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DESIGN AND ANALYSIS OF WIRELESS POWER TRANSFER SYSTEM FOR ELECTRIC VEHICLES WITH EFFICIENCY AND SAFETY EVALUATIONS

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Abstract: Wireless Power Transfer (WPT) is an emerging technology that enables electric vehicle (EV) charging without physical connectors, improving convenience, safety, and reliability. This project presents the design and analysis of three major WPT technologies: Inductive Power Transfer (IPT), Capacitive Power Transfer (CPT), and Hybrid Power Transfer (HPT). The systems are evaluated based on efficiency, waveform performance, misalignment tolerance, electromagnetic field exposure, and practical implementation using MATLAB/Simulink models. The study focuses on the use of resonant compensation techniques to improve power transfer capability under varying operating conditions. The effect of airgap variation and coil misalignment on system performance is also analyzed. In addition, the project investigates system losses, voltage and current characteristics, and safety considerations associated with wireless charging. Comparative analysis of the three methods is carried out to identify their advantages and limitations for EV applications. The research concludes that IPT provides higher efficiency, stable operation, lower EMF exposure, and simpler implementation compared to CPT and HPT systems. CPT and HPT offer advantages in compactness and coupling improvement but face limitations related to high-frequency operation and increased complexity. Overall, the study identifies IPT as the most practical and reliable wireless charging technology for present electric vehicle applications.

***Index Terms* -** Wireless Power Transfer (WPT), Inductive WPT (IPT), Capacitive WPT (CPT), Hybrid WPT (HPT).

I. INTRODUCTION

The rapid growth of electric vehicles (EVs) in recent years has increased the demand for advanced charging technologies that are efficient, safe, reliable, and user-friendly.

Conventional plug-in charging systems require physical connectors and cables, which may suffer from wear and tear, sparking, corrosion, maintenance issues, and safety risks under harsh environmental conditions. In addition, manual plug-in charging may not be convenient for autonomous vehicles and future smart transportation systems. To overcome these limitations, Wireless Power Transfer (WPT) technology has emerged as an effective solution for transferring electrical energy without direct physical contact between the power source and the load. Wireless Power Transfer is a technology in which electrical power is transferred from the source side to the receiving side through an air gap using electromagnetic fields. In electric vehicle charging applications, WPT improves convenience, reduces human intervention, enhances safety, and enables automatic charging systems. The technology also reduces cable management problems and increases system reliability. Due to these advantages, WPT has become an important research area in modern electric transportation systems. WPT systems for EV charging are mainly classified into three major technologies: Inductive Power Transfer (IPT), Capacitive Power Transfer (CPT), and Hybrid Power Transfer (HPT). Inductive Power Transfer uses magnetic field coupling between transmitter and receiver coils to transfer power wirelessly. IPT is the most widely adopted method because of its high efficiency, stable operation, good power transfer capability, and compatibility with international EV charging standards such as SAE J2954 and IEC 61980. It operates effectively at lower frequencies and provides smoother voltage and current waveforms with lower electromagnetic interference. Capacitive Power Transfer uses electric field coupling through capacitive plates for transferring power. CPT systems are lighter in structure and can reduce the size of magnetic components. However, CPT requires very high operating frequencies and voltages to achieve sufficient power transfer, which may increase electromagnetic interference (EMI), switching losses, and safety concerns. In addition, CPT performance is significantly affected by air-gap variations and alignment conditions. Hybrid Power Transfer combines both inductive and capacitive coupling mechanisms to improve overall system performance. HPT systems are designed to enhance power transfer capability and misalignment tolerance by utilizing the advantages of both IPT and CPT methods. Although HPT systems provide improved coupling characteristics, they also introduce additional circuit complexity, complicated control requirements, and increased implementation cost.

In WPT systems, resonant compensation networks play an important role in improving power transfer efficiency under loosely coupled conditions. High-frequency inverters are used to generate alternating current at suitable operating frequencies, and resonant circuits are designed to minimize reactive power losses and maximize energy transfer between the transmitter and receiver sections. Parameters such as coupling coefficient, resonant frequency, air-gap distance, coil alignment, waveform quality, and electromagnetic field exposure significantly affect the overall performance of the system. Therefore, detailed analysis and optimization of these parameters are necessary for efficient wireless charging operation. This project focuses on the design and comparative analysis of IPT, CPT, and HPT systems for electric vehicle charging applications using MATLAB/Simulink models. The systems are evaluated based on important performance parameters such as efficiency, transferred power, voltage and current waveforms, system losses, misalignment tolerance, electromagnetic field exposure, and safety aspects. The impact of air-gap variation and lateral misalignment on wireless power transfer capability is also investigated. Furthermore, the project studies the practical implementation challenges associated with each technology, including high-frequency operation, electromagnetic interference, and thermal effects. The main objective of this work is to identify the most practical, efficient, and reliable WPT technology for present and future EV charging applications. Through detailed simulation and performance comparison, the research aims to provide a better understanding of wireless charging technologies and support the development of safer and more efficient electric vehicle charging systems.

II. PROPOSED METHODOLOGY

The proposed methodology of this project is based on the design and simulation of Wireless Power Transfer (WPT) systems for Electric Vehicle (EV) charging using MATLAB/Simulink. The work mainly focuses on analyzing and comparing Inductive Power Transfer (IPT), Capacitive Power Transfer (CPT), and Hybrid Power Transfer (HPT) systems under practical operating conditions. Initially, the AC input supply is converted into DC using a rectifier and filter circuit. The obtained DC voltage is then supplied to a high-frequency inverter, which converts the DC power into high-frequency AC power required for wireless energy transfer. Resonant compensation circuits are connected on both transmitter and receiver sides to achieve resonance and improve power transfer efficiency by reducing reactive power losses.

In the IPT system, wireless power transfer takes place through magnetic coupling between the primary and secondary coils. The high-frequency alternating current flowing through the transmitter coil produces a magnetic field, which induces voltage in the receiver coil. The received power is rectified and filtered before supplying it to the EV battery or resistive load.

In the CPT system, capacitive plates are used instead of coils to transfer energy through electric field coupling. High-frequency AC voltage creates an electric field between the transmitter and receiver plates, enabling wireless power transfer across the air gap.

The HPT system combines both inductive and capacitive coupling methods to improve power transfer capability and misalignment tolerance. The hybrid structure utilizes both magnetic and electric field coupling to enhance overall system performance. MATLAB/Simulink models are developed for all three systems to observe voltage and current waveforms, transferred power, efficiency, switching performance, and system losses.

The simulation outputs obtained from the model show stable waveform characteristics and efficient power transfer under resonant operating conditions. The effects of air-gap variation and lateral misalignment are also analyzed to evaluate system reliability under practical EV charging conditions. Furthermore, electromagnetic field (EMF) exposure and safety aspects are studied to ensure safe operation of the wireless charging system. Based on the comparative analysis of simulation results, the efficiency, waveform stability, implementation complexity, and practical suitability of IPT, CPT, and HPT systems are evaluated. The research concludes that the IPT system provides better overall performance, higher efficiency, and safer operation compared to CPT and HPT systems for present EV charging applications.

The Fig.1 shows an Inductive Wireless Power Transfer (IWPT) system based on magnetic coupling between transmitter and receiver coils. The input AC source is processed by the PFC stage to maintain a high power factor and generate a stable DC link voltage V_i . Capacitor C_1 filters the DC voltage, while switches M_1–M_4 form a full-bridge inverter that produces high-frequency AC excitation. The resonant compensation components L_1 , L_2 , C_2 , and C_3 help achieve resonance for efficient power transfer. The primary coil L_3 generates an alternating magnetic field, which induces power into the secondary coil L_4through mutual inductance M with a turns ratio of 1: . Capacitors C_4 and C_5 provide resonance compensation to maximize transferred power and reduce switching losses. The received AC energy is rectified by the diode bridge D_1–D_4, filtered by capacitor $C_6$and inductor L_o, and then supplied as a regulated DC output voltage $V_{out}$to the load. IWPT systems are widely used in electric vehicle charging, biomedical implants, and consumer electronics because of their high efficiency and safe contactless energy transfer capability.

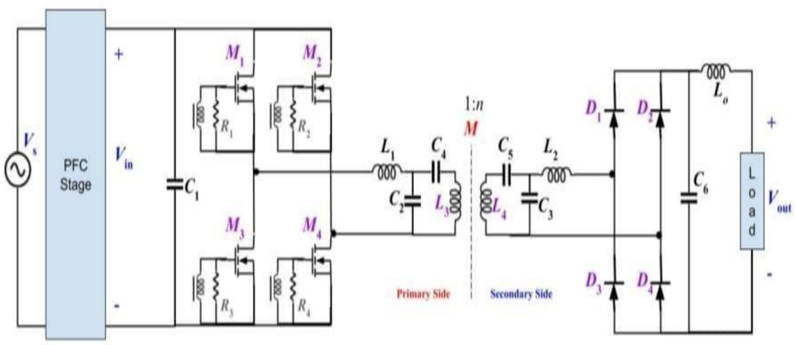

Fig.1 Circuit diagram of IPT

The below Fig.2 illustrates a Capacitive Wireless Power Transfer (CWPT) system, where electrical energy is transferred through electric field coupling between metal plates instead of magnetic coils. The AC supply V_s is converted into regulated DC power through the PFC stage and filtered by capacitor C_1 . The full bridge inverter formed by switches $M_1 – M_4$ generates high-frequency AC signals required for efficient wireless transmission. Inductors L_1 and L_2 together with capacitors C_2 and C_3 create a resonant compensation network to improve power transfer efficiency. The coupling capacitors C_4 and C_5 act as wireless transmission plates that transfer energy across the air gap using electric fields. On the secondary side, the received AC power is rectified by diodes $D_1 – D_4$ into DC voltage. The output filter composed of capacitor C_6 and inductor L_o smooths the output before supplying the load with a stable DC voltage V_{out}. CWPT systems are advantageous for low-profile designs, reduced electromagnetic interference, and applications where compact wireless charging is required.

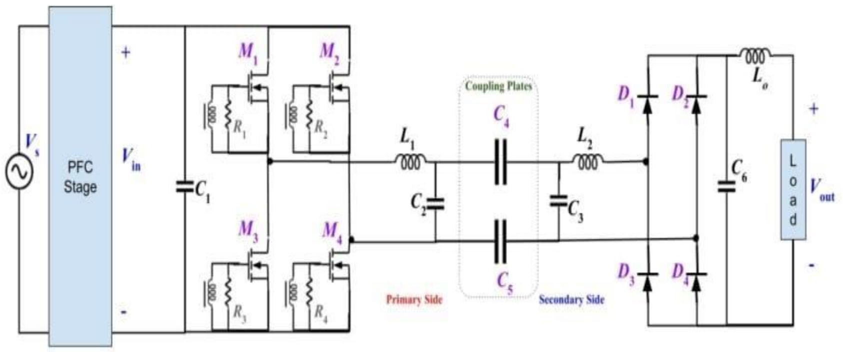

Fig.2 Circuit diagram of CPT

The below Fig.3 represents a hybrid Wireless Power Transfer (WPT) system that combines both inductive coupling and capacitive coupling for efficient wireless energy transmission.
The AC input source V_s is first connected to a Power Factor Correction (PFC) stage, which improves the input power quality and converts the AC supply into a stable DC voltage V_i . Capacitor C_1smooths the DC output. The four MOSFET switches M_1–M_4 form a full-bridge high-frequency inverter that converts the DC voltage into high-frequency AC power. The generated AC power is transferred wirelessly through the resonant network consisting of inductors $L_1$and L_2, coupling capacitors $C_4$and C_5, and compensation capacitors C_2 and C_3 . In this structure, both magnetic coupling (through coils) and electric field coupling (through coupling plates) are used to transfer power across the air gap. On the receiver side, diodes D_1–D_4 form a rectifier circuit that converts the received AC power into DC power. The filter capacitor C_6 and output inductor L_o reduce ripple and provide a smooth DC output voltage $V_{out}$to the load. This hybrid topology improves transfer efficiency, power density, and tolerance to misalignment compared to conventional WPT systems.

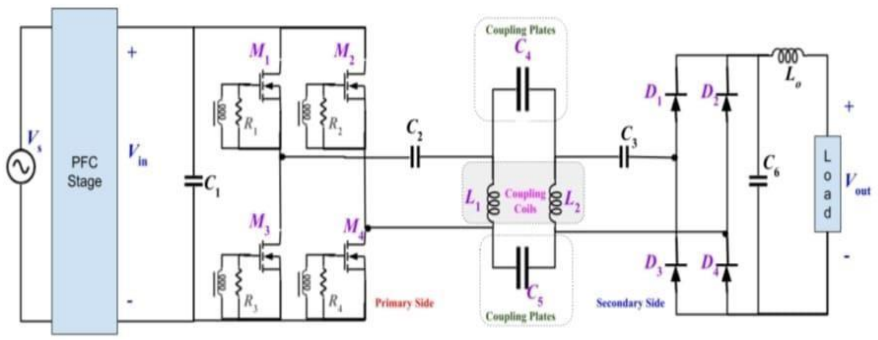

Fig.3 Circuit diagram of HPT

The proposed outcome of this project is the successful design and comparative analysis of Inductive Power Transfer (IPT), Capacitive Power Transfer (CPT), and Hybrid Power Transfer (HPT) systems for Electric Vehicle (EV) charging using MATLAB/Simulink. The project is expected to demonstrate efficient wireless transfer of electrical power under resonant operating conditions with stable voltage and current waveforms. The simulation results are expected to show that the IPT system achieves higher efficiency, improved power transfer capability, lower electromagnetic field (EMF) exposure, and better operational stability compared to CPT and HPT systems. The CPT system is expected to exhibit limitations such as higher electromagnetic interference, reduced efficiency at larger air gaps, and dependency on high-frequency operation. The HPT system is expected to provide improved coupling and better misalignment tolerance, but with increased circuit complexity and control requirements.

The project is also expected to provide a detailed understanding of the effect of air-gap variation, lateral misalignment, and resonant compensation on wireless charging performance. In addition, the work will help in evaluating safety aspects related to EMF exposure and system reliability. Overall, the proposed project is expected to identify IPT as the most practical, efficient, and reliable wireless power transfer technology for present and future EV charging applications.

III. RESULT AND DISCUSSION

The Wireless Power Transfer (WPT) systems namely Inductive Power Transfer (IPT), Capacitive Power Transfer (CPT), and Hybrid Power Transfer (HPT) were simulated using MATLAB/Simulink to analyze their performance for Electric Vehicle (EV) charging applications. The systems were compared mainly based on power transfer efficiency under similar operating conditions.

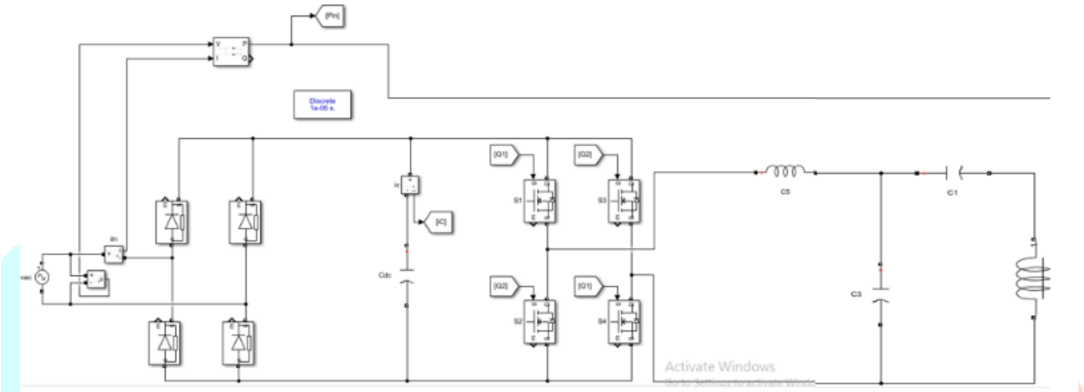

Fig.4 Primary side circuit description of IPT

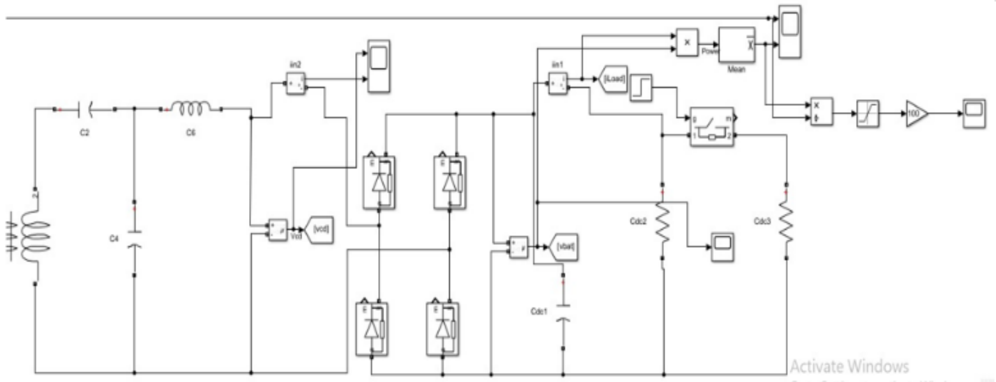

Fig.5 Secondary side circuit description of IPT

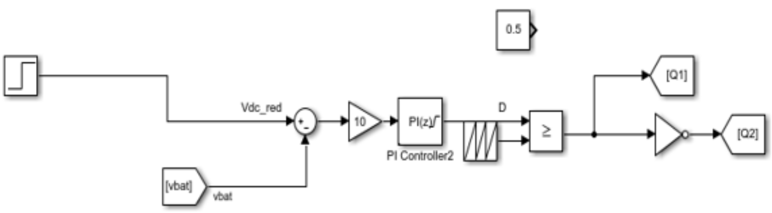

Fig.6 Control circuit description of IPT

AC supply is converted to DC using a rectifier. DC is converted into high-frequency AC using an inverter. The primary coil generates a magnetic field. The secondary coil receives this magnetic field and produces AC voltage. The AC is rectified and filtered to produce DC output. The control circuit regulates the output using PWM control.

Similarly, the circuit is built for CPT and HPT. And the comparison is done among them to know which method is most efficient. The efficiency will observed through the scope for low load, full load, low power and high power.

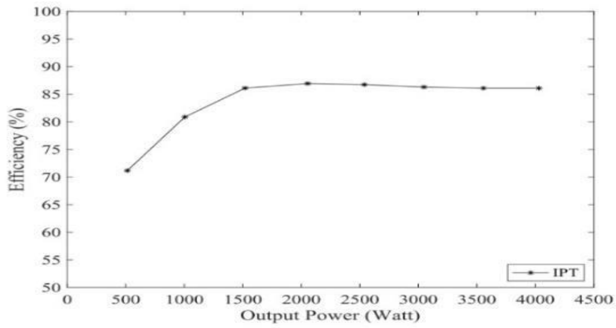

Fig.7 Efficiency of IPT

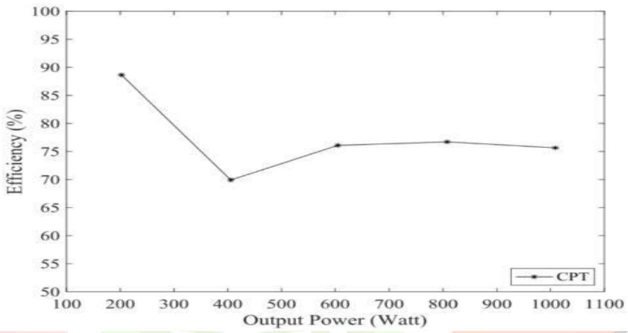

Fig.8 Efficiency of CPT

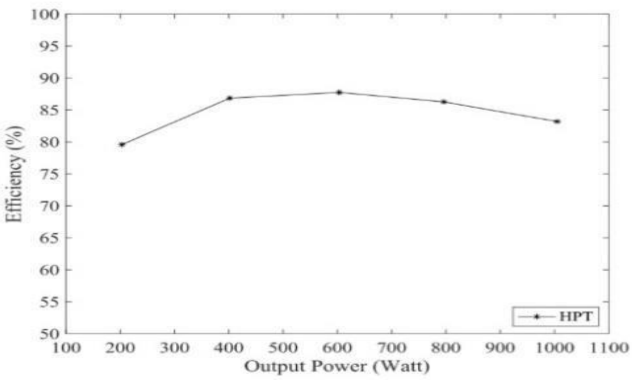

Fig.9 Efficiency of HPT

The efficiency comparison graph obtained from the simulation results shows that the IPT system achieved the highest efficiency among the three methods due to effective magnetic coupling and stable resonant operation. The CPT system showed comparatively lower efficiency because of high-frequency losses and weaker electric field coupling across larger air gaps. The HPT system provided moderate efficiency improvement by combining both inductive and capacitive coupling techniques, but increased circuit complexity affected the overall system performance.

Parameters	Inductive Power Transfer (IPT)	Capacitive Power Transfer (CPT)	Hybrid Power Transfer (HPT)
Input voltage(Vin)	~350V	~250V	~250V
Output voltage(Vout)	~390 - 400V	~190 - 220V	~190 – 220V
Input power range	500W - 4000W	200W - 1000W	200W – 1000W
Output power range	~4000W(4kW)	~1000W(1kW)	~1000W(1kW)
Efficiency(Max)	~86% - 87%	~76% - 77%	~83% - 89%
Efficiency at Rated load	~85%	~75%	~80%

Table.1 comparison of WPT methods

Therefore, the simulation results conclude that the IPT system is the most efficient and reliable wireless charging method for present EV applications.

IV. CONCLUSION

The research concludes that among the three Wireless Power Transfer (WPT) technologies analyzed, Inductive Power Transfer (IPT) provides the best overall performance for electric vehicle charging in terms of efficiency, stability, safety, and practical implementation. Capacitive Power Transfer (CPT) and Hybrid Power Transfer (HPT) offer certain advantages, but they face challenges related to high-frequency operation, electromagnetic interference, and system complexity. Therefore, IPT is identified as the most reliable and suitable WPT technology for present EV charging applications.

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