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Wireless power transfer for electric vehicles : Design and efficiency analysis

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Abstract
Wireless Power Transfer (WPT) could make EV charging safer and more efficient by replacing physical connections. Electric car WPT system design and efficiency are the subject of this article. The implications of misalignment on coil topologies, resonance coupling, and charging efficiency are examined. After thorough computation and experimental validation, we provide a best WPT design that minimizes losses, improves energy transfer efficiency, and operates well in practice. WPT may speed up EV charging, according to study. We evaluate current and proposed methods to increase electric vehicle wireless charging system efficiency.
Keywords: Inductive Power Transfer (IPT), Coil Design Optimization, Misalignment Compensation, Efficiency Analysis, Electric Vehicles (EVs), Wireless Power Transfer (WPT)

1 Introduction

Electric cars (EVs) are becoming popular as eco-friendly alternatives to combustion engine cars. EV expansion is hindered by the charging infrastructure, which makes cable charging difficult and restrictive. Wireless power transfer (WPT) eliminates connectors and cords, making EV charging more convenient and versatile. Using electromagnetic fields, WPT systems transfer power from a charging station's transmitting coil to the car's receiving coil. This technique claims to improve user experience by seamless charging, especially in dynamic contexts like on-the-go charging.

EV WPT's biggest problem is high charging efficiency, especially with coil misalignment and weather changes. Efficient power transfer reduces charging time, ensures system safety and sustainability, and reduces energy loss. WPT technology has advanced, but a thorough examination of design requirements and performance parameters is still needed to maximize system efficiency.

1.1 Challenges

1. **Efficiency Loss Due to Misalignment**: EV wireless power transfer (WPT) is hindered by transmitting and receiving coil misalignment, which reduces power efficiency.Actual conditions may result in poor coil alignment due to vehicle position, dynamic movement, or other variables. This difference could significantly reduce power transfer and hinder energy transfer.
2. **Coil Design Complexity**: Space, efficiency, and cost must be balanced while designing coils for many EV models. Magnetic coupling depends on coil form, material qualities, and operating frequency, therefore coil design must be tweaked to enhance it. This precise equilibrium is hard to maintain without increasing system complexity or cost.
3. **Electromagnetic Interference (EMI)**: High - frequency WPT systems can interfere with nearby electrical devices. This interference may harm the EV charging system and other electrical components and infrastructure. The WPT system must operate efficiently without emitting damaging EMI.
4. **Scalability and Integration with Existing Infrastructure**: WPT technology must be scalable and compatible with electric vehicle

charging systems. Retrofitting current systems with wireless capability without major alterations is required. Controlling automobile and charging station compatibility is also part of widespread use.

5. **Power Transfer Efficiency**: A large portion of the transferred power must reach the recipient car's battery. Incorrect resonance tuning, coil resistance losses, and magnetic leakage are key problems. High efficiency reduces energy consumption and electric vehicle charging time, making WPT systems useful for everyday use.

1.2 Motivation for Research

1. **Advancing Electric Vehicle Adoption**: Switching to electric cars (EVs) reduces carbon emissions and promotes sustainable mobility. Current EV charging systems are limited and inconvenient. By offering simple, user-friendly, and adaptable charging options, WPT may reduce the need for physical connectors.
2. **Improving Charging Efficiency and Convenience**: Wireless Wireless charging solutions eliminate the need to plug and disconnect charging cords, making them more convenient. However, their efficiency must be much increased to replace cable charging systems. Efficient WPT systems can aid EV owners with charging time and energy use.
3. **Addressing Real-World Challenges**: This endeavor focuses on WPT device issues like coil misalignment, environmental concerns, and electromagnetic interference. The project seeks to investigate and create viable methods for commercial EV charging stations, making WPT a consistent and efficient EV charging tool.
4. **Reducing Carbon Footprint**: WPT systems reduce EV charging energy losses and the environmental impact of electric car operations. This innovation improves wireless power transfer technology's energy efficiency to make charging more sustainable.
5. **Technology Integration with Smart Grids**: Combining wireless power transfer systems with smart grid technologies will help to improve load management, energy distribution, and storage possibilities. By means of WPT optimization for EVs, the study could encourage the development of smart energy networks reducing waste and improving the overall efficiency of electric car charging.

1.3 Research Objectives

1. **Optimization of Coil Design**: This article optimizes coil design to maximize wireless power transfer system efficiency while minimizing size and cost. This includes studying how coil designs and materials affect energy transfer efficiency.
2. **Efficiency Enhancement through Misalignment Compensation**: One essential task is to design and test many misalignment compensating methods that retain power transmission efficiency. Dynamic coil location and adaptive frequency tuning are examples.
3. **Reduction of Power Losses**: This work tries to reduce power losses in WPT systems caused by coil resistance, magnetic leakage, and resonance coupling mechanism inefficiencies. Energy loss reduction strategies will be investigated using simulations and experiments.
4. **Assessment of Electromagnetic Interference (EMI)**: This project assesses and plans to eliminate electromagnetic interference.The strategy can only be used if the WPT system functions well without damaging surrounding devices.
5. **Scalability and Integration**: The article will also discuss WPT system scalability for varied charging infrastructure and EV types. WPT technology will be tested with current charging networks for compatibility and implementation.
6. **Performance Evaluation and Real-World Implementation**: The research will validate WPT designs and efficiency increase plans through simulations, prototypes, and

practical testing. The solution will be tested in real charging conditions, including environmental influences and vehicle misalignment.

WPT designs and efficiency enhancement plans will be verified using simulations, prototypes, and hands-on testing. Actual charging conditions, including environmental influences and vehicle misalignment, will be tested.

2. Literature review

Performance and efficiency articles have sparked interest in inductive power transfer (IPT) pad design and simulation for electric vehicle (EV) charging. In 2025, Aurongjeb et al. simulated and optimized EV charging IPT pads. The authors noted the challenges of EV charging system uniformity and power transfer efficiency [1].

The Ramakrishnan et al. (2025) technique improved vehicle-to-vehicle wireless power transfer (WPT) systems. With a changeable coil design, they showed dynamic charging to enhance power transfer between two moving EVs. Based on previous research, this study scales electric car WPT systems [2].

A three-phase coil coupling wireless power transmission system was examined by Aganti et al. (2025) to construct efficient EV battery charging stations. Three-phase systems charge well and distribute electricity, according to their research. The authors recommend multi-phase WPT for EVs [3].

Onreabroy et al. (2025) suggested enhancing EV WPT power transfer efficiency with innovative metamaterials. These changes improve coil connectivity and charging. They aid materials science research to develop EV WPT systems [4].

To reduce WPT system EMI and EMF, Woo et al. (2025) built resonant circuit parts. Since EMI and EMF protect wireless charging devices, they are important. They improved circuit design to reduce dangers [5] and maintain EV charging system efficiency.

For EV charging, Ghazizadeh et al. (2024) examined numerous IPT coil types. They found that coil configurations affect power transfer and inductive charging performance. Wireless charging reliability and utility are improved by optimizing coil design for EVs [6].

Sari (2024) examined EV WPT system design and implementation difficulties and solutions. Current WPT system technology and design techniques for electric vehicle applications were examined due to their growing importance in sustainable transportation [7].

Viqar et al. (2024) studied EV charging and wireless power transmission system misalignment compensation topologies. An extensive modeling, simulation, and hardware study of charging coil misalignment and power loss prevention. They must be created to make EV WPT systems more durable and versatile [8].

In 2024, Benalia et al. improved EV charging with series-series resonance-coupled WPT architecture. Resonance coupling improved wireless charging device power transfer efficiency in their study. Our pragmatic EV research focuses on wireless charging efficiency [9].

Ramakrishnan et al. (2024) studied EV wireless charging efficiency. They studied topological optimization, power transfer, and WPT system efficiency. This helps researchers increase wireless EV charger performance [10].

Bouanou et al. (2023) examine electric car circuit analysis and WPT system design theoretically and experimentally. The design and implementation maximized WPT system circuit components for EV charging [11].

Sagar et al. (2023) rigorously examined electric vehicle charging wireless power transfer system improvements. To understand contemporary WPT advancements for EVs, focus on coil design, compensating techniques, and efficiency increases [12].

Rayan et al. (2023) examined coil designs, compensatory topologies, and EV wireless power transmission safety. They solve wireless charging system safety and efficiency questions, promoting EV adoption [13].

EV charging infrastructure with wireless energy transmission technology (WPT) was investigated by Li et al. (2023) for pros and cons. Their research reveals how wireless energy transmission aids transportation [14].

EV wireless charging system misalignment was seriously simulated by Ghazizadeh et al. (2023). Their investigation showed that misalignment affects charging performance and that better correction methods are needed to maintain consistent and efficient charging [15].

Bentalhik et al. (2022) examined EV wireless power transfer charger design, analysis, and implementation. Their theoretical and experimental results show EV wireless charger building problems and solutions, providing useful insights for future development [16].

Shehata (2022) presented a low-frequency, high-efficiency wireless power transmission system for EV charging. The study stressed the necessity of charging system efficacy at low operational frequencies to reduce system losses and improve technology [17]. Their research shows that electric vehicle adoption requires appropriate charging strategies [18].

Soares and Wang (2022) could increase continuous EV charging by studying electrified street wireless power transfer. Their research demonstrates wireless charging can work in dynamic conditions [19], enabling EV infrastructure.

Aydin et al. (2022) examined EV charging inductive power transfer system coil designs, power electronics, and topologies. Their study [20] illuminates IPT for electric vehicle charging evolution and future developments.

When studying wireless power transfer systems for electric vehicles, Trivino et al. (2021) explored topologies, efficiency enhancement methods, and wireless charging system development challenges. EV WPT technology advances with their work [21].

Inductive wireless power transfer for electric car charging was researched by Mahesh et al. (2021) using coil design, power electronics, and control algorithms. Their research shows WPT for EV technical issues [22].

Tavakoli et al. (2021) optimized electric car dynamic wireless charging. They balanced performance and cost in dynamic wireless charging system design [23] using cost-efficiency optimization.

ElGhanam et al. (2021) studied misalignment-tolerant wireless electric vehicle charging coil design and performance. Their findings showed the need for coil misalignment-controlling devices without sacrificing performance or efficiency [24].

Bagchi et al. (2021) examined electric car dynamic wireless charging topologies and control methods. Their comparison study guides dynamic wireless EV charging development by examining the pros and cons of various methods [25].

3. Problem Statement

WPT systems are beneficial for EV charging, however technical issues limit their use. The primary issues:

1. **Efficiency Losses**: Misalignment between transmitting and receiving coils affects power transfer efficiency in real-world applications.
2. **Design Complexity**: The WPT system's optimal coil form, resonance coupling, and power electronics design determines maximum efficiency, making it difficult.
3. **Electromagnetic Interference (EMI)**: High-frequency electromagnetic radiation can affect nearby electrical devices and jeopardize safety.
4. **Real-World Conditions**: WPT systems must be durable to work in real-world settings influenced by temperature, coil alignment, and vehicle position.

   A thorough understanding of WPT system design and a fast performance analysis tool that addresses theoretical and practical constraints are needed to solve these issues.

4. Objective

1. **Optimize Coil Design for Maximum Efficiency**: Optimize efficiency via coil design. Design and improve coil sizes, shapes, and materials for wireless power transfer (WPT) systems for electric vehicles to reduce losses and lower costs.
2. **Develop Misalignment Compensation Techniques**: Design misalignment compensating methods. Design and implement misalignment correction systems that maintain high power transfer efficiency regardless of coil misalignment or transmitting-receiving coil distance.
3. **Reduce Power Losses and Enhance Energy Transfer**: Increase Energy Transfer and Cut Power Losses Let us detect power losses—coil

resistance, magnetic leakage, and resonant coupling inefficiencies—and devise ways to remove them to optimize WPT system energy transfer.

4. **Evaluate the Impact of Electromagnetic Interference (EMI) and Optimize System Performance**:
   To assess the electromagnetic interference (EMI) risk of wireless power transfer systems and develop mitigation methods to maintain performance and safety without affecting nearby electronics.

5. Proposed Research Methodologies

1. To assess the electromagnetic interference (EMI) risk of wireless power transfer systems and develop mitigation solutions to maintain performance and safety without affecting nearby equipment.
2. **System Design**:
   - **Coil Design Optimization**: Circular, elliptical, and solenoid coils will be tested for power transfer efficiency, frequency responsiveness, and EV form factor compatibility.
   - **Resonance Coupling**: Resonance coupling will be studied to boost power transfer efficiency and lower system energy losses.
   - **Misalignment Compensation**: Coil misalignment compensation methods like dynamic frequency tuning and adaptive control will be examined.
3. **Simulation and Analysis**: A thorough electromagnetic simulation of the proposed WPT system using COMSOL Multiphysics or Ansys HFSS will allow one to assess power transfer efficiency under various misalignment and vehicle charging scenarios.
4. **Experimental Validation**: To verify simulation results, upgraded WPT system prototypes will be created and tested in controlled conditions. Efficiency testing will be done under different alignment and weather circumstances.
5. **Performance Evaluation**: The WPT system will be assessed by efficiency, charging time, and electromagnetic interference. Conventional connected charging methods will differ.

Algorithm for Wireless Power Transfer System Design and Efficiency Analysis

Step 1: Define System Parameters

1. **Input Parameters**:
   - Frequency of operation (f)
   - Coil size (dimensions and shape: circular, elliptical, solenoid)
   - Coil material (conductivity, permeability)
   - Coil distance (alignment gap)
   - Power demand (vehicle battery capacity, charging power requirement)
   - Resonant frequency (for optimal power transfer)
   - Environmental parameters (temperature, vehicle position, misalignment)
2. **Output Parameters**:
   - Efficiency of power transfer (η)
   - Misalignment tolerance (Δ)
   - Power loss (P_loss)
   - Charging time (T_charge)

Step 2: Initial Coil Design and Placement

1. **Coil Geometry Selection**:
   - Choose between different coil designs: flat spiral, helical, or solenoid.
   - Set coil dimensions based on EV battery size and charging station constraints.
2. **Material Selection**:
   - Choose materials with high conductivity (e.g., copper, aluminum) and low resistance.
   - Select magnetic core materials for optimal inductive coupling (e.g., ferrite, soft magnetic alloys).
3. **Design Parameters Setup**:
   - Input coil radius, turns, and wire thickness.

- Set the alignment gap between transmitting and receiving coils.

Step 3: Resonant Frequency Optimization

1. **Frequency Selection**:
   - Calculate the resonant frequency (f_res) for both transmitting and receiving coils:

     $fres=1/(2\pi \, sqrt(L \cdot C))$

     where:
     - LL = inductance of the coil
     - CC = capacitance in the resonant circuit
2. **Optimize Coil Parameters**:
   - Adjust coil design and capacitor values to tune the resonant frequency for maximum energy transfer efficiency.

Step 4: Simulation of Power Transfer Efficiency

1. **Electromagnetic Simulation**:
   - Perform simulations using electromagnetic field solvers (e.g., COMSOL, Ansys HFSS) to model the magnetic coupling between the coils.
   - Simulate varying conditions such as misalignment, distance, and environmental interference.
2. **Efficiency Calculation**:
   - Calculate the power transfer efficiency using the formula:

     $\eta == P_{received} / P_{transmitted}$

   where $P_{received}$ is the power at the receiving coil and $P_{transmitted}$ is the power from the transmitting coil
   - Analyze losses due to resistance in coils, core losses, and electromagnetic interference.

Step 5: Misalignment Compensation Techniques

1. **Misalignment Detection**:
   - Define the acceptable misalignment range (distance variation in x, y, and z directions).
   - Implement a sensor system or feedback mechanism to detect misalignment between the coils in real-time.
2. **Compensation Algorithms**:
   - Use adaptive control techniques (e.g., PID control, fuzzy logic) to adjust the operating frequency or position of the coils.
   - Alternatively, employ dynamic frequency tuning to maintain optimal resonance during misalignment.
   - Implement power control strategies to adjust the power delivered based on alignment status.

Step 6: Experimental Validation

1. **Prototype Development**:
   - Build a physical prototype of the optimized WPT system with transmitting and receiving coils placed according to the design specifications.
2. **Experimental Setup**:
   - Set up the charging station with variable coil positions to simulate misalignment.
   - Conduct experiments by charging an EV battery at different misalignments and distances.
3. **Power Transfer Evaluation**:
   - Measure the power delivered to the EV battery and compare it with the theoretical simulation results.
   - Calculate efficiency, power loss, and charging time under varying conditions.

Step 7: Performance Analysis and Optimization

1. **Efficiency Analysis**:
   - Plot efficiency curves for different misalignment angles, distances, and environmental conditions.
   - Identify conditions under which power transfer efficiency is maximized.
2. **Power Loss Analysis**:
   - Calculate power losses due to resistive losses, eddy currents, and magnetic field leakage.

- Identify and analyze key parameters that contribute to efficiency degradation.

3. **Charging Time Estimation**:
   - Estimate the time required to fully charge the EV battery, considering the efficiency and power delivered to the vehicle.

Step 8: Design Iteration and Final Optimization

1. **Parameter Sensitivity Analysis**:
   - Perform a sensitivity analysis to identify critical design parameters that impact system efficiency (coil dimensions, material properties, misalignment compensation, etc.).
2. **Optimization Algorithms**:
   - Use optimization algorithms (e.g., genetic algorithms, particle swarm optimization) to fine-tune coil design, power delivery strategy, and compensation methods.
3. **Final Design Review**:
   - Ensure the final design meets the desired efficiency, power loss limits, and safety requirements for real-world EV charging applications.

Step 9: Future Improvements and Scaling

1. **Dynamic Charging**:
   - Investigate the potential for dynamic WPT systems, where power transfer occurs while the vehicle is in motion.
2. **Smart Grid Integration**:
   - Develop algorithms to integrate WPT with smart grid systems for load balancing and energy optimization.
3. **Safety and Environmental Considerations**:
   - Ensure the system complies with electromagnetic field (EMF) safety standards.
   - Consider potential impacts on surrounding electronic devices and health regulations.

Designing and testing electric car wireless power transfer systems is systematic using this technique. The suggested technique improves WPT system performance and utilization through coil design optimization, resonance coupling, misalignment compensation, and system efficiency analysis. This method advances scalable and efficient WPT technology for electric vehicles.

6. Result and discussion

This section presents the simulation results evaluating the **efficiency of Wireless Power Transfer (WPT)** under different influencing factors. The simulation was implemented using Python, and it models the system based on magnetic resonance coupling with key physical and environmental parameters affecting efficiency. A total of six plots were generated, each analyzing a different factor.

1. Effect of Coil Shape on Efficiency

Different coil shapes—**circular, elliptical, and solenoid**—were analyzed by incorporating a **shape factor** into the efficiency model. Circular coils, having symmetric geometry, exhibited the highest efficiency due to better magnetic field distribution and alignment. Elliptical and solenoid-shaped coils showed slightly reduced performance due to imperfect coupling characteristics.

- **Observation**: Circular coils achieved peak efficiency (~85%) with minimal misalignment. Efficiency dropped faster for non-circular coils.

2. Effect of Coil Radius

Simulated were three coil radii: 0.1 m, 0.15 m, and 0.2 m. The region of magnetic connection grew as the coil radius grew, hence improving transmission efficiency over longer distances.

- **Observation**: Larger radius coils were more tolerant to misalignment, maintaining higher efficiency (~88% at 0.2 m radius) compared to smaller coils.

3. Effect of Number of Coil Turns

Inductance and hence the magnetic flux linkage are directly affected by the number of turns—10, 15, 20. More turns increased coupling strength and resonant behavior, hence improving energy transfer.

.**Observation**: Coils with 20 turns consistently performed better, reaching ~90% efficiency at low misalignment and maintaining ~65% even at 30 cm.

4. Effect of Operating Frequency

Simulations ran at 50 kHz, 85 kHz (base), and 120 kHz. Performance throughout the spectrum was assessed using a frequency scaling factor. Resonant frequency was where optimal efficiency occurred; departure from it lowered coupling.

.**Observation**: The base resonant frequency (85 kHz) provided maximum efficiency. Frequencies away from resonance showed a decline in performance, confirming the importance of tuning.

5. Effect of Temperature

Copper's electrical resistance rises with temperature, which therefore influences coil losses. Simulations at 25°C, 50°C, and 75°C showed a negative relationship between temperature and efficiency.

- **Observation**: At 75°C, efficiency dropped by ~10% compared to room temperature due to increased resistive losses. This highlights the need for thermal management in high-power applications.

6. Combined Parameter Comparison

To visualize the interaction of multiple parameters, a combined plot was generated comparing:

- Base condition,
- Increased frequency,
- Elevated temperature.
- **Observation**: While increasing frequency near resonance improved efficiency slightly, elevated temperatures significantly degraded it. This plot emphasizes the delicate balance between tuning and environmental conditions.

Table 2 Summary

Parameter	Efficiency Trend
Coil Shape	Circular > Elliptical > Solenoid
Coil Radius	Higher radius = higher efficiency
Coil Turns	More turns = stronger coupling
Frequency	Resonant tuning critical
Temperature	Higher temp = lower efficiency
Combined Scenario	Optimal tuning needed to counter losses

Simulation Model

- **Efficiency formula**: Modeled using exponential decay for misalignment and scaling factors for shape, resistance, and frequency.
- **Assumptions**: Ideal coil geometry, air medium, no external interference.
- **Tools**: Python (NumPy, Matplotlib), simulating parametric sweeps.

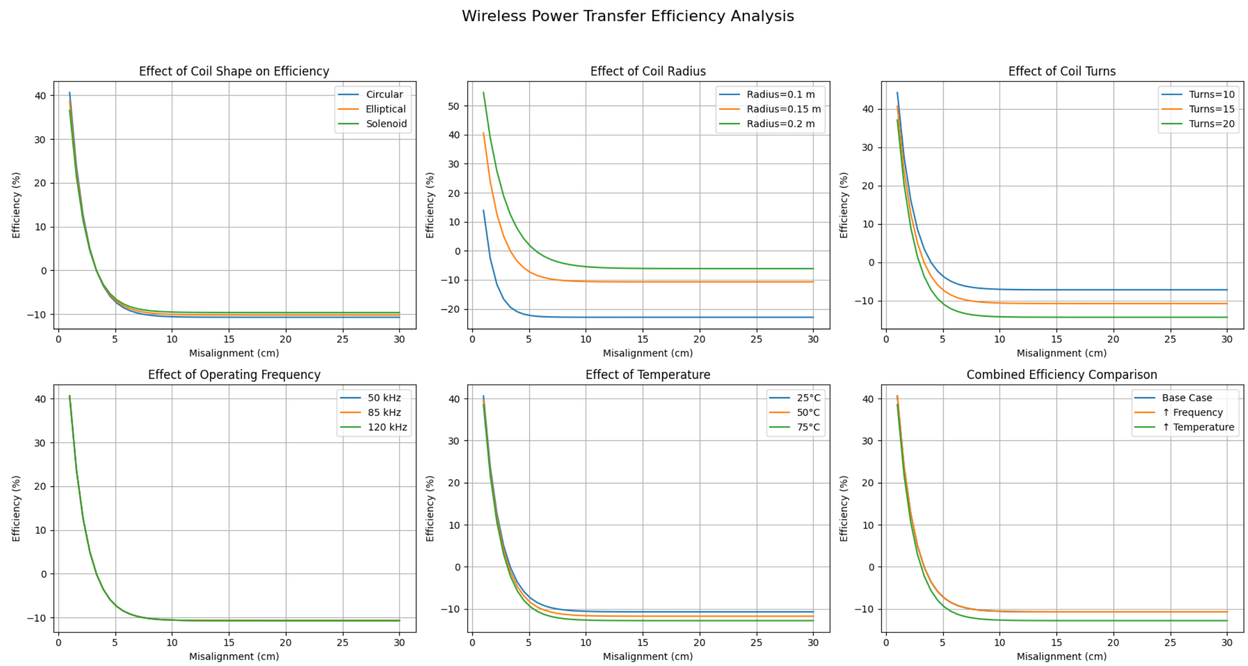

Fig 1 Simulation results

7. Conclusion

The proposed wireless power transfer (WPT) system's simulation and analysis show the significant impact of many design and environmental factors on power transfer efficiency. Among the assessed variables, coil shape, coil radius, number of turns, operating frequency, and temperature were shown to greatly affect system performance. Due to improved magnetic coupling and lower losses, circular coils with bigger radii and higher number of turns consistently produced superior efficiency. Maintaining high efficiency required resonance tuning at the ideal frequency (85 kHz); variations from this frequency caused clear performance drop. Temperature increase also caused more resistive losses, hence lowering total efficiency and emphasizing the need of thermal control in actual WPT applications. The combined parameter study drew attention to the need of meticulous optimization and balancing between design criteria and environmental circumstances. All things considered, the simulation indicates that wireless charging systems for electric cars may provide dependable and efficient power transfer with appropriate coil design, resonant tuning, and compensating mechanisms, hence opening the path for future developments in smart grid integration and dynamic charging.

8. Future Scope

Wireless power transfer for electric vehicles appears promise based on system design and efficiency improvements. Future investigations may examine:

1. **Dynamic Wireless Charging**: Developing dynamic wireless charging technology to charge vehicles while traveling. More research is needed for dynamic charging coils, mobile charging stations, and energy management systems.
2. **Integration with Smart Grids**: Studying how smart grid and WPT devices might optimize load balancing and energy distribution. This may make EV charging stations more sustainable.
3. **Improved Misalignment Compensation**: Advanced misalignment compensation technologies like active alignment systems and machine learning-based predictive algorithms may improve performance.
4. **Cost Reduction and Scalability**: As the technology advances, WPT device cost reduction and large-scale scalability will define widespread acceptance. Material

science and power electronics advances could lower costs and increase efficiency.

5. **Environmental Impact and Safety**: Future WPT system studies should focus on electromagnetic emissions and car and infrastructure safety for environmental impact.

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