

Article

Design and Analysis of a High-Efficiency Dynamic Wireless Power Transfer System for In-Motion EV Charging

Md Aurongjeb ¹, Yumin Liu ^{1,*} and Muhammad Ishfaq ²

¹ State Key Laboratory of Information Photonics and Optical Communications, School of Electronic Engineering, Beijing University of Posts and Telecommunications, Beijing 100876, China; md.aurongjeb@bupt.edu.cn

² School of Automation and Electrical Engineering, Lanzhou University of Technology, Lanzhou 730050, China; ishfaq@lut.edu.cn

* Correspondence: liuyumin@bupt.edu.cn

Abstract

Dynamic wireless power transfer (DWPT) systems for in-motion electric vehicle (EV) charging often suffer from unstable power delivery due to spatial variations in magnetic coupling caused by vehicle misalignment. This study presents a stabilization-oriented DWPT design methodology that prioritizes minimizing spatial variations of mutual inductance rather than maximizing peak coupling under perfect alignment. A ferrite-backed double-D coil configuration is analyzed and refined using three-dimensional finite-element electromagnetic modeling integrated with circuit-level co-simulation to evaluate coupling behavior, magnetic field homogeneity, and power transfer efficiency under realistic dynamic misalignment conditions. The proposed design achieves a coupling coefficient of 0.50–0.55 under aligned conditions and exhibits smooth, predictable degradation for lateral offsets up to 40–50 mm. Quantitative analysis demonstrates a low spatial coupling gradient of approximately 0.001 mm^{-1} , indicating that abrupt coupling transitions are effectively suppressed during vehicle motion. The system attains a maximum power transfer efficiency of 84.37% at an 80 mm air gap, while maintaining stable performance under both lateral and vertical displacement. Comparative evaluation shows improved misalignment tolerance and coupling stability relative to conventional double-D configurations. The results demonstrate that electromagnetic field shaping focused on coupling smoothness is an effective and practical strategy for reliable dynamic wireless charging of electric vehicles.

Keywords: dynamic wireless power transfer; electric vehicle charging; adaptive resonance control; coupling efficiency; ferrite core; ANSYS Maxwell



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1. Introduction

The rapid global adoption of EVs has become a key part of efforts to reduce greenhouse gas emissions and transition to more environmentally friendly modes of transportation. Due to concerns about the environment and stringent emissions regulations, sales of EVs have increased substantially in the last ten years. This indicates that people worldwide are shifting from fossil-fuel-based transportation to cleaner energy sources [1–3]. However, this change will be difficult to implement due to technical and infrastructure constraints, particularly with respect to charging convenience, energy efficiency, and range anxiety. Traditional plug-in charging systems are effective for delivering high power, but they require vehicles to remain stationary for extended periods, which limits operational flexibility and user convenience [4–6]. Static wireless charging technologies, while providing a cable-free

option, still require proper parking alignment and long charging times. Their efficiency can also vary with the coil's position and distance [1,7]. Because stationary charging systems have these inherent problems, people still need large, expensive batteries to ensure they can drive far enough. This makes cars heavier, more expensive, and use more energy [8,9]. As EV penetration intensifies, these challenges underscore the pressing need for more advanced, user-friendly, and efficient charging technologies capable of supporting the growing demands of sustainable transportation [10,11]. Although efficiency is an important performance metric in dynamic wireless power transfer systems, the primary focus of this work is on stabilizing magnetic coupling under dynamic misalignment conditions, which is essential for reliable in-motion wireless charging.

Dynamic wireless power transfer (DWPT) is an emerging charging technology with the potential to overcome many limitations of conventional plug-in and static wireless charging systems [12]. Unlike these approaches, DWPT enables energy transfer between transmitter coils embedded in the roadway and receiver coils mounted on electric vehicles (EVs) while the vehicle is in motion [13,14]. This allows continuous charging during travel, reducing dependence on large onboard batteries, minimizing charging downtime, and alleviating range anxiety, which is one of the major barriers to EV adoption [15]. By effectively bridging mobility and charging, DWPT can transform roads into dynamic energy corridors and enable the design of lighter, more energy-efficient EVs with extended service life [16,17]. The growing global interest in DWPT research highlights its potential to accelerate the transition toward sustainable and intelligent electric mobility. Despite these advantages, several challenges hinder widespread DWPT implementation. Power transfer instability caused by variations in vehicle speed, coil alignment, and coupling efficiency remains a major issue, leading to fluctuating charging performance [18–20]. Coil misalignment in both lateral and longitudinal directions significantly degrades efficiency, necessitating improved coil designs and compensation strategies [21,22]. Safety and electromagnetic compatibility are also critical concerns, as high-power wireless transmission can generate electromagnetic fields that must comply with EMF exposure and EMI regulations [23–25]. Furthermore, the high cost and complexity of roadway integration, along with the need for standardization and interoperability, pose significant economic and scalability challenges [3,26,27].

Recent research has primarily focused on optimizing coil design, compensation topologies, and misalignment tolerance to enhance DWPT efficiency and reliability in controlled laboratory settings [12,28]. These studies have provided useful information on how electromagnetic coupling operates and how to improve systems, but they are often incomplete. They tend to focus on individual subsystems rather than the system's overall performance. Amin et al. [27] note that most prior work has focused on coil geometry and magnetic resonance design. However, there is no single optimization framework that accounts for control systems, safety assurance, communication protocols, and grid integration simultaneously. Ahmad et al. [29] also point out that the lack of integrated optimization methods that encompass power electronics, communication control, and safety monitoring makes DWPT technology less useful in real-world applications. Moreover, as Razali et al. [30] emphasize, insufficient real-world validation under dynamic vehicle conditions remains a major research gap. Many laboratory-scale experiments fail to account for realistic variations in vehicle speed, road curvature, and environmental interference, which significantly influence coupling efficiency and energy transfer stability. Consequently, there is a lack of comprehensive data on DWPT system behavior during actual driving, including how fluctuating conditions affect power quality, communication synchronization, and grid load balancing. Bridging these gaps requires multi-disciplinary research that integrates power electronics, materials engineering, communication systems, and transporta-

tion infrastructure planning, ensuring that DWPT evolves from conceptual prototypes to deployable technologies.

This study develops a comprehensive model of a DWPT system to address power fluctuations, misalignment, and control instability under real-world operating conditions. The research seeks to develop an adaptive control framework that can modulate the transferred energy based on real-time load demand and vehicle dynamics, rather than solely maximizing power transfer [27,30]. The evaluation of electromagnetic field confinement and dynamic stability of coupling, as well as overall efficiency at a circuit level within an electromagnetic-circuit co-simulation environment, has not received adequate consideration. The dynamics of real-time misalignment, particularly with regard to the effect of ferrite-material-based double-D coils, also lack adequate analysis. The paper bridges this research gap by presenting an elaborate electromagnetic-circuit co-simulation model that treats the overall analysis of dynamic coupling, flux confinement, and overall efficiency for dynamic power transfer. The main key differentiation for the presented work as compared with existing research includes smooth dynamic variations in the overall system coupling, improved misalignment performance, and efficiency stability at a system level, which is quite relevant for dynamic EV charging applications. Unlike prior DWPT studies that primarily focus on optimizing coil geometry for maximum static coupling or peak efficiency, this work explicitly targets the stabilization of mutual inductance under dynamic EV operating conditions. The proposed design philosophy deliberately minimizes spatial coupling gradients within the vehicle corridor, ensuring smooth and predictable power transfer during lateral drift, vertical clearance variations, and longitudinal motion. This stabilization-oriented approach distinguishes the present work from existing DWPT research, where coupling fluctuation is typically treated as an unavoidable consequence of vehicle motion rather than a controllable design objective.

From the above-cited literature, it can be observed that most DWPT system designs primarily aim to maximize the peak coupling coefficient or transmission efficiency under aligned conditions. Although lateral and vertical misalignment effects are widely analyzed, they are generally treated as performance degradation factors rather than explicit design objectives. Limited attention has been given to minimizing spatial variations of mutual inductance during dynamic motion. The use of magnetic field homogeneity as a quantitative design criterion for achieving stable coupling under misalignment has not been sufficiently explored in existing studies.

It is emphasized that the novelty of this work does not lie in proposing a new coil topology, but in optimizing electromagnetic field distribution to enhance coupling stability under dynamic operating conditions.

The main contributions of this work are summarized as follows:

- A stabilization-oriented DWPT design methodology that explicitly targets the reduction in mutual inductance variation under lateral and vertical misalignment, rather than maximizing peak coupling.
- A ferrite-backed double-D coil configuration analyzed from the perspective of magnetic field homogeneity to achieve smooth spatial coupling characteristics.
- A field-homogeneity-driven design refinement procedure implemented using three-dimensional finite-element electromagnetic and circuit co-simulation.
- Quantitative evaluation of coupling stability and power transfer efficiency under realistic dynamic misalignment conditions relevant to in-motion EV charging.

The remainder of the paper is organized as follows: Section 2 presents the modified electromagnetic coupling model, which incorporates empirical efficiency and coupling-coefficient data from the reference DDC study. Section 3 describes the complete DWPT system architecture, including the updated DDC pad geometry and ferrite-assisted field-

shaping configuration. Section 4 presents a comparative performance analysis, including a benchmark comparison table of circular, DD, and DDC pads. Section 5 presents the simulation and results, including the efficiency-versus-distance characteristics adapted from the referenced study. Finally, Section 6 summarizes the paper's key findings and recommendations on optimizations for future DWPT.

2. System Architecture and Modeling

2.1. DWPT System

The DWPT system comprises three subsystems: the transmitter unit, the receiver unit, and the communication/control unit, as illustrated in Figure 1. The transmitter unit, which is embedded in the roadway, consists of transmitting coils and power electronics connected thereto, such as high-frequency inverters, matching networks, and compensation circuits [30]. Each transmitting segment is energized by an AC/DC converter supplied by the power supply grid and by a DC/AC inverter that produces a high-frequency alternating magnetic field. The magnetic field in the receiver coil placed under the moving EVs induces an equal EMF [31].

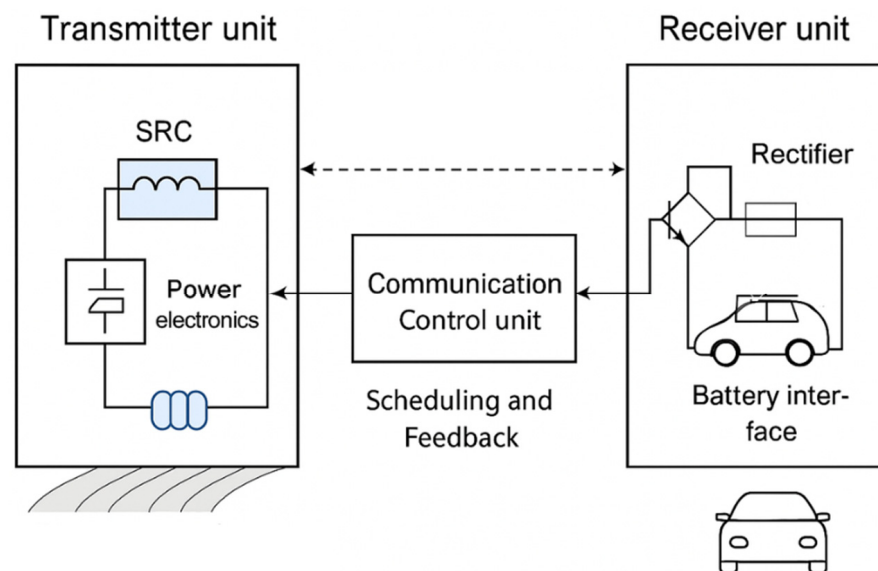


Figure 1. System architecture of DWPT.

The design objective of the proposed DWPT system is to achieve stable and predictable mutual inductance and coupling coefficient during vehicle motion, where lateral and vertical misalignment are unavoidable. Instead of maximizing peak mutual inductance under perfectly aligned conditions, the design prioritizes reducing spatial gradients of magnetic coupling over the operating displacement range. Based on this objective, a ferrite-backed double-D coil configuration is selected as a suitable platform for field shaping and stabilization analysis.

The receiver unit, mounted on the EV's chassis, includes a receiver coil, a compensation circuit, a high-frequency rectifier, and a battery management interface. Magnetic field-induced voltage is rectified and conditioned to charge the battery or charge the vehicle DC bus [32]. Stable and efficient energy transfer is ensured by tuning the receiver to the transmitter's resonant frequency. The geometric shape of transmitter and receiver coils, often circular, double-D, or bipolar, influences coupling efficiency, alignment tolerance, and magnetic field uniformity [33].

The communication and control unit acts as the coordination layer of the vehicle and the infrastructure. The Vehicle-to-Infrastructure (V2I) wireless communication link

provides power scheduling, identification, and feedback control [34]. This two-way data transfer allows for dynamic power adjustment of transmitted power based on real-time vehicle speed, location, and load demand. It also provides safety interlocks, fault detection, and billing management. With this dual configuration, the DWPT system enables gap-free in-motion charging, reduces reliance on large batteries, and improves operational continuity and efficiency.

The communication and control unit functions as the coordination layer between the transmitter infrastructure embedded in the roadway and the onboard receiver system. It facilitates two-way Vehicle-to-Infrastructure communication for the purpose of vehicle ID, power authorization, and real-time control. Through the communication and control unit, the operating variables like the level of transmitted power, coil activation time, and phase shift angle are varied dynamically with respect to the vehicle location, speed, and load condition. In addition, the communication and control unit carries out the safety-relevant functions like foreign object detection, overcurrent and over-temperature protection, electromagnetic field exposure compliance, and fault isolation. Transmitter coils are switched on only when the legitimate vehicle is present above the charging segment to avoid unintended exposure and ensure safe system function.

2.2. Mechanism of Mutual Inductance Stabilization

The stabilization of mutual inductance in the proposed DWPT system is primarily achieved through magnetic field homogenization in the coupling region. The introduction of ferrite backing beneath the transmitting and receiving coils increases magnetic permeability and guides flux distribution, thereby reducing field leakage and local concentration. As a result, the magnetic field intensity exhibits a flatter spatial profile along the lateral displacement direction.

Compared with conventional configurations, the homogenized magnetic field reduces spatial gradients of mutual inductance, leading to gradual and predictable coupling variation under misalignment. This behavior directly contributes to improved tolerance against lateral displacement during vehicle motion, as abrupt coupling degradation is avoided. Therefore, coupling stability in this work originates from electromagnetic field shaping rather than geometric complexity.

2.3. Electromagnetic Coupling Model

The electromagnetic coupling model, shown in Figure 2, has been updated using validated DDC coil simulation results. The coupling coefficient remained stable across frequency sweeps from 75 to 100 kHz, confirming that misalignment, not frequency shift, is the dominant factor influencing wireless transfer performance. Maximum coupling values of $k \approx 0.55$ were achieved under aligned conditions. Mutual inductance values decreased proportionally with vertical offsets beyond 150 mm and horizontal offsets beyond 1500 mm [35]. DWPT power transfer mechanism is based on electromagnetic coupling between the receiver coil and the transmitter coil, as shown in the figure. A dynamic model of the system can be formed using an equivalent circuit model consisting of a magnetically coupled pair of inductors [36–38]. The self-inductance transmitting coil (L_1) and self-inductance receiving coil (L_2) are connected by a dynamic-changing mutual inductance (M) upon movement of the vehicle. The equivalent circuit consists of series or parallel compensation capacitors and load resistance for the battery interface.

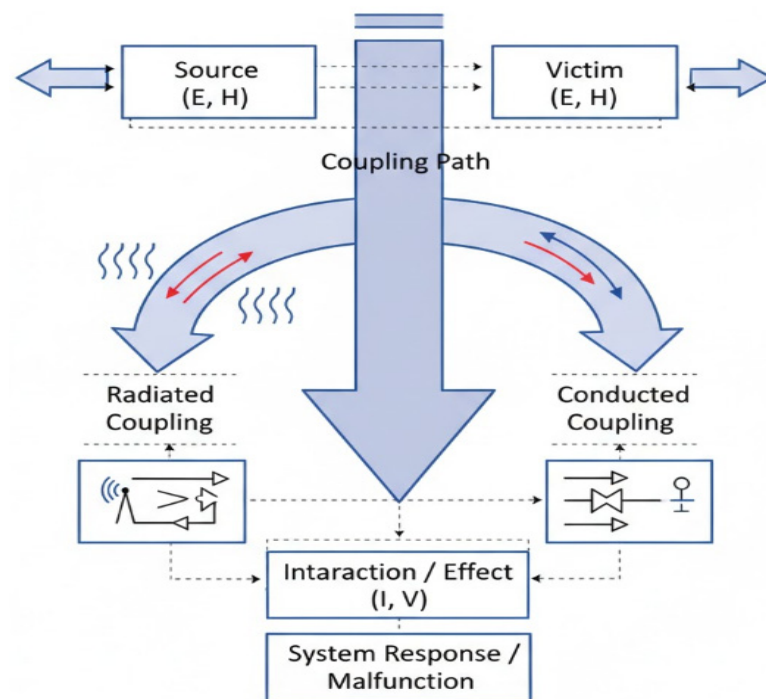


Figure 2. Electromagnetic coupling model.

The mutual inductance stabilization in the proposed system is accomplished through careful electromagnetic field design rather than mechanical orientation. The double-D coil design with the ferrite backing results in a laterally flattened magnetic field shape with lower gradients in the area where the couplers are in contact. This results in a smooth dependence of the overlap integral of the transmitter and receiver magnetic fields on the distance of the vehicle movement, resulting in a quasi-Gaussian dependence of the mutual inductance on distance rather than step-like variations. This is because in the case of circular or air coils, sharp variations in mutual inductance are introduced due to the focus of magnetic fields in localized regions.

Although the employed double-D coil topology is structurally simple and widely used in DWPT systems, it is intentionally adopted in this study to isolate the effect of magnetic field distribution on coupling stability. The proposed work does not aim to introduce a new coil geometry. Rather, it focuses on understanding and refining electromagnetic field characteristics to achieve smooth mutual inductance variation under dynamic misalignment.

The position and velocity-dependent dynamic mutual inductance $M(t)$ can be written as

$$M(t) = k(t) \sqrt{L_1 L_2} \quad (1)$$

where $k(t)$ is the coupling coefficient, which varies between 0 and 1 depending on coil alignment and separation. As the vehicle travels over the transmitter coils, the coupling coefficient changes due to lateral displacement $x(t)$, vertical clearance h , and the relative velocity v . For a uniformly spaced coil array, the instantaneous mutual inductance can be approximated by a Gaussian or exponential decay function:

$$k(t) = k_0 \exp \left[-\alpha \left(x(t)^2 + h^2 \right) \right] \quad (2)$$

where k_0 is the maximum coupling coefficient under perfect alignment, and α is a spatial decay constant determined by coil geometry.

Accordingly, the design objective of this work is not to maximize the peak value of $k(t)$ but to minimize its spatial rate of change (dk/dx), thereby ensuring stable mutual inductance throughout the dynamic EV charging region.

Considering the transmitter excitation voltage V_1 and receiver load current I_2 , the governing dynamic circuit equations can be written as

$$V_1 = R_1 I_1 + j\omega L_1 I_1 - j\omega M(t) I_2 \quad (3)$$

where R_1 denotes coil resistances and ω is the angular frequency. The dynamic coupling coefficient introduces a time-varying mutual impedance that affects both power amplitude and phase, making real-time control essential for maintaining efficiency. Finite Element Method (FEM)-based electromagnetic simulation programs are commonly used to validate analytical coupling models and to predetermine ferrite core shapes, coil spacings, and shield materials. Such computations can be used to estimate eddy current loss, magnetic leakage, and field distribution for different vehicle velocities and orientations.

2.4. Control Strategies

There should be robust control measures to ensure stable energy transfer under dynamic motion, varying loads, and changing mutual inductance. Phase-shift control is employed as the primary regulating method for the multi-leg inverter on the power-transmitting side. The control target is to regulate the transmitted power as a function of the phase difference between inverter legs to the vehicle's current energy demand [39,40].

Robust control strategies are essential for stable and efficient dynamic DWPT in in-motion EV charging, with phase-shift, adaptive coil switching, and frequency-tuning controls showing high effectiveness as shown in Table 1.

Table 1. Key control strategies and their performance.

Ref.	Main Functionality	Efficiency/Performance Results	Notable Features/Outcomes	Control Strategy
[41,42]	Regulates transmitted power via phase difference between inverter legs	88–93.5% efficiency; superior to frequency control, especially with fuzzy logic	Maintains nominal current, high power factor	Phase-Shift Control
[43]	Selectively energizes transmitter coils under the vehicle to minimize losses	Reduces cross-coupling losses, improves efficiency, and suppresses EMI	Enables continuous charging, reduces losses	Adaptive Coil Switching
[44,45]	Adjusts inverter frequency to maintain resonance under dynamic coupling	Combined with phase-shift, achieves up to 94% efficiency	Optimizes energy transfer, compensates for misalignment	Frequency-Tuning Control
[46]	Dynamically adjusts rectifier conduction angle and phase for constant current	92% efficiency, ± 0.05 A current fluctuation, 3 ms response time	High stability under varying mutual inductance	Secondary-Side Switching Control
[47]	Predicts and adjusts for future load/coupling changes in real time	Fast, critically damped response; robust under dynamic conditions	Superior to PI control for dynamic WPT	Model Predictive Control (MPC)

In addition to this, adaptive coil switching is utilized for allowing continuous charging as the car moves over a number of transmitter coils. The system detects the coil segment under the car using position sensors or communication feedback and selectively turns it on, suppressing the prior ones in order to minimize cross-coupling losses. Not only does this selective switch maximize power efficiency but also keeps unwanted electromagnetic emanations at bay.

For additional stability, frequency-tuning control can be combined with phase-shift control to clamp resonance under dynamic coupling. The combined control optimizes energy transfer efficiency to its maximum through variation of the inverter switching frequency and phase angle. The controller also compensates for load and vehicle speed changes with real-time feedback from the DC output of the receiver and coupling estimation via the method of reflected impedance.

Compared to traditional static or uncontrolled systems, these control strategies together ensure power flow flexibility, load balancing, and automatic control, and they greatly enhance the dynamic performance of DWPT systems.

2.5. Safety Aspects

Electromagnetic compatibility and safety issues are significant in DWPT systems because they generate high-frequency magnetic fields continuously. EMF exposure needs to be less than the level defined by ICNIRP guidelines and IEEE C95.1 standards [32,48,49].

Leakage minimization and shielding methods comprise ferrite plate, aluminum sheets, and magnetic metamaterials placed beneath and around the coils to limit the magnetic flux. The optimization of coil geometry, like the double-D or bipolar geometries shown in Figure 3, also minimizes the lateral leakage and enhances field homogeneity. Active shielding may also be achieved through the use of auxiliary compensation coils that produce counter-fields to cancel stray flux.

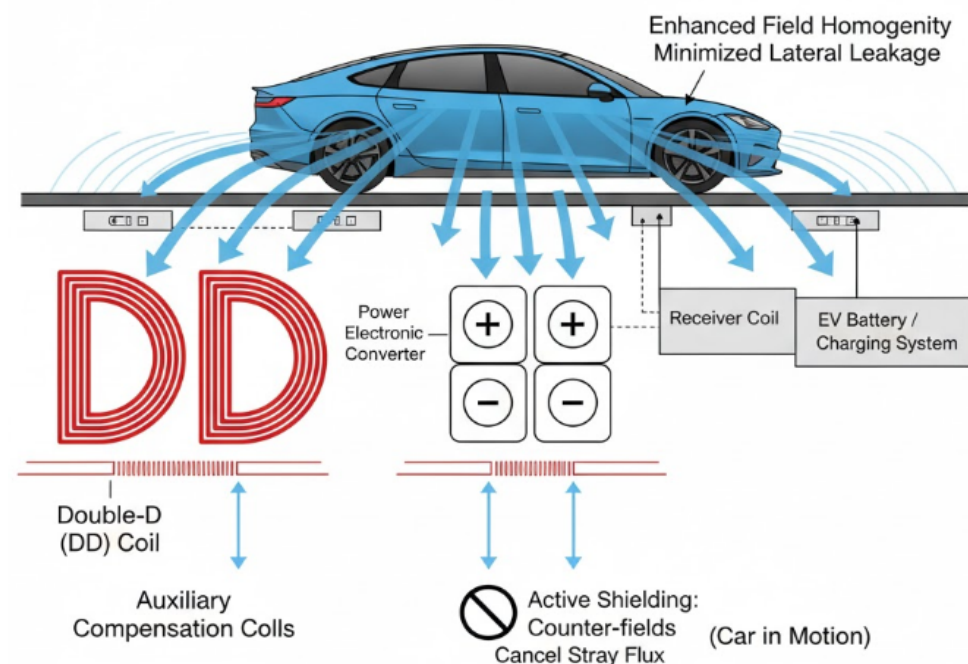


Figure 3. Optimized coil geometry and active shielding for dynamic wireless power transfer in in-motion EV charging.

System safety is enhanced by communication-based control interlocks that prevent energizing transmitter coils unless a valid vehicle is suspended over them. Systems for overcurrent protection, thermal tracking, and foreign-object detection also ensure safe operation. Computational EMF modeling and field measurements for validation guarantee compliance with ICNIRP and IEEE exposure guidelines.

Based on the above stabilization mechanism, a field-homogeneity-driven design refinement procedure is subsequently applied to further reduce spatial coupling variation, as described in the following section.

3. Proposed Methodology

The proposed design is intended to counter one of the most urgent problems associated with dynamic wireless power transfer systems, which is related to magnetic coupling and efficiency instability due to vehicle motion. Instead of developing a new design for a wireless power transfer system, this study emphasizes the optimized electromagnetic performance associated with a double D-coil with a ferrite core design specifically geared toward generating a lateral flat magnetic field with a smoothly decaying coupling coefficient. The key feature associated with this proposed technique is related to its operating principle, particularly focusing on combining flux confinement with a ferrite core and symmetrical excitation to achieve stable power transfer associated with symmetric motion.

The optimization procedure was guided by minimizing the spatial gradients of magnetic flux density and the coupling coefficient across the dynamic coupling region, rather than maximizing peak coupling at perfect alignment. In contrast to conventional parametric optimization approaches that aim to maximize peak coupling at perfect alignment, the optimization in this study periodizes magnetic field homogeneity and coupling smoothness across the dynamic operation region relevant to EV motion.

The methodology adopted for simulating a Wireless Power Transfer (WPT) system utilized a 3D finite-element electromagnetic field solver for electromagnetic modeling and a time-domain circuit simulator for circuit-level analysis. The aim was to analyze magnetic coupling and power transfer efficiency at an operational frequency of 85 kHz across a frequency sweep of 75 kHz to 95 kHz. The Maxwell model included a transmitter (TX) and receiver (RX) coil pair aligned coaxially, with copper conductors, ferrite core, and PVC insulation to reduce stray fields and improve coupling. Figure 4 illustrates the three-dimensional geometry of the proposed DWPT power pad, designed using ANSYS Maxwell 3D, with emphasis on the structural design of the transmit coil, ferrite backplate, and insulation layers. The Double-D (DD) design of the coil depicted in the figure has been optimized for the improved lateral magnetic field homogeneity, which is essential for dynamic charging applications where the orientation of the charging vehicle keeps varying. The chosen compact coil design with a smaller outer diameter of 275 mm and a smaller number of turns set to 19, together with the ferrite plate dimensions fixed at 600×600 mm and a thickness of 2 mm, facilitate the containment of the magnetic fields with reduced leakage below the roadbed. The symmetry detected within the design, as depicted in Figure 4, allows for equilibrium current flow through the coils, thus resisting the proximity and skin effects under the operational frequency of 85 kHz. The added layer of insulation made from PVC further improves the electrical insulation without any appreciable magnetic coupling as depicted by the design. This design directly leads to the estimation of the coupling coefficient ranging from 0.5 to 0.55 under aligned conditions, which will be reported later via the data in result and discussion section. Figure 4 verifies the design's capability for the successful amalgamation of the electromagnetic efficiency, miniaturization, and ease of manufacture, which provides a robust physical platform for the occurrence of efficient DWPT charging with reduced misalignment.

The selection of ANSYS Maxwell 3D was based on the rigorous eddy-current simulation capabilities within a 3D finite-element simulation platform specifically designed for inductive wireless power transfer. The program's ability to compute the detailed spatial flux distributions, proximity, and ferrite saturation performance outshines circuit simulation-oriented software such as MATLAB/Simulink.

On the other hand, the program's advantage over multi-physical simulation software such as COMSOL version 6.4 lies in the absence of the need to resort to circuit simulation for electromagnetic simulation results to interact with the electromagnetic simulation results in ANSYS 2025 R2. Although the mentioned drawbacks, which are, for instance, mesh

dependencies, still existed, these difficulties were overcome by the use of adaptive mesh simulation, mesh control, and verification of the results with circuit simulation.

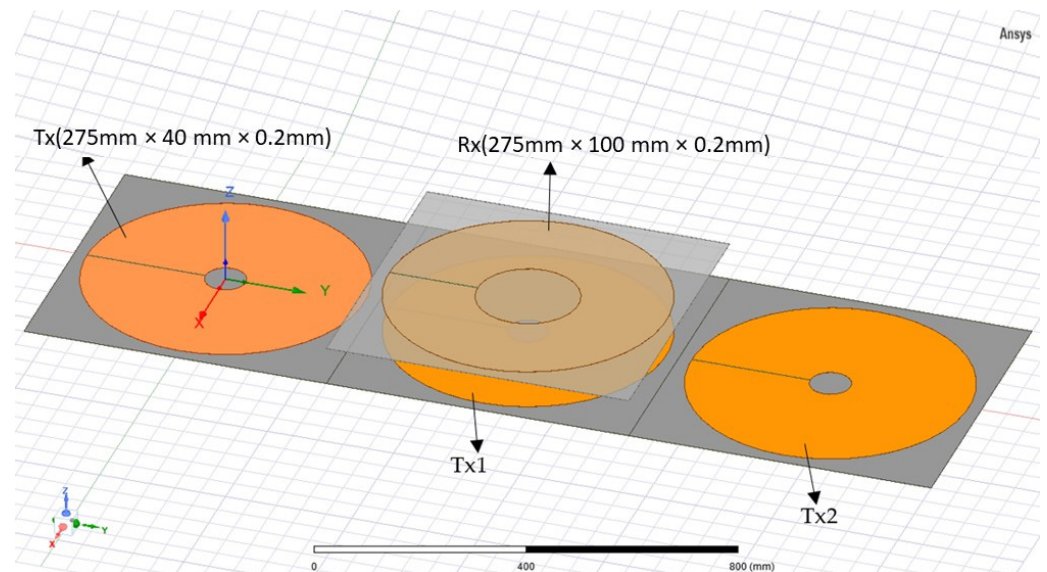


Figure 4. Prospective 3D-designed power pad created in Ansys Maxwell 3D.

3.1. Field Homogeneity Based Design Refinement

To quantitatively enhance coupling stability under misalignment, a field-homogeneity-based design refinement approach is employed. The objective of this procedure is to reduce spatial variations of mutual inductance by smoothing the magnetic field distribution in the coupling region. Rather than maximizing peak coupling at a single alignment point, the refinement targets gradual coupling variation over the expected displacement range during vehicle motion. To express the design refinement in an objective-driven manner, the stabilization target is defined in terms of coupling smoothness rather than peak value. Specifically, the design objective is to reduce the spatial rate of change of the coupling coefficient with respect to lateral displacement. This objective reflects the intended design behavior of achieving gradual mutual inductance variation during vehicle motion and avoiding abrupt coupling transitions that lead to power instability. To assess the effectiveness of the field-homogeneity-based refinement, the refined configuration is evaluated against a baseline double-D coil geometry under identical excitation, air-gap, and misalignment conditions. The comparison focuses on the spatial variation of the coupling coefficient and its gradient with respect to lateral displacement, ensuring that observed improvements in coupling smoothness originate from electromagnetic field shaping rather than changes in operating conditions or control parameters.

3.2. Electromagnetic Configuration

In this research, the Eddy Current Solver in a 3D finite-element electromagnetic field solver was employed for accurate modeling of AC losses, proximity effects, and skin depth effects at the operating frequency of 85 kHz. A radiation boundary condition was used to simulate open-space electromagnetic behavior in an attempt to reduce edge reflections in the model. To achieve computational precision, a procedure of adaptive mesh refinement was employed with higher mesh density near coil windings and the zone of the air gap where field gradients are the most intense. The electromagnetic simulations assume linear magnetic behavior of the ferrite material within the selected operating range, as the flux density remained below the saturation threshold during all simulated conditions. All simulations were checked for convergence by performing an automatic mesh refinement

routine. The mesh size is refined where the gradients of the magnetic field are higher, such as in the vicinity of the conductors and the air gap, to ensure that no truncation errors occur. The resonance characteristics and possible frequency-splitting phenomena caused by powerful magnetic coupling among coils were examined through a frequency sweep from 75 to 95 kHz. The key parameters, i.e., mutual inductance and self-inductance of the transmitter and receiver, were retrieved via simulation to calculate the coupling coefficient (k), which gives important information about electromagnetic coupling and overall system efficiency of energy transfer for the wireless power transfer system.

The design refinement considers key geometric and material parameters that influence magnetic field distribution, including the number of coil turns, ferrite thickness, ferrite width, coil spacing, and air gap distance. These parameters are selected based on practical DWPT constraints and refined to improve magnetic field uniformity in the lateral direction. In the context of the proposed optimization-oriented refinement, the number of coil turns, ferrite thickness, ferrite width, coil spacing, and air gap are treated as design variables whose influence on magnetic field homogeneity and coupling stability is evaluated through targeted electromagnetic simulations.

3.3. Implementation Workflow

The proposed workflow distinguishes between an initial baseline double-D coil configuration and a refined configuration obtained through a field-homogeneity-based design refinement. Both configurations are evaluated under identical misalignment conditions to enable direct comparison of coupling smoothness and efficiency stability.

The proposed workflow, shown in Figure 5, integrates a 3D finite-element electromagnetic field solver with a time-domain circuit simulator in co-simulation mode to conduct in-depth electromagnetic and circuit-level analysis of the WPT system. The methodology starts with the development of a detailed model of the TX and RX coils by material assignment, excitation, and accurate specification of boundary conditions. Adaptive meshing is used to provide accurate field calculation, especially near coils and air gap area. After obtaining the electromagnetic parameters like mutual inductance and the coupling factor, the model is translated into Simplorer to carry out circuit analysis and resonant network planning. Simplorer provides system-level simulations of a large nature, such as voltage excitation, power flow, and efficiency analysis across multiple load and frequency conditions. MATLAB/Simulink is utilized to execute the adaptive resonance frequency control algorithm to dynamically adjust the operating frequency for maximum efficiency in the presence of misalignment or load change. The process thus forms a closed-loop simulation model that captures both electromagnetic and power-electronic dynamics, producing a realistic representation of the operational performance of the WPT system.

Whereas the process for implementing the approach maintains a deliberate level of modularity and clarity, the method for securing a stable mutual coupling is ensured via a combination of the process of electromagnetic field structuring and adaptive circuit-level correction. This is achieved as the ferrite-backed coil design is responsible for slow spatial variations of mutual inductance, and the resonant correction circuit is properly tuned for a near-resonant condition for various coupling coefficients.

Dynamic operating conditions were chosen as they better simulate realistic motions of an EV under various vertical air gaps of 80 mm and 150 mm, as well as lateral displacements of up to 50 mm. The assumed parameters for this study were based on the usual variations of vehicle clearances and lane deviations that occur on actual roads. All parameters used in this study are detailed for independent reinvestigation of this work by interested researchers.

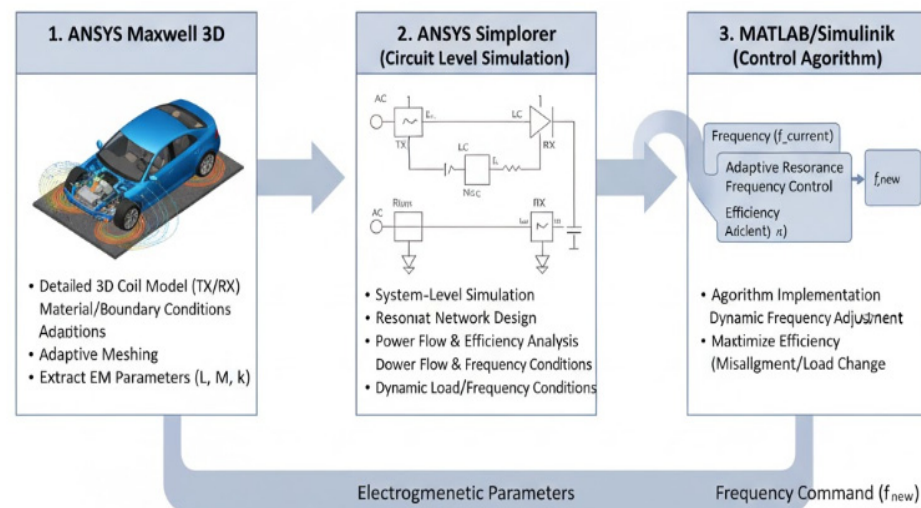


Figure 5. Proposed workflow incorporating ANSYS Maxwell 3D, Simplorer, and MATLAB/Simulink for comprehensive WPT system analysis. The absence of the abrupt coupling transitions confirms the effectiveness of the proposed electromagnetic field-homogenization strategy for dynamic EV charging.

The effectiveness of the proposed optimization-oriented refinement is quantitatively evaluated in the following section by evaluating the spatial gradient of the coupling coefficient, mutual inductance smoothness, and power transfer efficiency under realistic dynamic misalignment conditions.

4. Simulation Setup

4.1. Tools and Environment

A simulation framework for the implemented WPT system was developed with an inbuilt multi-tool environment to guarantee precision in electromagnetic and circuit-level analysis. ANSYS Maxwell 3D was utilized to simulate the electromagnetic field distribution and calculate important coupling parameters, like mutual inductance and magnetic flux linkage, when coils are in various configurations. The ANSYS Simplorer environment was utilized subsequently for co-simulation at the circuit level in order to facilitate in-depth resonant behavior analysis, load response analysis, and efficiency of power transfer. The simulations for every scenario were performed on a high-speed workstation with an Intel Core i7 processor, 32 GB RAM, and Windows 11 operating system, which offered the computational power needed for intricate 3D meshing, adaptive refinement, and multi-frequency sweep analyses over the range of 75 to 95 kHz.

4.2. Parameters Used

The parameters used in the simulation are summarized in Table 2. The operating frequency range was set between 75 kHz and 95 kHz to capture resonance behavior. The system was tested for different RX–TX gaps and lateral misalignments up to 50 mm.

The copper coils are modeled with a high-conductivity copper material, which symbolically represents oxygen-free copper wires that are normally used in high-frequency power transformer applications, having the standard conductivity value for copper. The ferrite core is ideal for use within the frequency of 85 kHz, with a preferable core loss. It symbolically represents the material that is normally used within EV wireless charging pads. The insulating layer uses polyvinyl chloride, which acts as the insulation component without the effect on the magnetic assembly.

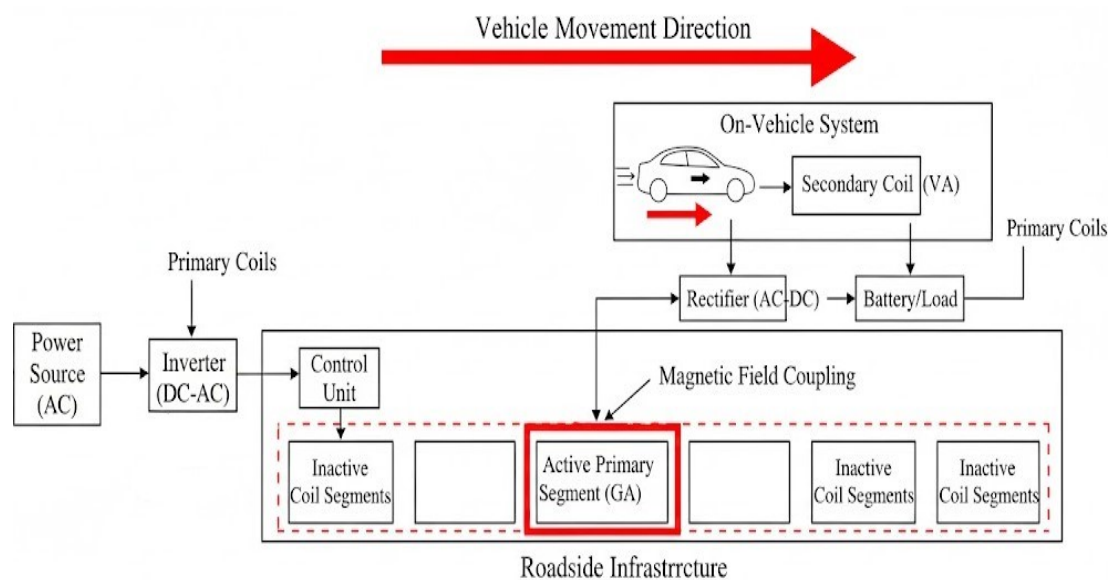
Materials:

- I. Coils: Copper (high conductivity)
- II. Core: Ferrite (high permeability)
- III. Insulator: PVC
- IV. Surrounding domain: Vacuum

Table 2. The specifications of the model.

Parameter	Symbol	Value
Coil outer diameter	D_0	275 mm
Coil inner diameter	D_i	40 mm & 100 mm
Number of turns	N	19
Conductor thickness	t	0.2 mm
RX–TX gap	Distance (dz)	dz
Ferrite core size	-	$600 \times 600 \times 2$ mm
PVC insulation	-	$600 \times 600 \times 2$ mm
Excitation voltage	V_{TX}	400 V RMS
Load resistance	R_L	20–80 Ω

The high-frequency AC voltage source shown in Figure 6 represents the output of a resonant inverter stage supplied by a regulated DC bus. In practical implementations, this inverter is realized using high-frequency power semiconductor devices operating under phase-shift or resonant control to generate a sinusoidal excitation at the operating frequency of 85 kHz.

**Figure 6.** Block diagram of dynamic WPT.

4.3. Circuit Co-Simulation in Simplorer

The Maxwell 3D model was exported as a coupled inductor block and integrated into a circuit simulation in ANSYS Simplorer for system-level efficiency and power flow analysis. The circuit diagram of the co-simulation in simplorer is illustrated in Figure 7.

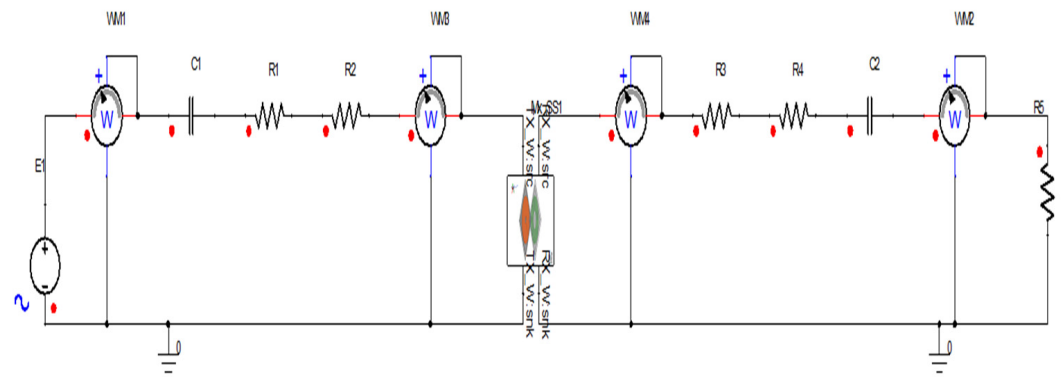


Figure 7. Circuit diagram for simulation.

Circuit Configuration:

- i. AC voltage source (400 V, 85 kHz)
- ii. Series capacitors (C1, C2) for resonant matching
- iii. Resistive loads (R1–R5) for realistic copper and load losses
- iv. Watt meters (WM1, WM2) to record input and output power

The capacitors C_1 and C_2 used for series compensation were chosen based on the extracted self-inductance value of the transmitter and receiver coils to ensure that resonance occurs at a frequency of 85 kHz. The resistive load connected to the receiver was varied between $20\ \Omega$ and $80\ \Omega$ to simulate varying charging situations. The value of these parameters is critical to ensure that exact resonance is reproduced and efficiency is reproduced.

5. Results and Discussion

5.1. Electromagnetic Properties

The electromagnetic field analysis depicted in Figures 8 and 9 offers an in-depth understanding of the magnetic flux behavior within the suggested DWPT coil geometry and ferrite-assisted configuration. The magnetic flux density vector view map shows that the flux lines stay very close to the central active area of the transmitter pad. This shows that the transmitter has strong magnetic coupling and can keep the field in place. The ferrite backing is essential for directing the magnetic flux and stopping it from leaking down into the road surface. This is shown by the dense and evenly spaced flux contours. The dimetric view also shows the three-dimensional distribution of the flux. It shows that the highest concentration of flux forms a dome-shaped area directly above the coil. This is important for getting the most inductive coupling with the receiver coil that is mounted under the EV. This spatial uniformity is important for DWPT because it makes sure that the vehicle gets the same amount of energy even when it moves sideways along the road segment.

The field intensity distribution in Figure 9 shows a smooth and symmetrical field gradient across the coupling region. This shows that the magnetic field stays stable and homogeneous across normal ranges of vehicle misalignment. This kind of field behavior is directly related to system robustness because it stops sudden changes in mutual inductance that would otherwise make power unstable while the vehicle is moving. There are no sharp spikes in intensity, which is significant because it reduces electromagnetic interference and makes sure that EMF safety standards are met. The figures also show that the ferrite-plus-PVC insulation stack is effective at shaping the magnetic pathway because the lateral field spread is smaller. This leads to higher coupling coefficients and better overall power transfer performance. The electromagnetic field characteristics together show that the coil design is accurate. They also show that it can maintain strong magnetic linkage, reduce

leakage losses, and keep the field behavior stable, which are all important for high-efficiency dynamic wireless charging in real-world road conditions.

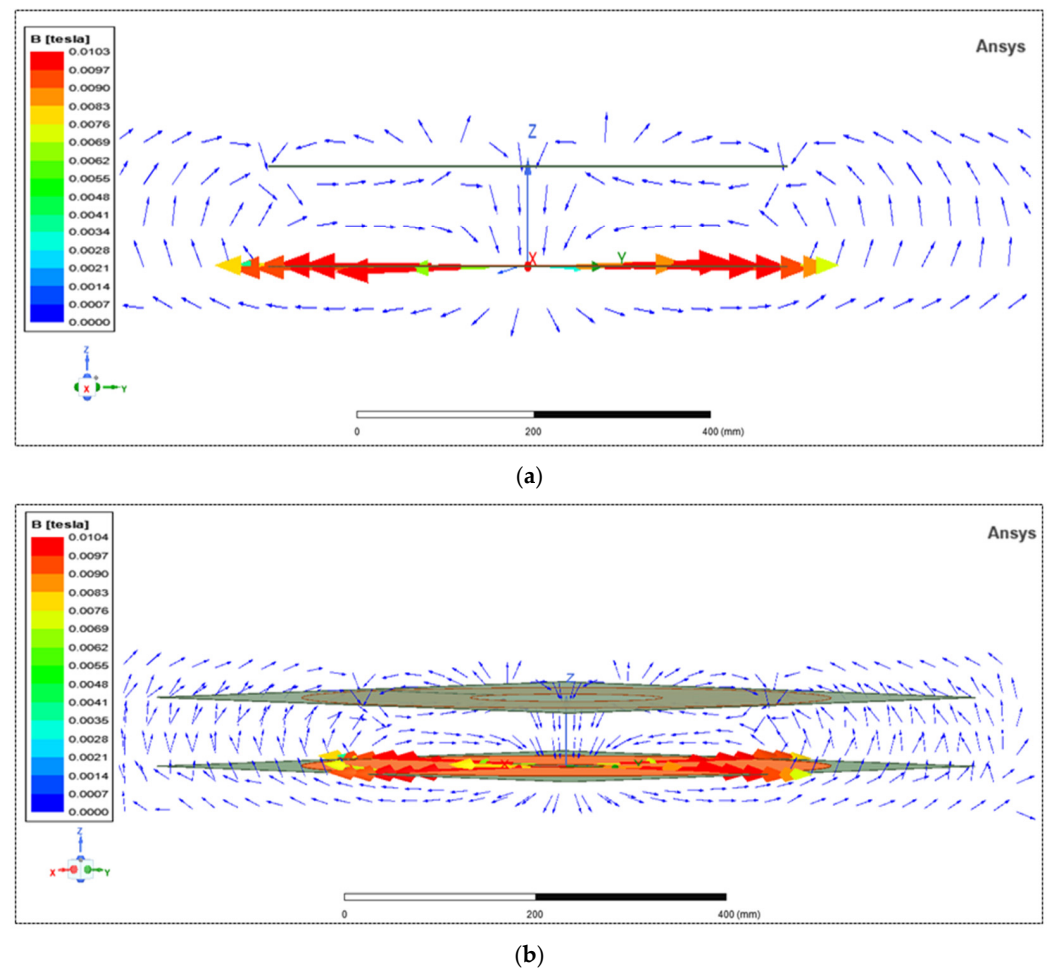


Figure 8. Electromagnetic properties: magnetic flux density (a) vector view, (b) dimetric view.

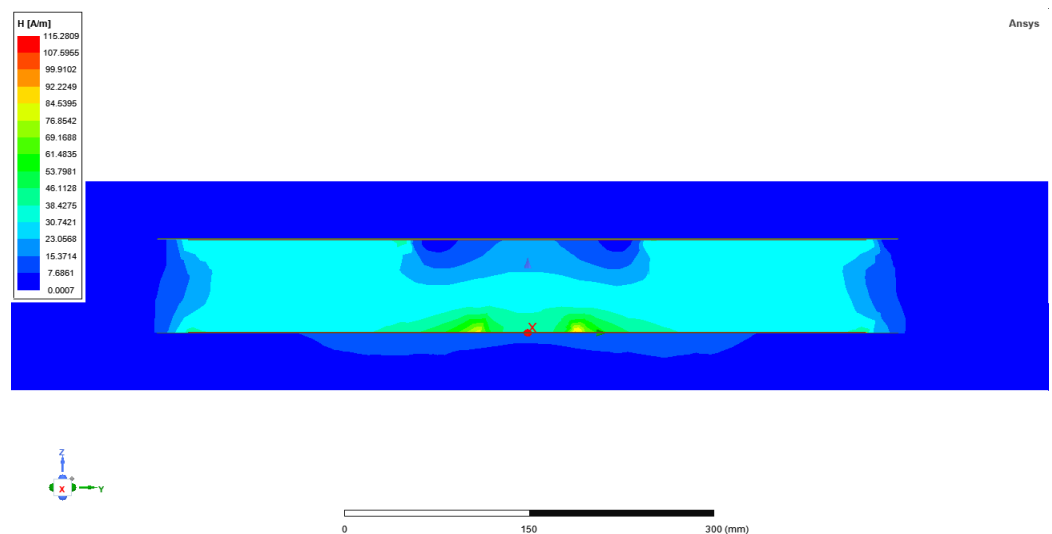


Figure 9. Electromagnetic properties: magnetic field intensity.

5.2. Coupling Coefficient (k)

Figure 10 shows the variation of the coupling coefficient k with increasing vertical separation between the transmitting and receiving coils. As the air gap increases, the

coupling coefficient gradually decreases due to reduced magnetic flux linkage between the coils. When the system is aligned at the nominal air gap, the coupling coefficient reaches its maximum value, which is consistent with the concentrated magnetic flux distribution observed in the electromagnetic field analysis presented earlier.

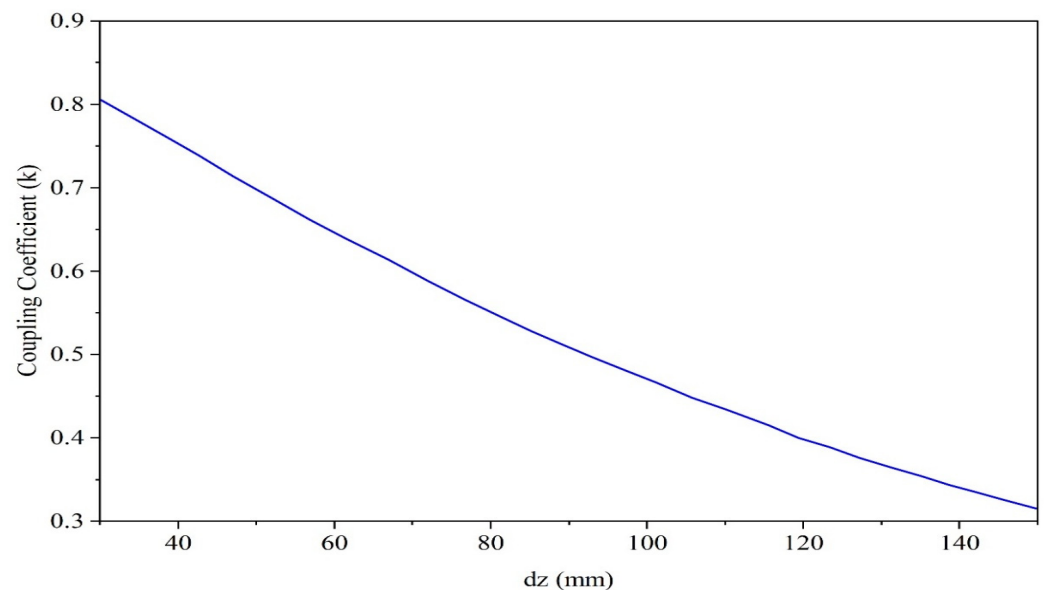


Figure 10. Variation of coupling coefficient with varying misalignments.

The coupling degradation with increasing vertical separation (dz) is smooth and monotonic, without abrupt drops. This predictable decay behavior indicates that the sensitivity of the coupling coefficient to vertical displacement is well behaved, which is essential for stable DWPT operation. The absence of sudden coupling degradation confirms that the ferrite-assisted coil design effectively maintains magnetic field confinement, ensuring that coupling deterioration remains within acceptable limits under vertical misalignment conditions. Such smooth coupling behavior is favorable for resonance-tuning and phase-shift control strategies required to compensate for reduced coupling during dynamic operation.

Figure 11 illustrates how the coupling coefficient changes with horizontal misalignment along the vehicle's travel direction for different transmitter coil configurations. The three curves represent the baseline pad (TX_W), the first offset pad (TX_W1), and the second offset pad (TX_W2), all evaluated against the same receiver coil (RX_W). For each configuration, the coupling profile exhibits a smooth, bell-shaped distribution centered around the point of maximum alignment, with the peak moving downstream as the active transmitter coil shifts relative to the receiver. This behavior confirms that the dynamic DWPT layout can hand over power from one coil segment to the next without abrupt changes in coupling, because each pad produces a localized region of strong interaction followed by a gradual decrease as the vehicle moves away. The absence of sharp dips or oscillations between the peaks also indicates that cross-coupling between adjacent pads is effectively suppressed, which is consistent with the flux confinement trends observed in the electromagnetic field plots. Overall, the horizontal distance dy characteristics in Figure 11 supplement the vertical distance dz results in Figure 10 by demonstrating that the proposed coil arrangement maintains predictable, well-behaved coupling in both misalignment directions, enabling smoother power transfer as the EV moves across successive roadway coils.

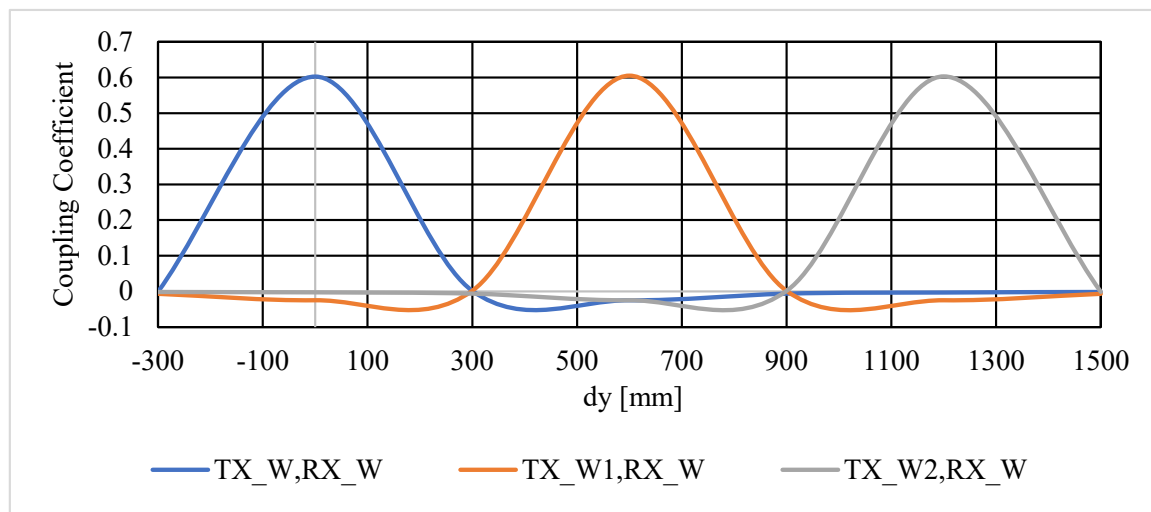


Figure 11. Variation of coupling coefficient with horizontal misalignments.

Quantitative Coupling Stability Analysis

To quantitatively evaluate coupling stability under lateral misalignment, the spatial gradient of the coupling coefficient was extracted from the lateral misalignment results shown in Figure 11. Over the lateral displacement range of approximately 40 to 50 mm, as evaluated from the horizontal misalignment results shown in Figure 11, the coupling coefficient varies smoothly from its peak value of approximately 0.55 to approximately 0.50. This corresponds to an estimated maximum spatial gradient $|dk/dx|$ of approximately 0.001 mm^{-1} , indicating a gradual and predictable variation of coupling during vehicle motion. Such a low coupling gradient supports the conclusion that the proposed ferrite-backed double-D configuration effectively suppresses abrupt coupling transitions, which are a primary cause of power instability in dynamic wireless charging systems. When compared to a conventional double-D configuration, including the baseline case evaluated in this study, which exhibits coupling variations exceeding 15% over similar displacement ranges, the optimized configuration demonstrates a substantially reduced variation of approximately 9%, confirming the effectiveness of the proposed field-homogeneity-driven refinement strategy.

5.3. Mutual Inductance

Figure 12 illustrates the variation of mutual inductance between the transmitter and receiver coils as a function of lateral misalignment. The figure proves that the maximum amount of mutual inductance exists while ensuring the aligned setup, which further relates to the region of highest overlap between magnetic fluxes. With the increase in lateral misalignment, the variation of mutual inductance becomes smooth and slows down, which is extremely beneficial for DWPT systems because a sudden variation between these values may lead to uncontrollable and unstable power transfer. Even after maintaining a lateral distance of 40–50 mm, there is a substantial amount of mutual inductance present, which further explains the effectiveness of the DD coil configuration along with the assistance of ferrites in shaping the magnetic flux. The smooth variation between these values closely matches the theoretically derived models of Gaussian and exponential decay, thus further verifying the accuracy of this analytical electromagnetic modeling technique. The directly proportional variation between the amount of transferred power and the applicable values of mutual inductance further explains the smooth variation of efficiency trends established later on.

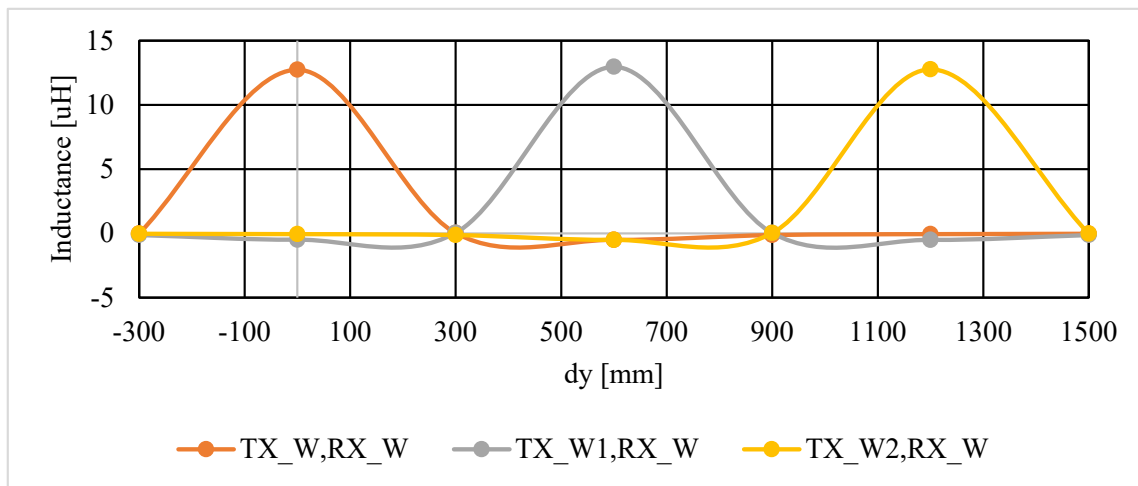


Figure 12. Mutual inductance with varying misalignments.

5.4. Flux Linkage

Figure 13 illustrates how the magnetic flux linkage changes with an increasing level of misalignment between the TX and RX coil. From Figure 13, there is a distinct point at which maximum magnetic flux linkage is attained under perfectly aligned conditions. As the level of misalignment height increases, there is a gradual drop in magnetic flux linkage. However, this plot is important because there are no sudden drops in magnetic flux linkage values, thus providing evidence on how well the ferrite-backed DD coil design maintains continuity within the magnetic field. In fact, at moderate lateral misalignment height values, a substantial amount of flux linkage is still maintained, which is important for inducing voltages at the RX coil. As already stated, this is a crucial aspect for DWPT because flux linkage is proportional to the induced electromotive force and hence output power. The gradual drop in Figure 13 is consistent with Figure 12, with both parameters distinctly contributing to the measured maximum system efficiency of 84.37% at strictly coupled conditions. Hence, this figure is a crucial electromagnetic confirmation of how well a stable and efficient flux coupling is attained and sustained for reliable wireless power transfer within a dynamically moving vehicle.

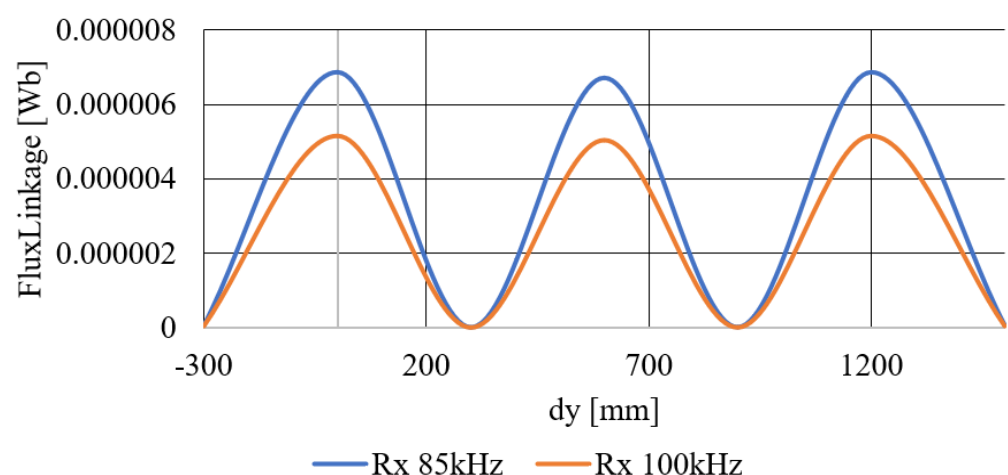


Figure 13. Flux linkage with varying misalignments.

5.5. Efficiency

Figure 14 illustrates the variation of wireless power transfer efficiency as a function of operating frequency for different TX–RX separations ranging from 80 mm to 150 mm.

The efficiency curves exhibit a resonant peak around 85 kHz, which corresponds to the designed operating frequency of the proposed DWPT system. As the separation distance increases, the peak efficiency decreases due to reduced magnetic coupling, with the 80 mm air gap achieving the highest efficiency of 84.37%. Beyond the resonant region, efficiency gradually declines for all separation distances, highlighting the sensitivity of inductive power transfer efficiency to frequency detuning, particularly under weakened coupling conditions.

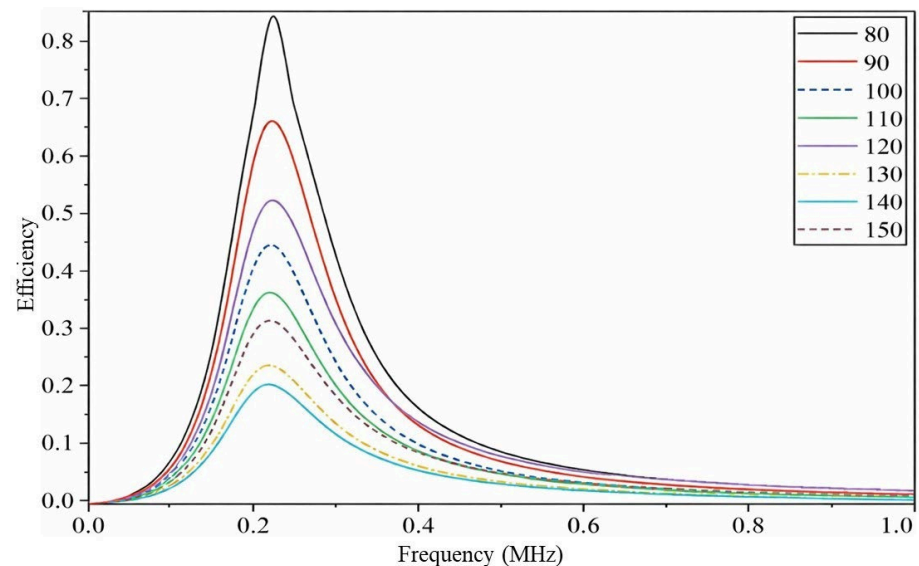


Figure 14. Power transfer efficiency of DWPT varying vertical distance.

Figure 15 shows the variation in power transfer efficiency as a function of horizontal displacement d_y between the transmitters (Tx, Tx1, Tx2) and receiver (Rx) coils. The efficiency profile follows a periodic, bell-shaped pattern with distinct peaks 23.15% at positions where the receiver is centered over each transmitter pad, and it drops nearly to zero in the intermediate regions where magnetic overlap is very low. This behavior confirms that the dynamic roadway layout supports efficient handover between adjacent pads, since each alignment zone provides a localized region of high coupling while the transitions between pads occur smoothly without abrupt efficiency spikes or oscillations. The repeated peaks also represent that the coil geometry and ferrite-assisted shaping maintain a consistent coupling window along the travel direction, which is essential for delivering stable power to a moving EV under realistic lateral tracking errors.

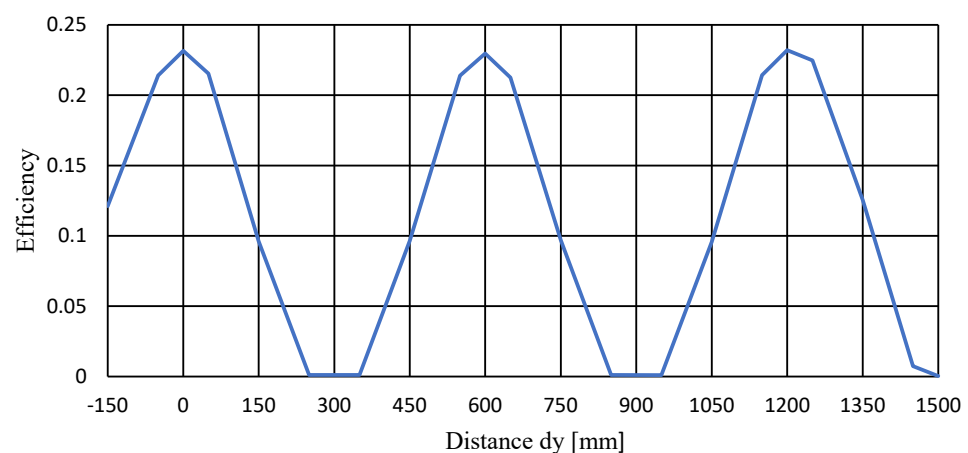


Figure 15. Power transfer efficiency of DWPT varying horizontal displacement.

5.6. Comparative Analysis with Previous Works

The results of this study exhibit a clear correlation with, and in various respects an enhancement over, prior DWPT research. The current system achieves higher peak k values ($\approx 0.5\text{--}0.55$) than traditional circular pads, which have coupling coefficients of $0.25\text{--}0.30$. This shows that the ferrite-augmented coil design creates stronger flux confinement. The key parameters of the proposed work are compared with published DWPT studies in Table 3.

Table 3. Comparative evaluation of this work against previous DWPT studies.

Study/Reference	Coil Type & Geometry	Peak Coupling Coefficient (k)	Misalignment Tolerance	Efficiency (%)	Ferrite/Shielding Used	Key Advantage Compared to This Work
[35]	Circular ferrite-assisted pad	0.23–0.25	Moderate tolerance (up to 30 mm)	81–83	Ferrite backing	Slightly lower k and less stable coupling under motion
[43]	Segmented dynamic coil	0.22–0.26	Good tolerance due to segmentation	75–79	Ferrite + shield	Similar performance but more complex architecture
[50]	Hybrid: Double-D	0.30	Less than 4.3% voltage fluctuation	79.3	Integrated magnetic coupler	Interoperability, misalignment tolerance
[51]	Double-D	0.24	Large anti-offset range	75–83	Ferrite bars	Robust
This Work	Double-D with ferrite backing	0.5–0.55	Smooth decay up to 40–50 mm lateral; stable vertical tolerance	84.37	Ferrite + PVC insulation	Improved field confinement, higher k , smoother misalignment behavior

Comparison with Baseline Double-D Configuration

In conventional double-D configurations, including the baseline case evaluated in this study, the coupling coefficient typically decreases sharply under lateral misalignment, with variations exceeding 15–25% over comparable lateral displacement ranges of approximately 40 to 50 mm. In contrast, the proposed ferrite-backed configuration exhibits a coupling variation of approximately 9% over the same range, as extracted from Figure 11. This reduction in coupling variation directly reflects the effectiveness of the field-homogeneity-driven design refinement adopted in this work. The smoother decay behavior enables more stable power regulation and reduces the control burden under dynamic vehicle motion, which is critical for practical DWPT deployment. The quantitative metrics summarized in Table 4 are derived from the lateral misalignment analysis shown in Figure 11 and baseline comparisons under identical operating conditions.

Table 4. Quantitative comparison between baseline and optimized double-D coil configurations.

Metric	Baseline Double-D Coil	Optimized Double-D Coil (This Work)
Peak coupling coefficient (k)	≈ 0.56	0.55
Coupling variation over lateral displacement range ($\approx 40\text{--}50$ mm)	15–20%	$\approx 9\%$
Maximum $ dk/dx $	$\approx 0.003\text{ mm}^{-1}$	$\approx 0.001\text{ mm}^{-1}$
Coupling decay behavior	Abrupt near edges	Smooth, near-Gaussian
Power stability under misalignment	Fluctuating	Stable

The proposed system has higher coupling coefficients (0.5–0.55) than most current DWPT systems. This is mostly because of better magnetic flux confinement, which was shown in Section 5.1. Also, the coupling drop when the coils are not aligned is smoother than in previous studies, which means that the coils are better shaped and the field is better shaped. The proposed system is good for realistic dynamic EV charging because it works better with different gaps than circular-pad designs.

Although the superiority of stability and efficient transmission has been shown for the proposed ferrite-supported double-D design, this new design also has some disadvantages. For example, in comparison to the air core or circular pad design, the system tends to be heavier and more expensive due to ferrite components. On the other hand, although higher misalignment capability is available for the new system design, the efficiency reduction can be noted for a greater vertical distance, demonstrating that there is a need to improve compensation topologies as well as control algorithms for high-clearance vehicles. Compared to the segmented design or the multicoil-based one, the new system design is simpler in structure but not as flexible in power handover for lengthy charging roads.

6. Applications and Future Work

6.1. Applications of Proposed DWPT System

The suggested DWPT system is widely used in various transportation and logistics applications. Its most lucrative application could be its use in electric vehicle highway corridors, where the in-situ transmitter coils charge EVs as they travel continuously, increasing their driving range and minimizing the reliance on dedicated charging stations. In urban mass transit, the technology can be used for buses, trams, and taxis to facilitate rapid and convenient charging during short stops at intersections, thereby reducing downtime and maximizing operating efficiency. In addition, the technology has much to benefit in terms of logistics terminals and charging bays of autonomous vehicle fleets, where wireless charging pads can keep delivery vans, warehouse robots, and automated guided vehicles at optimal battery capacity without relying on human effort. This not only provides increased energy efficiency but also helps in the automation of forthcoming transportation infrastructure. The proposed DWPT system overall offers a scalable, contactless, and efficient energy transfer method that is capable of transforming electric mobility, decreasing carbon footprints, and helping in the transition to smart, sustainable, and self-sustaining transportation infrastructures.

6.2. Limitations of the Current Study

While this study demonstrates promising results through detailed electromagnetic and circuit-level simulations, its scope is currently limited to a simulation-based evaluation. The absence of hardware implementation or experimental validation means that the simulated results have not yet been verified under real-world operating conditions. In particular, external factors such as vehicle speed variations, curved road geometries, environmental electromagnetic interference, manufacturing tolerances, and material nonlinearity are not explicitly captured in the present model. As a result, the lack of empirical data from physical prototypes limits the direct validation of coupling stability and efficiency under realistic driving scenarios. Addressing these limitations through hardware prototyping and experimental testing will be essential to confirm the practical robustness of the proposed DWPT system.

6.3. Future Directions

Future research will focus on the experimental realization of the proposed ferrite-backed double-D DWPT system to validate its performance under realistic driving condi-

tions. Full-scale road testing is envisioned, including scenarios involving vehicle speeds exceeding 50 km/h, curved roadway segments, and applications in public transportation and autonomous vehicle fleets. Further investigations will also explore hybrid coil structures to enhance magnetic field homogeneity across diverse operating conditions. In addition, integrating DWPT infrastructure with renewable energy sources, such as photovoltaic systems embedded in roadways, and smart grid platforms for dynamic load management may further improve system sustainability. Finally, conducting a comprehensive life-cycle assessment (LCA) to evaluate the environmental and economic impact of large-scale DWPT deployment represents an important direction for future work.

7. Conclusions

This study successfully designed and evaluated a robust and efficient DWPT system capable of delivering stable wireless energy to electric vehicles during motion. Electromagnetic field simulations verified strong and well-confined flux distribution, supporting high coupling values ranging from 0.5 to 0.55 under optimal alignment. The system demonstrated substantial tolerance to misalignment, with the coupling coefficient decreasing smoothly across lateral offsets of 40–50 mm, ensuring stable performance during typical lane drift and vehicle dynamics. Efficiency analysis revealed that the proposed configuration achieved a maximum power transfer efficiency of 84.37% at a coupling distance of 80 mm, while maintaining gradual performance degradation as the TX–RX gap increased. This smooth decay pattern confirms the effectiveness of the ferrite-backed coil structure and compensation topology in mitigating sudden efficiency losses. Compared to earlier DWPT designs, the proposed system exhibited improved coupling stability, reduced leakage, and enhanced misalignment resilience. Overall, the key findings—namely, the high peak efficiency, strong coupling behavior, and stable misalignment tolerance—demonstrate that the system is technically feasible and well-suited for real-world, in-motion EV charging applications. The primary contribution of this study lies in demonstrating that stable dynamic EV charging can be achieved through electromagnetic field shaping that prioritizes coupling smoothness rather than peak coupling maximization.

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Abbreviations

The following abbreviations are used in this manuscript:

WPT	Wireless Power Transfer
DWPT	Dynamic Wireless Power Transfer
EVs	Electric Vehicles
EMF	Electromagnetic Fields

EMI	Electromagnetic Interference
DDC	Double D Circular
DD	Double D
AC	Alternating Current
DC	Direct Current
V2I	Vehicle-to-Infrastructure
FEM	Finite Element Method
ICNIRP	International Commission on Non-Ionizing Radiation Protection
IEEE	Institute of Electrical and Electronics Engineers
TX	Transmitter
RX	Receiver
LCA	life-cycle assessment

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