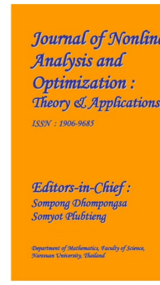
Journal of **N**onlinear **A**nalysis and **O**ptimization
Vol. 16, Issue. 1, No.2 : 2025
ISSN : **1906-9685**



ANALYSIS OF POWER TRANSFER IN WIRELESS MODE

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ABSTRACT:
Electric Vehicles (EVs) have emerged as a promising alternative to conventional gasoline-powered vehicles, offering environmental benefits and lower operating costs. However, a key challenge hindering the widespread adoption of EVs is their limited range due to battery energy storage constraints. We recognize the challenges in current EV technology and aim to overcome range limitations. WPT technology presents a compelling solution to this challenge by enabling convenient and efficient EV charging without the need for physical wires or connectors.
Keywords
- Electric Vehicle
- Wireless Power Transfer
- Charging System

INTRODUCTION:
The primary objective of this paper is to develop a highly efficient WPT system that can effectively transmit power for EV battery charging without the need conventional cables or conductive wires. Through a combination of analysis and practical experimentation, the paper aims to foster the widespread adoption and contributing to the sustainability goals of the automotive industry.

1. Explore WPT Technologies: Investigate and analyze inductive coupling, resonant coupling, and magnetic resonance coupling to determine their suitability for efficient wireless EV charging.
2. Optimize Power Transfer Efficiency: Develop methods to enhance power transfer efficiency through the utilization of resonant circuits and active power converters in the WPT system.

A. Sagar et al. [1] focused on the evolving Electric Vehicle (EV) market, driven by the demand for more efficient battery recharge methods. Wireless Power Transfer (WPT) methodology, eliminating the need for direct physical interaction, overcomes drawbacks associated with conventional conductive systems. Laura A. Walker et al. [2] conducted a comparative study of different coil geometries in wireless power transfer for electric vehicles. It explores the impact on coupling efficiency, magnetic field distribution, and overall system performance. Advantages discussed include increased spatial flexibility, reduced sensitivity to misalignments, and the potential for standardized coil designs. Alan B.Walker et al [3] compared comprehensive comparison between inductive and resonant coupling in wireless power transfer systems for electric vehicle charging. Through experimental analysis, the authors highlight the advantages and limitations of each approach, aiding in the selection of the most suitable technology for specific EV charging scenarios. Daniel C.White etal[4] investigated investigates the application of high-frequency switching techniques in wireless power transfer systems, emphasizing their role in power generation. The study explores how precise control of switching frequencies enhances power transfer efficiency and overall system performance. The findings contribute to the development of more reliable and efficient wireless charging systems for electric vehicles. David R. Clark etal [5] explored the seamless integration of wireless power transfer technology with smart grids to create an intelligent electric vehicle charging infrastructure. The study discusses how this integration enhances grid efficiency, optimizes charging schedules, and contributes to the overall sustainability of electric transportation systems. Anthony J.Turner [6] focussed on safety aspects, this paper provides a comprehensive review of potential hazards and safety considerations associated with wireless electric vehicle charging. The study addresses concerns related to electromagnetic fields, thermal issues, and outlines safety protocols and standards. A thorough understanding of safety considerations is crucial for the widespread acceptance of wireless charging technology.

WIRELESS POWER TRANSFER TECHNIQUES:

Wireless Power Transfer (WPT) techniques have emerged as innovative solutions to address the limitations of traditional wired power transmission systems. In the realm of technological advancements, WPT has garnered significant attention for its potential to revolutionize various industries. This transformative approach eliminates the need for physical connectors and enables the transmission of electrical energy over the air, contributing to increased convenience, mobility, and efficiency. Several WPT methods, such as electromagnetic induction, resonant inductive coupling, and radiofrequency energy harvesting, have been developed to cater to diverse applications ranging from consumer electronics to electric vehicles. The first period was related to Maxwell and Hertz. In 1873, Maxwell presented the equation for electromagnetic energy transmission in free space. Around 1885-1889, Hertz, through a series of experiments, verified Maxwell's predictions and the presence of electromagnetic radiation.

The second period is mostly associated with Nikola Tesla, the creator of Alternating Current (AC) and polyphase systems. Tesla aimed to transfer energy to any point on Earth by using the Earth and its atmosphere as a conductor. In 1896, Tesla transmitted microwave signals over a distance of 48 km, and between 1891 and 1904, he conducted numerous investigations on electromagnetic and electrostatic energy transmission.

Inductive Coupling WPT:

This Wireless Power Transfer (WPT) method relies on inductive coupling between two coils, operating in the near field. It utilizes mutual induction, where two coils in close proximity transfer energy without physical connection. This concept, seen in devices like electric brushes and charging pads, is simple and reliable but has limitations such as a short range (a few cm) and limited separation distance.

For optimal performance, the goal is to generate a high induced voltage, as per Faraday's Law. This involves maximizing the rate of change of flux in the secondary coil. To meet this, the primary coil should generate a magnetic field that mostly traverses the secondary coil. The frequency of the magnetic field should be as high as possible for near-field operation. While larger coils are preferred for the secondary side, practical applications impose size, weight, and cost constraints, particularly in biomedical and Electric Vehicle (EV) applications. Notably, WPT for EVs relies on advanced technologies beyond traditional inductive WPT.

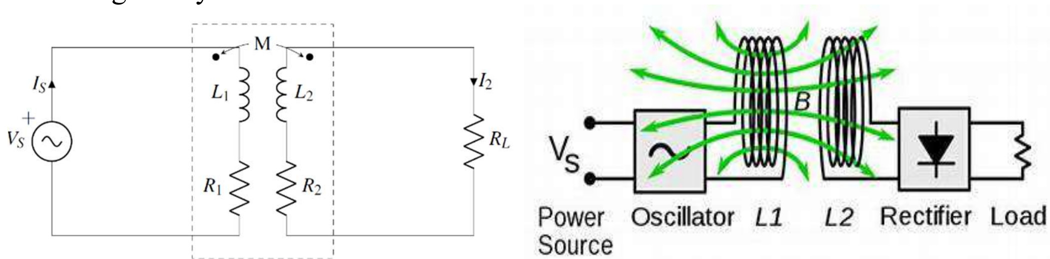

Figure 1**:** Equivalent Circuit and Coupling Diagram for Inductive WPT

Magnetic Resonance Coupling WPT:

Magnetic Resonance Wireless Power Transfer (WPT) is an advancement over inductive WPT, operating under resonant conditions. In this method, a pair of coils is connected to structures containing reactive elements like capacitors or additional coils, known as compensation networks. Compensation topologies can be simple, involving a single capacitor connected in series or parallel, referred to as mono-resonant, or more complex, known as multi-resonant.

This approach addresses some drawbacks of non-resonant inductive coupling in near-field power transfer. By utilizing resonance, where the natural and excitation frequencies match, maximum energy transfer occurs between coils. The receiver and transmitter coils are tuned to the same resonant frequency, allowing significant power transfer over an increased distance, typically up to 10 times the diameter of the transmitting coil. Magnetic resonance coupling offers advantages such as increased efficiency, reduced radiation, power loss, and directional transmission, but it is limited by the need for precise resonance frequency matching and is not suitable for long-range applications.

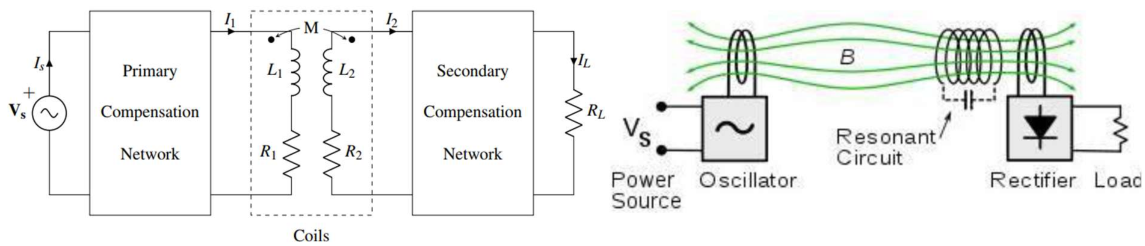

Figure 2: Equivalent Circuit and Coupling Diagram for Magnet Resonance WPT

CHARGING SYSTEM OF ELECTRIC VEHICLE USING WPT:

Due to the current environmental crisis, there is great interest in developing new trends in the sustainable transportation sector. In this context, EVs are expected to significantly decrease greenhouse gas emissions and, in turn, lead to a healthier living environment.

Battery Electric Vehicle (BEV): Power exclusively comes from batteries to drive the vehicle, with no Internal Combustion Engine (ICE) system.

Hybrid Electric Vehicle (HEV): These vehicles have two or more energy sources or storage types, with one being electric. Commonly, it combines an ICE with an electric powertrain activated by a battery. The system used depends on driving conditions, utilizing the electric component at low speeds and the ICE at high speeds. Both systems may work together for enhanced performance.

Plug-in Hybrid Electric Vehicle (PHEV): This vehicle primarily relies on the electric powertrain and switches to the ICE when needed, such as when the battery level is low, to extend the range. The battery can be directly charged when the vehicle is connected to the electrical grid.

Battery specifications vary by manufacturer. Table 1 displays key properties of batteries in popular Electric Vehicles (EVs).

Model	Vehicle type	Battery size (kWh)	Energy available (kWh)	Range (km)	Energy consumption (kWh/km)
Nissan Leaf	EV	39.5	37	240	0.165
Toyota RAV4	EV	41.8	32.18	160	0.20
Volkswagen Golf-e	EV	35.8	32	190	0.168
BMW i3	EV	33	27.2	200	0.13
Tesla Model 3 standard range	EV	55	46	310	0.148
Tesla Model S performance	EV	100	95	510	0.186
Audi e-tron	EV	95	83.6	360	0.232
Chevrolet Volt	PHEV	17.1	13.7	64	0.21
Toyota Prius	PHEV	8.8	7	40	0.175
Mitsubishi Outlander	PHEV	13.8	11	37	0.29
BMW 530e	PHEV	9.2	8	34	0.237

Table1**:** Properties of Batteries in Popular EVs

MATHEMATICAL MODELLING:

The primary aim is to model a advanced wireless power transfer system for charging the battery of EVs. The design sizing methodology employed is Series-Series (SS) topology for the Wireless Power Transfer (WPT) system. This methodology plays a crucial role in determining the optimal specifications for the WPT system, particularly in the context of its resonance frequencies at 40 kHz and 85 kHz. Considerations and steps undertaken in the design optimization process, shedding light on how the SS topology is tailored to meet the specific power requirements. These systems operate at resonant frequencies of both 40 kHz and 85 kHz, and their feasibility and performance are assessed for light-duty Electric Vehicle (EV) applications in the Grid-to-Vehicle (G2V) charging mode.

The bidirectional WPT system of SS-compensated topology is shown in Figure 3. The specific design steps for the SS topology of the WPT system are explained,

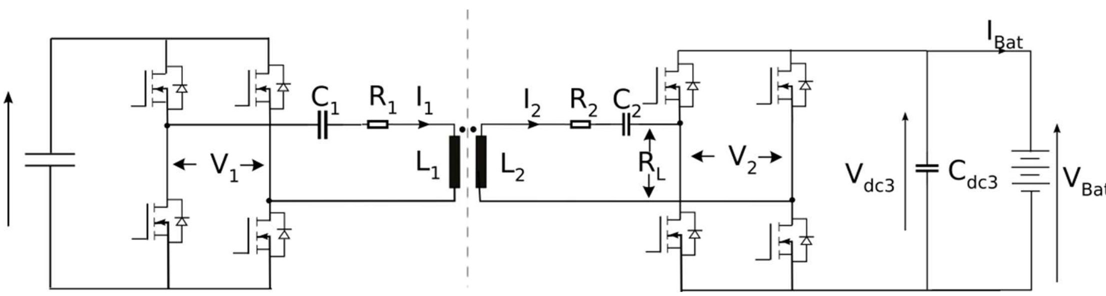

Figure 3: Bidirectional Wireless System Model for SS Topology

An equivalent circuit model of a WPT system with compensation capacitors arranged in an SS topology is shown in Figure 5.3.For simplification, the equivalent source resistance is neglected. Here, the subscripts "1" and "2" refer to the "primary" and "secondary" coil values of inductor L, resistance R, and capacitance C, respectively. V_1 is the source voltage of the primary circuit. R_L is the equivalent load resistance. I_1 is the source current flowing through the primary coil, and I_2 is the load current flowing through the secondary coil.

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The degree of the coupling between two coils can be expressed with the coupling coefficient*k*, which has a value ranging from 0 to 1, and is defined by Equation (5.1).*M* represents the mutual inductance between the primary and secondary coils.

$$k = \frac{M}{\sqrt{L_1 \times L_2}} \qquad (1)$$

The voltage equations in Figure 4 can be written using the mutual inductance, M. ω is the frequency of V_1.

$$V_1 = \left(\frac{1}{j\omega C_2} + j\omega L_1 + R_1\right) I_1 - j\omega M I_2 \qquad (2)$$

$$V_2 = j\omega I_1 \left(\frac{1}{j\omega C_2} + j\omega L_2 + R_2\right) I_2 \qquad (3)$$

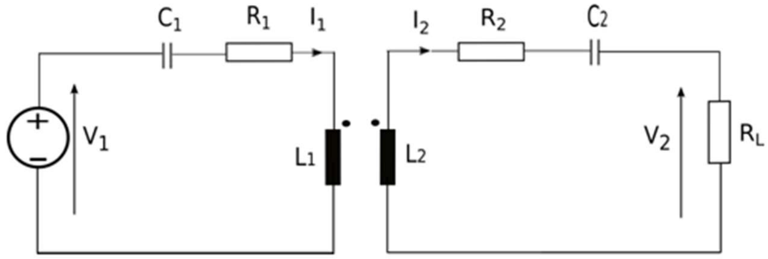

Figure 4: Equivalent Circuit Model for SS Topology

The resonant frequencies ω_0 at the primary coil and the secondary coil are assumed to be equal to

$$\omega_0 = \frac{1}{\sqrt{L_2 \times C_2}} = \frac{1}{\sqrt{L_1 \times C_1}} \quad (4)$$

At the perfect resonant frequency ω_0, Equation (2) and (3) can be rewritten as Equation (5) and (6) respectively

$$V_1 = R_1 I_1 - j\omega_0 M I_2 \quad (5)$$

$$V_2 = j\omega_0 M I_1 - R_2 I_2 \quad (6)$$

In Figure 3, the delivered power to the load P_L and the transfer efficiency η at the resonant frequency ω_0 can be obtained Equations (7) and (8)

$$P_L = \frac{\omega_0^2 M^2 V_1^2 R_L}{[R_1(R_L+R_2)+\omega_0^2 M^2]^2} \quad (7)$$

$$\eta = \frac{\omega_0^2 M^2 R_L}{R_1(R_L+R_2)^2 + \omega_0^2 M^2 (R_L+R_2)} \quad (8)$$

By defining the quality factor of the primary and secondary coils as Equations (9)

$$Q_1 = \frac{\omega L_1}{R_1} \quad (9)$$

$$Q_2 = \frac{\omega L_2}{R_2} \quad (10)$$

So the transferred efficiency Equation (7) replaced by Q_1 and Q_2 can be rewritten in Equation (11)

$$\eta = \frac{R_L}{\frac{(R_L+R_2)^2}{k^2 Q_1 Q_2 R_2} + R_L + R_2} \quad (11)$$

The maximum transmission efficiency η_{max} of the WPT system can be derived as:

$$\eta_{max} = \frac{k^2 Q_1 Q_2}{(1+\sqrt{1+k^2 Q_1 Q_2})^2} \quad (12)$$

From Equation (12), the maximum efficiency increases as $k^2Q_1Q_2$ increases. It should be noted that the maximum efficiency of a WPT system is limited by the product of the coupling coefficient k and the inductor quality factor Q. Therefore, the foremost design consideration in a WPT system is the attainment of the higher possible Q and k. These two vital parameters are functions of the shape, size, and the relative position of the primary and secondary coils. The main goal in the design of a WPT system is to achieve maximum efficiency and to optimize the power transfer capability according to the operating conditions. In EV wireless charging applications, the battery is usually connected to the coil through a diode-bridge rectifier or via a controlled converter. The battery could be represented as a resistance $R_b = U_b/I_b$, where U_b and I_b are the battery voltage and current, respectively. If the battery is connected to the rectifier directly in an SS-compensated WPT system, the equivalent AC side resistance R_L could be calculated by Equation (12).

Thus, a battery load could be converted to an equivalent resistive load.

$$R_L = \frac{8}{\Pi^2} \times R_b$$

RESULTS:

A series-series (SS) topology with resonant coupling to facilitate wireless power transfer (WPT) has been implemented. This section delineates our process of model creation using Simulink to emulate this specific configuration for WPT.

After successfully testing the physical model, we observe that the battery of the electric vehicle (EV) indeed gets charged as intended. This outcome validates the effectiveness of our wireless charging system with the demonstrating that the electromagnetic induction between the transmitter and receiver coils efficiently transfers power to the EV's battery while it's in motion over the road surface.

CONCLUSION:

This paper provides a comprehensive understanding of Wireless Power Transfer technologies, their optimization strategies, and their specific applications with a focus on the development of an Advanced Wireless Power Transfer System for EV charging.

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