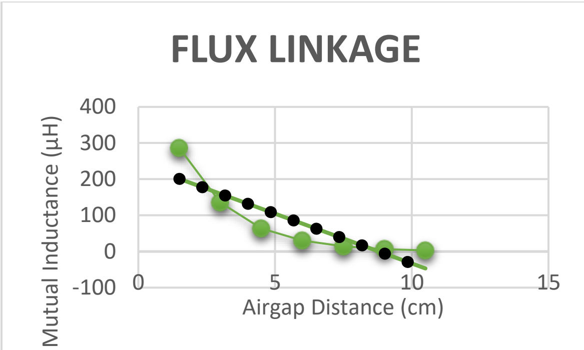


Figure 10: Flux Linkage between Coil

VII Conclusion:

Employing a quite precise design and analysis is crucial in wireless power transfer (WPT) systems for electric vehicles (EVs). In fact, we found out that reducing the air gap between the transmitting as well as receiving coils are important to enhancing power transfer efficiency with best results aimed at 1.5cm air gaps. Also, these results showed that carefully placing the coils and the configuration of compensation networks are crucial to maximize the efficiency of WPT systems. Furthermore, such findings reveal that reactance could be reduced when there is an addition of Series-Series compensation network both on receiving and transmitting coil sides which enhance resonance that eventually improves coupling coefficient. Simulated EV charging strategy has provided through this insight a good starting point for research aimed at advancing EVs charging technology and area to consider in practical applications for tuning WPT systems to fit majority of EV infrastructures.

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