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# High-Frequency Capacitive Wireless Charging Using a 4-Plate Structure

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## ABSTRACT

***Electric vehicles (EVs) are traditionally charged in a stationary position using wireless power transfer (WPT) systems. However, dynamic charging—where EVs are charged while in motion—offers a more flexible and efficient alternative. Most current dynamic charging systems are based on Inductive Power Transfer (IPT), which, despite its maturity, is limited by high costs and considerable eddy current losses associated with inductive coils. To address these limitations, this study proposes a high-power dynamic charging system utilizing Capacitive Power Transfer (CPT) for electric vehicle applications. The research focuses on the design and implementation of a capacitive-coupled WPT system, particularly emphasizing the significance of mutual capacitance in the coupler design. Mutual capacitance directly influences the power transfer capability and overall efficiency of the system. By exploring various coupler configurations and optimizing the capacitive plate design, the study aims to enhance the practicality and cost-effectiveness of dynamic EV charging through CPT technology.***

**Keywords**—Electric Vehicle, Capacitive Coupling, Mutual Capacitance, Power Transfer

## INTRODUCTION

Electric vehicles (EVs) during parking are charged by a wireless power transfer method called stationary wireless charging, a more famous method. On-road EVs charging is also possible by the wireless power transfer method, known as dynamic charging. Most of the dynamic charging infras- tructure was developed by the Inductive Power Transfer (IPT) method and applied in EVs. But the difficulty of this method is high cost and more eddy current losses due to inductive coils. Hence, to reduce the cost of the on-road charging system, a high power capacitive dynamic charging system is proposed to promote the Capacitive Power Transfer (CPT) method in EVs dynamic charging applications [1]. The CPT technology has many application areas in wireless charging concept. Compensation topologies, converter topologies, and coupler structures play an essential role in the performance of CPT systems and therefore they should be designed carefully to obtain the desired power level to be competitive. In addition, the effects of dielectric materials on capacitive coupler struc- tures have great importance for increasing the power transfer capability and electric field strength [2]. Figure 1 represents the capacitive wireless power transfer in EVs.

Particularly, DWPT technology for dynamic wireless charg- ing enables continuous charging even during movement, ad- dressing challenges related to battery capacity and charging infrastructure. As such, it has been actively studied for electric vehicle (EV) applications. However, DWPT technology is not limited to EVs. It is a necessary technology that should be developed to provide a continuous power supply across all power-consuming devices, including industrial robots, equip- ment, smart appliances, and IoT devices. The structure of a four-plate CPT coupler is categorized into parallel and stacked configurations. Generally, the parallel structure fea- tures two transmitting metal plates and two receiving metal plates arranged to face each other.

In the stacked structure, the two transmitting plates are stacked vertically, and the receiving plates are arranged in the same manner, with the two plates on each side layered on top of each other. These two configurations can be designed and applied according to specific objectives. One plate is on the ground side or roadside, and another is fixed on the vehicle side to transfer the power. The coupling capacitance depends on the area & distance between the plates and the dielectric material used. The compensation circuit used in the CPT system helps to increase the voltage on the plates to transfer the power [3].

Capacitive Power Transfer (CPT) is an emerging wireless power transfer (WPT) technology that utilizes electric fields instead of magnetic fields (as in Inductive Power Transfer, IPT). The main purpose of the paper [4][4] is to review CPT applications in terms of performance parameters, advantages, disadvantages, and also challenges. The paper [5] proposes a double-sided LC-compensation circuit for a loosely coupled, long-distance capacitive power transfer (CPT) system. In [6], it presents a capacitive wireless power transfer system for electric vehicle charging that achieves high efficiency and

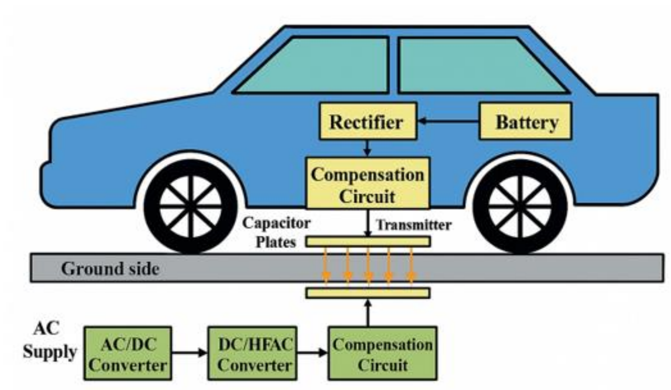


Fig. 1. Capacitive Wireless Power Transfer

record-breaking power transfer density. The paper [7] is built and has regrouped the needed sections that can define the wireless recharge concept based on an alternative energy source. Simulation results were adapted by the MATLAB Simulink platform, where more than one situation is tested and examined. The paper [8] investigates the performance of wireless charging topologies in a Capacitive Power Transfer system. The research work describes a design and implemen- tation of materials characteristics for the capacitive coupling wireless power transfer system. There were two types of Wireless Power Transfer (WPT) that have widely been used and studied by researchers: Inductive Power Transfer (IPT) and Capacitive Power Transfer (CPT). Electric fields transmit by the electrostatic induction phenomena between transmitter and receiver.

## MODELLING OF THE SYSTEM

The capacitive WPT system consists of several key stages. Initially, an AC supply is converted into DC voltage using an AC/DC converter, which ensures a stable power source. This DC voltage is then converted into high-frequency AC (HFAC) using a DC/HFAC converter, which is essential for efficient capacitive coupling. The high-frequency AC is then fed into a compensation circuit at the transmitter end, which optimizes power transfer by matching impedance and enhanc- ing efficiency. The transmitter plates generate an alternating electric field, which is picked up by the receiver plates through capacitive coupling. Once the electric field is transmitted, the received HFAC signal is processed by a compensation circuit at the receiver end to improve power reception and enhance transfer efficiency. The AC signal received by the plates is then converted into DC using a rectifier, which smoothens the voltage to eliminate ripples and fluctuations. A compensation network consisting of reactive components such as inductors and capacitors is used to further regulate the power and minimize losses.

The 4-plate configuration consists of two transmitter plates (Tx1 and Tx2) and two receiver plates (Rx1 and Rx2), forming two capacitive links. These plates are arranged in such a way that the alternating electric field is efficiently transferred between them. The advantage of this configuration over a traditional 2-plate system is improved coupling efficiency and enhanced power transfer stability [6]. The two pairs of plates create additional capacitance, reducing power losses and increasing overall system performance. In a capacitive WPT system, a high-frequency AC voltage source is applied to the transmitter plates, generating an alternating electric field between the transmitter and receiver plates. Due to the alternating voltage, a time-varying electric field is established, causing displacement currents to flow across the capacitive interface between the plates. This displacement current is responsible for energy transfer between the transmitter and receiver. The receiver plates capture the alternating electric field and induce a corresponding AC voltage. The received AC voltage is then passed through a rectifier circuit, which converts it into DC power suitable for the load. Additional power conditioning circuits, such as voltage regulators or filters, may be used to stabilize the output. The final stage involves delivering the conditioned DC power to the intended load, such as a battery or an electronic circuit. Capacitive coupling-based WPT relies on the principle of displacement current, as described by Maxwell’s equations. Unlike inductive coupling, which depends on magnetic fields, capacitive WPT uses an electric field to facilitate energy transfer.

A high- frequency AC voltage is applied to the transmitter plates, creating an oscillating electric field between the capacitive interface. The receiver plates, placed in proximity, capture this field and convert the energy back into usable power. The arrangement of plates and dimension specification is shown in Fig.2.

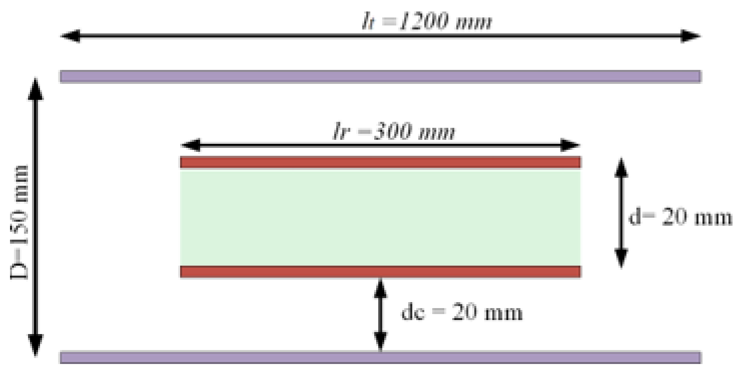


***Fig. 2. Plates Arrangement for Capacitive Coupling***

The power transfer is facilitated using horizontally arranged capacitive plates, with capacitances CM1 CM2 playing a crucial role in this process. The Mutual capacitance can be calculated using the following formula.

$$C_{M1} = \varepsilon_0 \frac{l^2}{d}[1 + 2.343 * (\frac{d}{h})^{0.891}] \quad (1)$$

where,
$\varepsilon_0$ = Permitivity of free space = $8.854 * 10^{-12}$ F/m
d = air gap length = 150 mm
By substituting the values in Equation 1, we can get $C_{M1}$ = 36.7pF.
And capacitive reactance can be calculated as,

$$X_c = \frac{1}{2\pi f C} \quad (2)$$

The coupler capacitance can derived from the Fig.3.

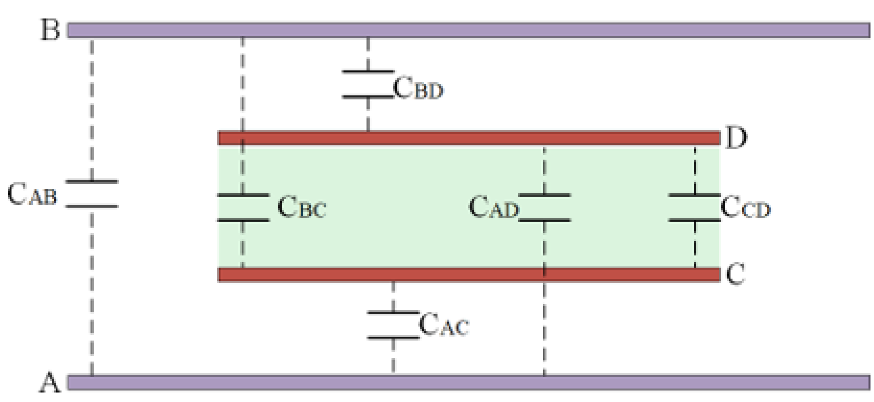


Fig. 3. Coupler Capacitance

$$C_A = C_{AB} + \frac{(C_{AC}+C_{AD})(C_{BC}+C_{BD})}{C_{AC}+C_{AD}+C_{BC}+C_{BD}} \quad (3)$$

$$C_B = C_{CD} + \frac{(C_{AC}+C_{BC})(C_{AD}+C_{BD})}{C_{AC}+C_{BC}+C_{AD}+C_{BD}} \quad (4)$$

$$C_M = \frac{(C_{AC}.C_{BD}) - (C_{BC}.C_{AD})}{C_{AC}+C_{BC}+C_{AD}+C_{BD}} = \frac{C_{M1}.C_{M2}}{C_{M1}+C_{M2}} \quad (5)$$

The Voltage at each plate can be [9],

$$V_1 = I_1 \frac{1}{j\omega C_A} + V_2 \frac{C_M}{C_A} \quad (6)$$

$$V_2 = I_2 \frac{1}{j\omega C_B} + V_2 \frac{C_M}{C_B} \quad (7)$$

Hence, the currents at each side can be calculated as,

$$I_1 = j\omega C_A V_1 - j\omega C_M V_2 \quad (8)$$

$$I_2 = j\omega C_B V_1 - j\omega C_M V_1 \quad (9)$$

**RESULTS & DISCUSSION**

*A. MATLAB Simulation Diagram*

The simulation of capacitive coupled power transfer is carried out using the following capacitance values based on the calculations and power transfer requirement.

TABLE I
SIMULATION DESIGN PARAMETERS

| Parameter | Value | Parameter | Value |
|---|---|---|---|
| $V_1 = V_{in}$ | 265 V | $V_2 = V_{out}$ | 280 V |
| $f_s$ | 1 MHz | $k_c$ | 0.15 |
| $L_a = L_b$ | 11.6 $\mu H$ | $C_a = C_b$ | 2.18 nF |
| $L_1$ | 231 $\mu H$ | $C_1 = C_2$ | 100 pF |
| $L_2$ | 242 $\mu H$ | $C_M$ | 18.35 nF |

The simulation diagram for the proposed power transfer is given in Fig.4.

Fig.5 shows the simulation input waveform with respect to time. For 265V, 9A input the waveforms were obtained as shown below. Fig.6 shows the simulation output waveform with respect to time. For 265V, 9A input, the output voltage and current is 160V, 9A obtained and simulation result as shown below.

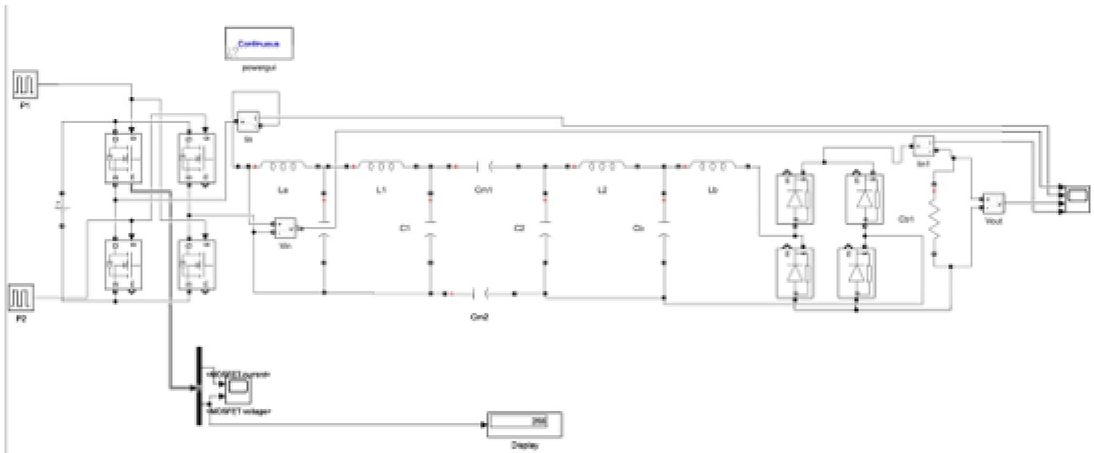

Fig. 4. Simulation Diagram for CPT

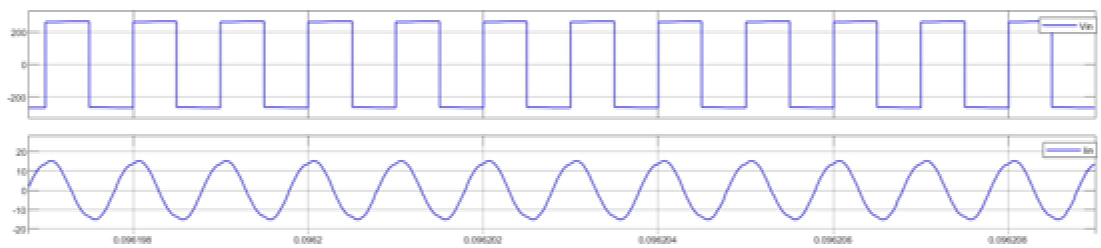

Fig. 5. Input Voltage and Current Waveform

B. Hardware Implementation

The capacitive coupled wireless power transfer is realised using the oscillator circuits with high frequency. The hardware implementation is shown in Fig.7. Fig.8 depicts the output voltage waveform with a frequency of 1 MHz. The hardware realization of this system is shown in Fig. 7. It consists of oscillator circuits that generate the required high-frequency signal, a pair of capacitive plates configured to act as the transmitter and receiver, and the associated circuitry for power conditioning and load connection. These components work together to create an efficient path for wireless power delivery. Fig. 8 further illustrates the output voltage waveform measured at a frequency of 1 MHz, showing a consistent sinusoidal signal, which confirms the effective operation of the oscillator and the capacitive coupling mechanism at this frequency. The relationship between input and output voltages with respect to frequency is presented in Fig. 9. At lower frequencies, the input voltage remains relatively stable, indicating that the oscillator operates efficiently and the circuit experiences minimal losses. However, as the frequency increases beyond a certain point, the input voltage begins to drop, accompanied by a more noticeable decline in output voltage. This decreasing trend in the output voltage indicates frequency-dependent attenuation, a common phenomenon in resonant circuits. At higher frequencies, parasitic effects such as stray capacitance and inductance become more significant, causing a mismatch in impedance and reducing the overall power transfer capability.

Interestingly, after reaching a minimum point, the efficiency exhibits a slight recovery at even higher frequencies. This suggests the existence of an operational region where system losses stabilize or compensating effects—such as improved impedance matching or secondary resonances—contribute to a temporary increase in efficiency. However, the recovered efficiency remains lower than the initial value observed at lower frequencies, highlighting the challenge of maintaining high performance across a broad frequency range.

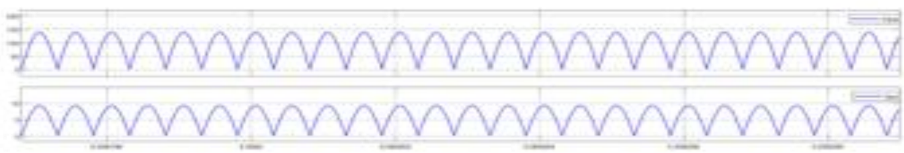

Fig. 6. Output Voltage and Current Waveform

Fig. 7. Hardware Implementation

Fig.11 depicts the relationship between power efficiency and frequency. Initially, efficiency is relatively high at lower frequencies but gradually declines as frequency increases, reaching a minimum at a certain point. After this minimum, efficiency shows a slight recovery at higher frequencies, though it remains lower than the initial value. The decline in efficiency is likely due to increased losses caused by switching effects, impedance variations, or thermal factors, which become more significant at higher frequencies. The slight improvement at higher frequencies may suggest an op- erational range where system losses stabilize or compensating factors enhance efficiency. To achieve optimal performance in CCWPT systems, careful consideration must be given to circuit design, frequency selection, and component quality. Key parameters such as coupling capacitance, plate alignment, dielectric material, and parasitic element control play critical roles. Future enhancements may include adaptive frequency tuning, active compensation networks, and the use of high- permittivity, low-loss dielectric materials to improve system robustness, range, and efficiency across varying operational conditions.

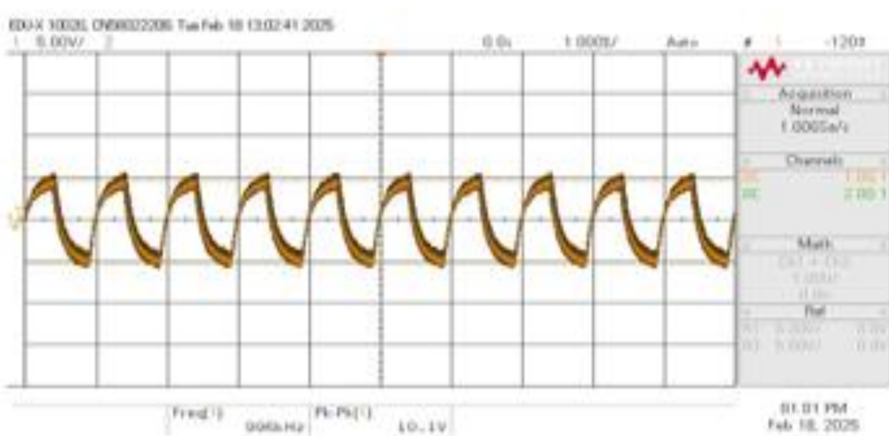


Fig. 8. High Frequency Output

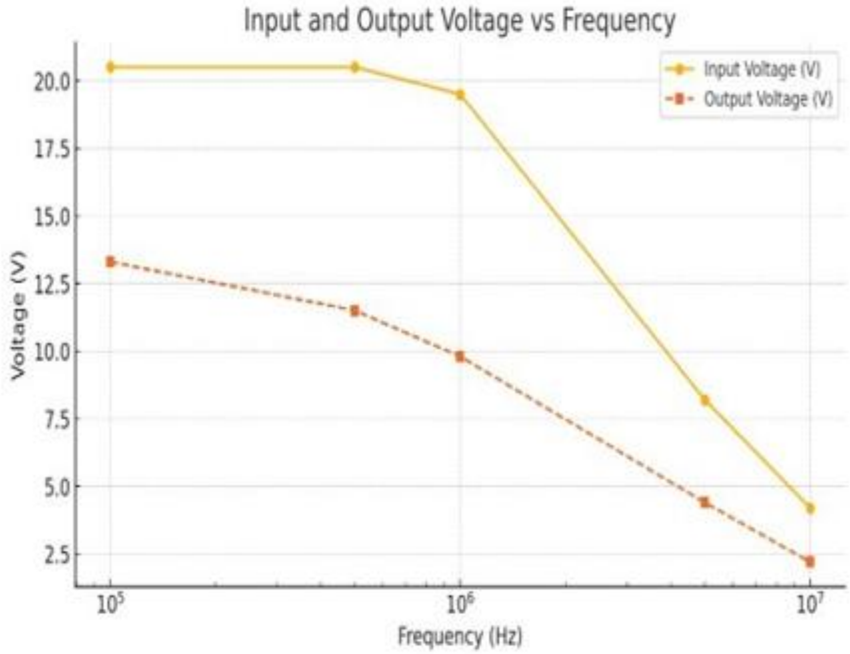


Fig. 9. Impact of Input and Output Voltage with Frequency

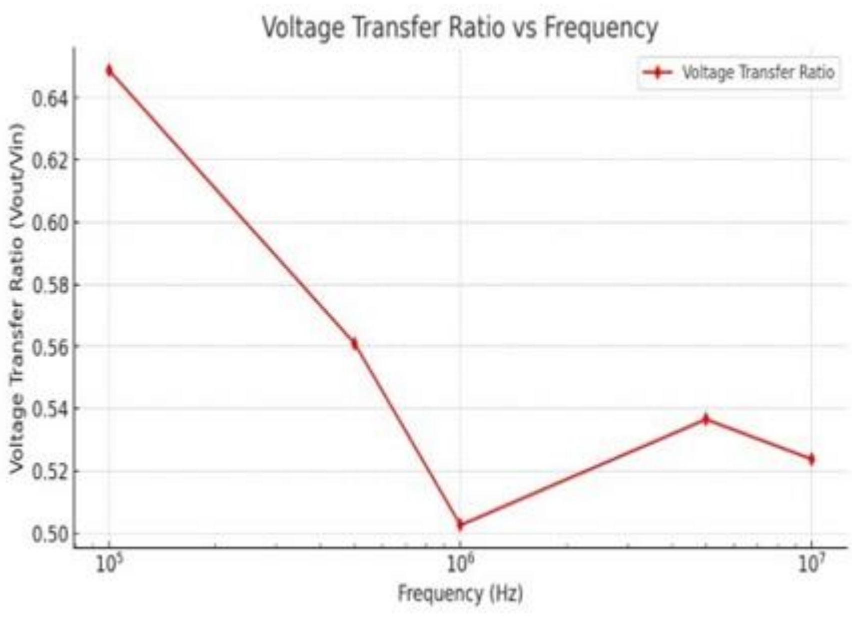


Fig. 10. Voltage Transfer Ratio

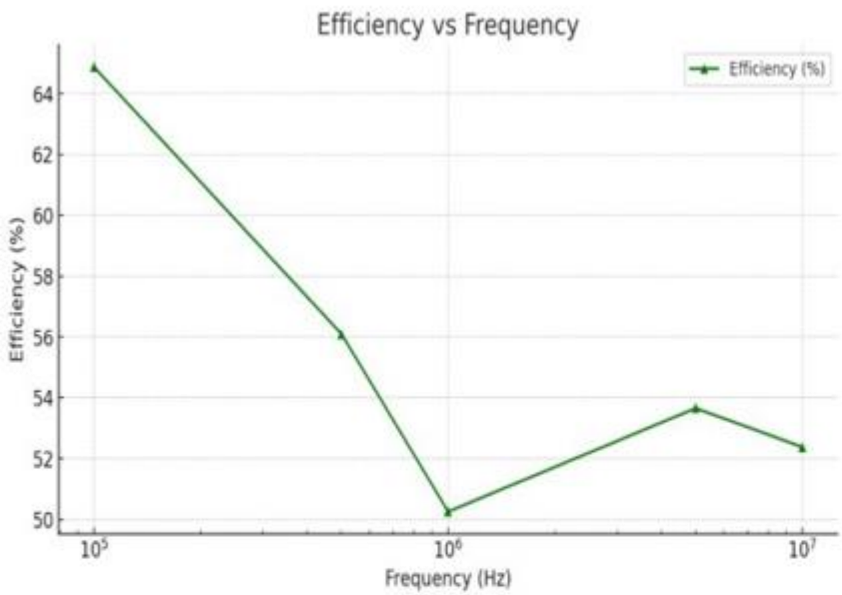


Fig. 11. Efficiency Vs Frequency

## CONCLUSION

This analysis explores the fundamental principles of capac- itive coupling, its benefits, and the challenges associated with its application. System efficiency is influenced by key factors such as operating frequency, coupling capacitance, and circuit design. While higher operating frequencies improve power transfer efficiency, they also necessitate careful management of parasitic effects and impedance matching. The choice of dielectric materials is critical in minimizing energy losses and enhancing overall system performance. Despite its advantages, capacitive WPT systems face challenges, including limited power transfer distance, sensitivity to misalignment, and the risk of dielectric breakdown. Overcoming these challenges requires further research into advanced circuit topologies, active compensation methods, and the development of high- permittivity dielectrics to improve coupling efficiency and system stability.

## AUTHOR CONTRIBUTION

All authors have equal contributions. Conceptualization, review, and editing - Dr.MS.

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