International Research Journal on Advanced Engineering Hub (IRJAEH)
e ISSN: 2584-2137
Vol. 03 Issue: 04 April 2025
Page No: 1904-1911
https://irjaeh.com
https://doi.org/10.47392/IRJAEH.2025.0277

Comprehensive Analysis and Design of Dynamic Wireless Power Transfer technologies used for Electric Vehicles Charging Station

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Abstract

Fossil fuel-based vehicles emit toxic gases and other pollutants in the atmosphere. A big fraction of environmental pollution is caused by these fossil fuel-based vehicles. To create a pollution-free environment, people are encouraged to switch to electric vehicles. However, the major concern of electric vehicle owners is range anxiety. Undeveloped charging infrastructure and the lack of fast chargers are major reasons people do not own an electric vehicle. The increasing adoption of electric vehicles (EVs) has highlighted challenges related to battery capacity, charging methodology and infrastructure. Dynamic Wireless Power Transfer (DWPT) is an emerging solution that enables the continuous charging of EVs while in motion, reducing the need for large battery packs and minimizing charging downtime. With the proper development of a dynamic wireless charging system, need of large size of the battery of the electric vehicle can be reduced and as a result of this the price of the vehicle will be reduced by a major margin, and the electric vehicle will fall into the category of affordable range attracting more buyer. This paper explores design and optimization of dynamic wireless charging systems using various WPT topologies, including inductive, capacitive, resonant inductive, and hybrid systems, analyzing their performance based on critical parameters such as power transfer efficiency, misalignment tolerance, electromagnetic field (EMF) structure. This paper discusses comparison of different topologies and configuration of dynamic wireless charging systems. ANSYS software is used to select proper size of transmitter and receiver coil. ANSYS simulation is used to identify optimum design of WPT system. By providing a comprehensive analysis of current WPT technologies and proposing design guidelines for efficient EV charging infrastructure, this work contributes to the advancement of future-ready contactless charging solutions.

Keywords: *Wireless Power Transfer (WPT), Electric Vehicle (EV) Charging, Inductive Power Transfer (IPT), Capacitive Power Transfer (CPT), Sustainable Electric Mobility (SEM).*

1. Introduction

Wireless Power Transfer (WPT) technology has revolutionized energy transmission by enabling contactless power delivery to eliminate physical connect need [1]. The historical foundations of WPT can be traced back to Nikola Tesla's pioneering experiments in the late 19th century, where he demonstrated the potential for long-distance wireless energy transmission using resonant inductive coupling. While Tesla's vision was far ahead of its time, modern advancements in power electronics, materials science, and control systems have revitalized and accelerated the development of WPT technologies [2]. This innovation is widely used in various applications such as electric vehicle charging, consumer electronics, and biomedical equipment. Deflorio, F., & Castello, L. (2017). highlighted the electrical energy transfer through electromagnetic fields between a transmitter coil which is often embedded in the ground of charging station and a receiver coil installed in the device or vehicle. This approach not only enhances convenience but also mitigates safety risks associated with exposed connectors, offering automated and reliable charging solutions [3-4]. This paper represents comparative analysis of different topology of wireless power transfer. Second section explain wireless power system and various topology. While section 3 briefs various topology and compensation techniques used in WPT. Section 4 discusses coil design for WPT and its mathematical modelling and section 5 explains results and comparative analysis.

2. Literature Review

Primary coil of WPT operates on Lenz's Law which indicates a constant current in a conductor generates a constant magnetic field. While Faraday's Law states that emf induced in a nearby secondary coil by capturing this magnetic field which can transfer power wirelessly when a load is connected. Wang et al. (2005) presented that stronger magnetic coupling enhances energy transfer efficiency. However, advancement in electronics can done effective power transfer even in loosely coupled systems, such as wireless charging of EV battery. Lo rico (2011) noted that magnetic field strength decreases with distance, limiting efficiency over large gaps. This challenge is addressed using high-frequency magnetic resonance, requiring careful tuning of circuit parameters like resistance, capacitance, and inductance. Cannon (2009) introduced a single-coil model with double induction and better efficiency due to stronger resonant coupling [4]. Kurs and Karalis (2007) demonstrated 40% efficiency in powering a 60W bulb across 2 meters using resonant inductive coupling [5]. Many researchers highlighted that WPT still suffers from transmission losses, which could be reduced using composite conductors in power lines [6-7] Sample (2011) developed a system with adaptive frequency tuning, maintaining up to 70% efficiency at 70 cm, despite coil movement [8].

3. Wireless Power Transfer System

The fundamental principle of WPT involves converting electrical energy into a suitable form for wireless transmission through magnetic resonant or inductive coupling-and then reconverting it into usable power at the receiver side [9-10]. For EV charging applications, achieving high efficiency, safety, and system reliability is crucial, especially when integrating with existing grid infrastructure and vehicle architectures [11]. Figure 1 represents basic block diagram representing working principle of wireless power transfer system.

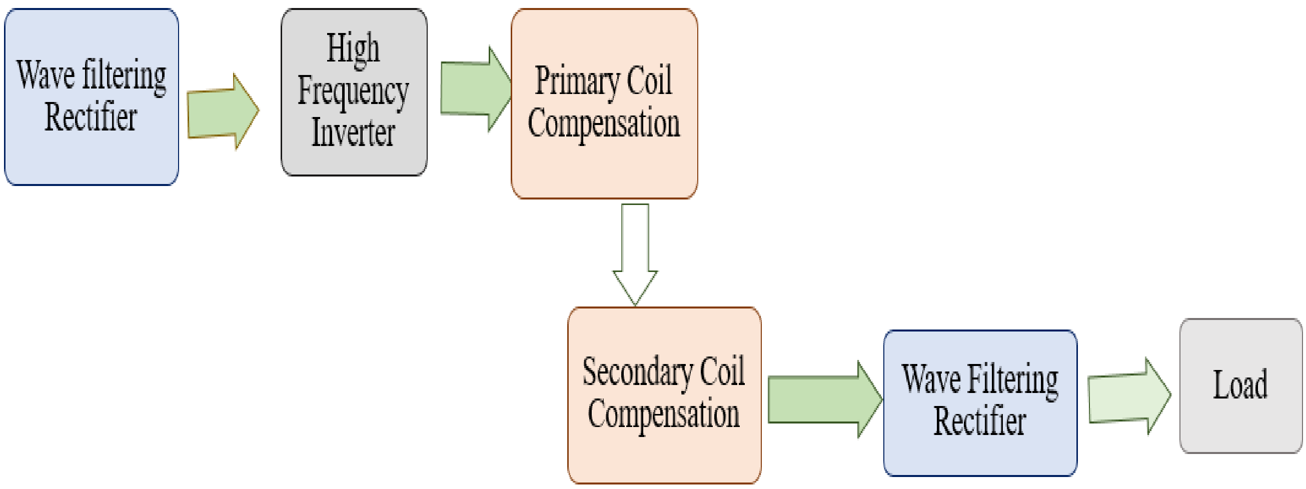

Figure 1 **Block Diagram of WPTS**

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3.1 WPT topologies

Various WPT methods are classified as shown in figure 2 and explained as below.

- **Inductive Power Transfer (IPT):** It uses magnetic fields between coils and wirelessly transfer power at high efficiency at short distance but highly sensitive to misalignment and commonly used in EV charging. It needs bulky ferrite cores [10-12].
- **Capacitive Power Transfer (CPT):** It transfers energy via electric fields between metal plates and requires high frequency and voltage for long range power transfer [12]. This topology is more tolerant to misalignment and lighter with lower EMI than IPT.
- **Hybrid IPT–CPT Systems:** Hybrid systems combine magnetic and electric coupling to leverage the strengths of both IPT and CPT [12-13].
- **Far-Field WPT:** FFWPT is suitable for low power remote application like microwave and laser transfer power over long distances without coupling but face challenges like low efficiency, line-of-sight requirements, and safety concerns. Figure 3 represents various topology usage percentage by different researchers in different research.

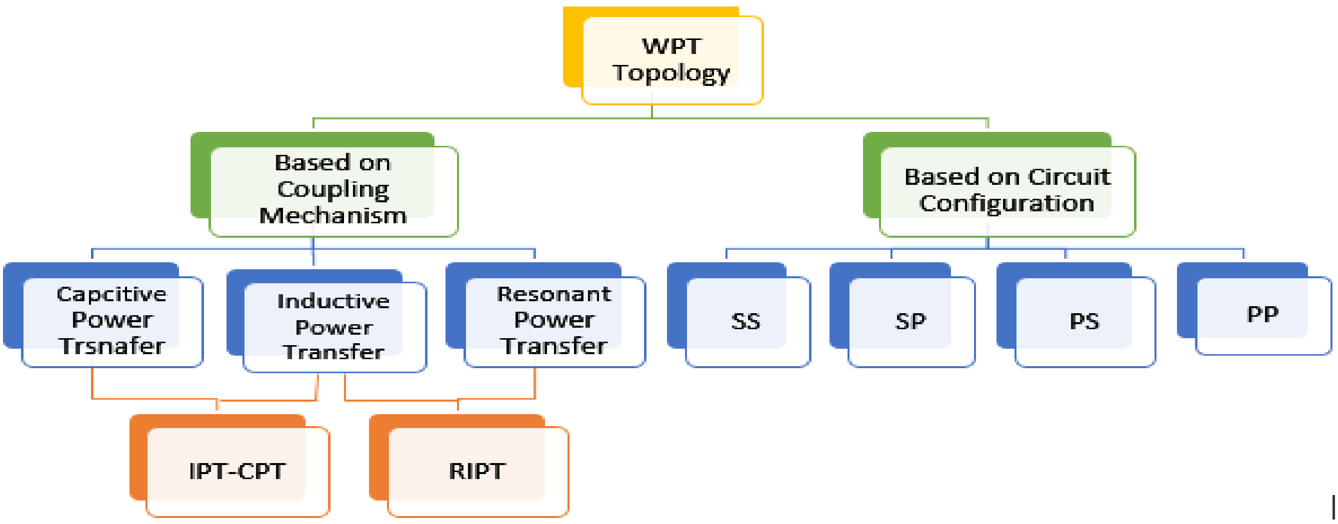

Figure 2 Classification of WPT Topology

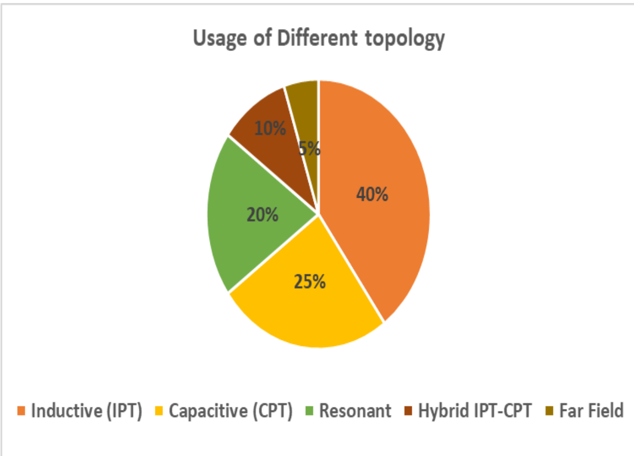

Figure 3 % Usage of WPT Topology

IPT is the most widely adopted for high power levels while CPT typically operates at lower power levels. Due to recent innovations CPT capabilities increases the kilowatt ratings. By connecting resonant circuits at both sides of IPT coils, efficiency can be enhanced for large air gap power transfer. Sensitivity against metallic object is reduced in CPT and also reduces electromagnetic emissions. Genrally, CPT works at lower efficiencies with compare to IPT [13-14]. Various researcher has explored combine inductive and capacitive coupling mechanisms to get higher efficiency under misalignment conditions. Some research demonstrated a capability of IPT- CPT to deliver power up to 2.84 kW with 94.5% efficiency

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at a 1 MHz switching frequency. Microwave uses far-field techniques to enables long distance energy transmission. Laser-based power transfer is under exploration for long-distance power transfer but needs line-of-sight requirements and safety concerns which make it less suitable for EV charging system [14]. These emerging technologies are also investigated by various researcher for long distance power transfer but they are in experimental stages for EV applications [15].

4. WPT Compensation Topology

Performance of WPT system depends on its design considerations like frequency, electromagnetic field, misalignment angle, distance, safety, power transfer efficiency and compensation topology. Figure 4 presents use of various compensation techniques in various research.

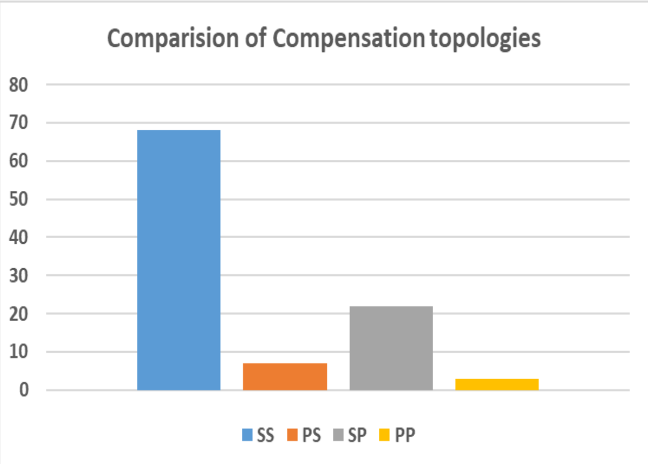

Figure 4 **% Usage of Compensation Topologies**

Among these, the Series-Series (SS) compensation topology is widely adopted for electric vehicle (EV) charging due to its simplicity and robust performance under varying operating conditions. This paper focuses on a comparative analysis of SS, SP, PS and PP topologies under coil configurations. The study combines theoretical modeling with finite element method (FEM) simulations to optimize performance within practical design constraints. Under vehicle misalignments, DWPT systems faces significant efficiency challenges where power transfer losses can exceed more than 15%. The performance variability across different compensation topologies configurations remains insufficiently quantified for the real-world dynamic conditions. Existing research is not considering electromagnetic safety, infrastructure cost and not compliance with interoperability standards. This gap is filled by evaluation of DWPT architectures which assesses in terms of misalignment tolerance, transfer efficiency at an 85 kHz resonant frequency, and EMF leakage. These evaluation makes positive insights for EV manufacturer and urban roadways planners to implement cost-effective and electromagnetic loss free dynamic wireless power charging system. The key factors of different topologies are shown in table 1.

Table 1 **Key Factors of Different Topologies**

TOPOLOGY	PRIMARY APPLICATIONS	EFFICIENCY	ADVANTAGES
SS	EVs, Industrial	85–97.5%	Simplicity, stability under misalignment
SP	High-load EVs, Weak coupling	85–90%	Improved voltage gain
PS/PP	Robotics, High power	98–99%	High efficiency, weak coupling support
Hybrid (LC-S)	Biomedical, EVs	82–95%	Adaptive load/ coupling variations
IPT-CPT	EVs, Long-distance	94.5%	Combines magnetic/electric field benefits

5. Design of Coils for WPT

To ensure high efficiency, strong magnetic coupling, and tolerance to misalignment, WPT systems used for EV charging must be optimized for coil design, material selection, and compensation networks. An excellent electrical and thermal conductivity of copper is preferable coil material for efficient high-power transmission with minimum resistive losses. Skin and proximity effects can be minimized by lit wire and used for high-frequency operation while ferrite materials help magnetic flux and reduce

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leakage. Coil geometry significantly impacts performance; hybrid shapes such as square-hexagonal coils have shown improved magnetic coupling and reduced sensitivity to lateral misalignments when compared to traditional square or circular designs. These innovative shapes help maintain efficiency even with moderate air gaps. Additionally, compensation network topologies like LCC-LCC are widely used to stabilize power transfer and maintain zero-voltage switching (ZVS) under varying alignment conditions.

5.1 Mathematical Modelling

$l_p=2\pi r_p$=length of primary coil in cm. (1)

$l_s= 2\pi r_s$=length of secondary coil in cm (2)

r_p =Primary coil in radius in cm.

r_s =Secondary coil in radius in cm.

$Ap= \pi(r_p)^2$=Area of primary coil in cm^2 (3)

$As= \pi(r_s)^2$=Area of secondary coil in cm^2. (4)

$L_P=(\mu_0*\mu_r(Np)^2Ap)/lp$ (5)

$Ls=(\mu_0*\mu_r(Ns)^2As)/ls$ (6)

Lp and Ls are Primary and Secondary coils leakage inductance,μ_0 is Permeability of air=$4\pi * 10^{-7}$ wb/Am and μr=Relative permeability

R_p = & Rs are Primary and secondary coil resistance

$$Rp=\frac{\varrho*l_p}{A_p}\Omega.\ \&\quad R_s=\frac{\varrho*l_s}{A_S}.\Omega \tag{7}$$

$$K=\frac{M}{\sqrt{L_P}*\sqrt{L_S}} \tag{8}$$

$$M=K*\sqrt{L_P}*\sqrt{L_S}. \tag{9}$$

Where M is mutual inductance in mH, K=Coupling coefficient set between 0.1 to 0.5 because air is between two coil.In Wireless Power Transfer Systems (WPTS), performance is strongly influenced by the coupling coefficient, which depends on the coil size, shape, and distance The relationship between the coupling coefficient and distance between two coil is given by equation (10).

$$K=\frac{1}{[1+2^{\left(\frac{2}{3}\right)}*\left(\frac{D}{\sqrt{Rp*\sqrt{Rs}}}\right)^2]^\wedge\left(\frac{3}{2}\right)} \tag{10}$$

In above equation,D=Distance between two coil in cm.,Rp=Radius of primary coil in cm.,R_s=Radius of secondary coil in cm.The equation (11) represents magnetic field dB at a point P due to a current element. **As per Biot–Savart Law**. The total magnetic field is found by integrating this expression over the entire current path

$$dB=\frac{\mu 0I\ dLsin\theta}{4\pi r2} \tag{11}$$

5.2 3D Modeling of a Transmitter and Receiver Coil

The 3D modeling of a transmitter and receiver coil is designed by using ANSYS Maxwell software. Both coils consisted of copper for high electrical conductivity. Magnetic field is captured by transparent plate between two coils. Two lids connect to each of the transmitting and receiving coils respectively for current excitation. The lid consists of copper of given below specifications. A region of $1000mm^3$ composed of air where simulations will take place. The solving of ANSYS Maxwell is done by creating a boundary to place the two coils. Various combination of coil connections, diameter is checked and effect of misalignment and frequency on WTP performance is checked. The figure 5 shows the transmitting coil and the receiving coil in ANSYS Maxwell software and figure 6 demonstrate dimension set board.

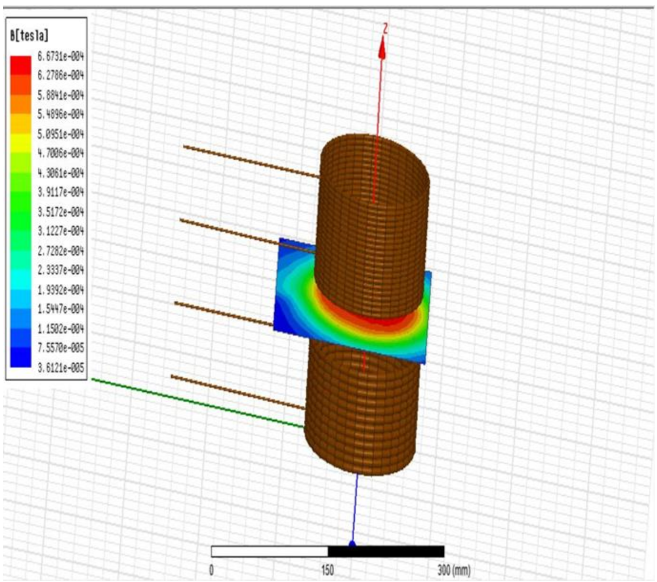

Figure 5 3d Modelling of Coils Using Ansys

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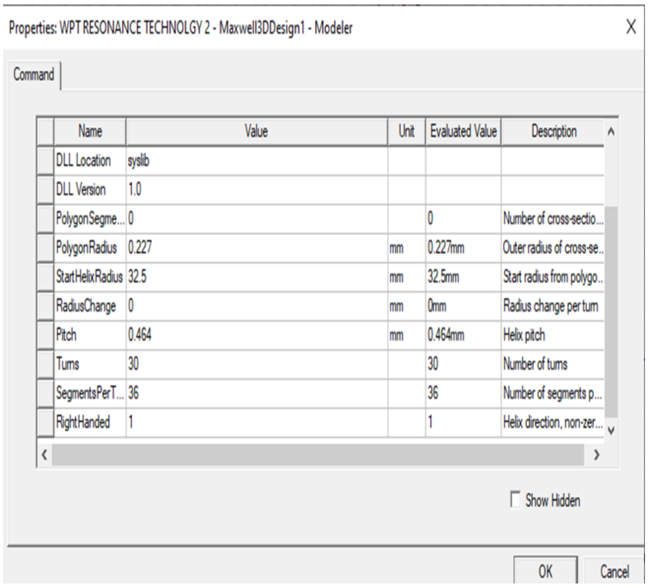

Figure 6 Coil Dimension Set Board

Figure 7 shows the flux density values by keeping transmitter coil with 20 turns and 6 cm diameter are kept constant, and the receiver coil diameter is varied at a fixed distance of 50 mm.

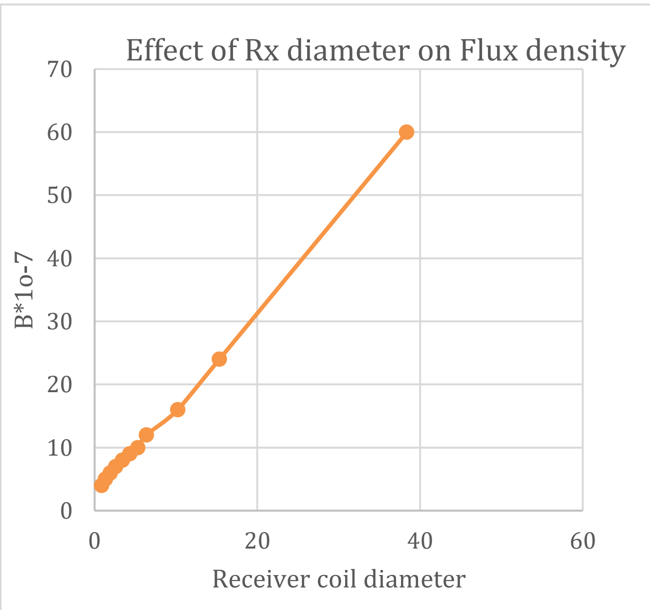

Figure 7 Effect of Receiver Coil Dimension on Flux Density

Effect of Tx and Rx diameter variation and distance variation on flux density is summarized in table 2.

Table 2 Flux Density for Different Parameters

Tx Dia (cm)	Rx Dia (cm)	Distance (mm)	Flux Density (T)
5	5	10	2.3132×10^{-6}
6	6	10	4.7966×10^{-6}
10	10	10	3.7011×10^{-5}
10	16	10	1.2791×10^{-6}
12	24	10	2.3024×10^{-6}
30	60	10	1.4390×10^{-5}
5	5	20	5.7830×10^{-7}
6	6	20	1.1992×10^{-6}
10	10	20	9.2528×10^{-6}
10	16	20	3.1978×10^{-7}
12	24	20	5.7560×10^{-7}
30	60	20	3.5975×10^{-6}
5	5	30	2.5702×10^{-7}
6	6	30	5.3296×10^{-7}
10	10	30	4.1123×10^{-6}

Misalignment between Tx and Rx coil effects on mutual inductance. Figure 8 demonstrate reduction in mutual inductance due to change in misalignment angle from 0 to 45^0. Distance between coils is varied from 0 to 300 mm and efficiencies are compared for different topologies like SP, PS, SS and PP and results are shown in figure 9. PS and PP topologies demonstrate lower overall efficiency, with PS showing the sharpest decline with increasing distance.

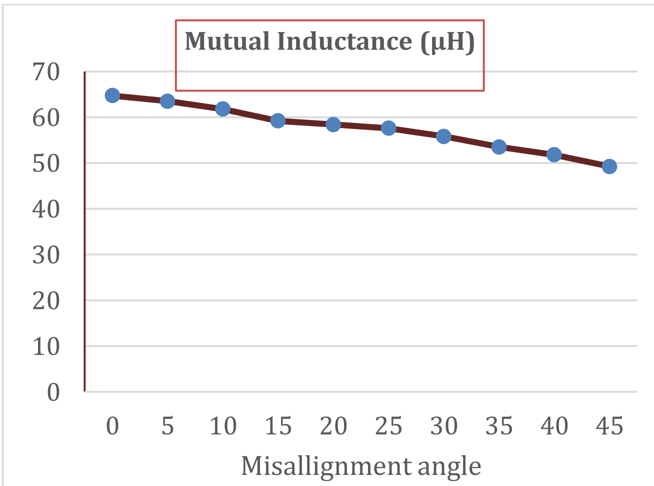

Figure 8 Effect of Misalignment on Mutual Inductance

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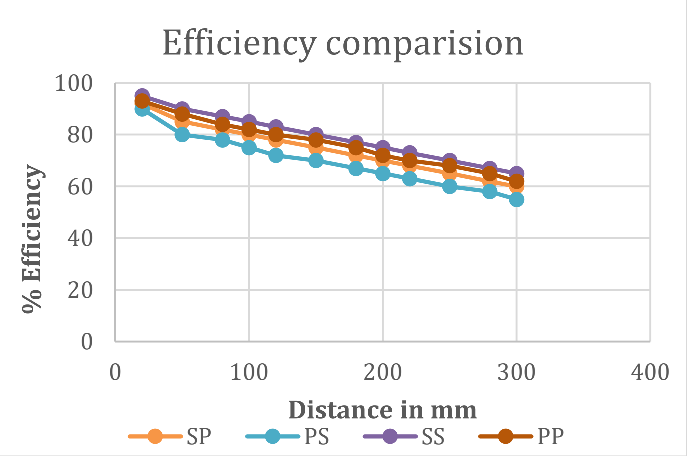

Figure 9 **Efficiency Vs Distance Curve**

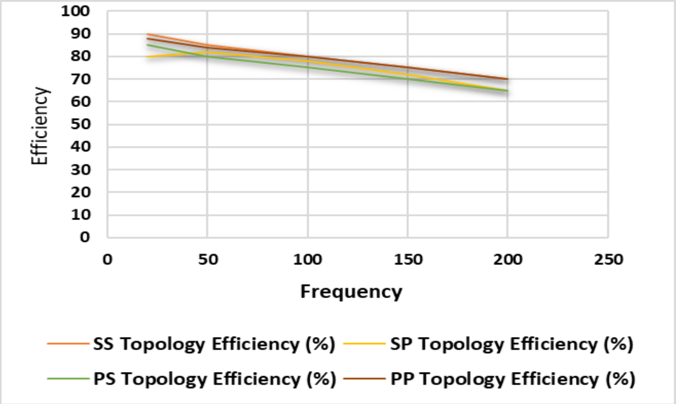

Figure 10 **Efficiency Vs Frequency Curve**

Figure 10 demonstrate effect of frequency variation on efficiency for all four topologies for Tx 12cm and Rx 24 cm. SS performs optimally at frequencies below 300 kHz, while SP benefits from higher frequencies. Figure 11 shows Efficiency Vs Distance Curve.

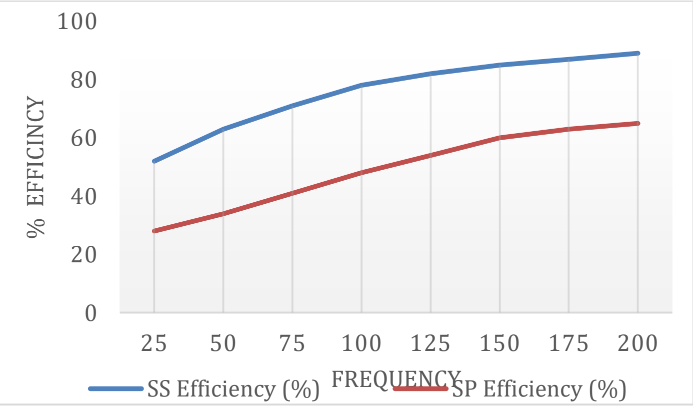

Figure 11 **Efficiency Vs Distance Curve**

Conclusion

This study investigates the performance and efficiency of WPT systems using four compensation topologies SS, SP, PS, and PP across various coil geometries, distances, and operating frequencies. Results shows that transmitter coil size significantly influences magnetic coupling and efficiency. Transmission coils of 30 cm maintain higher flux densities over longer distances and have optimal power transfer up to 50 cm with smaller receiver coils pair. SS topology consistently performs best in symmetrical coil configurations and maintain 95% efficiency at 20 mm and 65% at 300 mm. SP shows superior results in asymmetrical setups and maintain approximate 60% efficiency at 300 mm. SS topology is best suited for applications requiring high efficiency over short to medium distances with symmetrical coils. SP topology is more effective for unsymmetrical or misaligned configurations. Hybrid topology are useful to enhance WPT performance by adaptive control techniques under variable and dynamic conditions.

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