International Journal of Research Publications in Engineering, Technology and Management (IJRPETM)

|www.ijrpetm.com | ISSN: 2454-7875 | editor@ijrpetm.com |A Bimonthly, Peer Reviewed & Scholarly Journal|

||Volume 3, Issue 2, March-April 2020||

DOI:10.15662/IJRPETM.2020.0302001

Advancements in Wireless Power Transfer Technologies for Electric Vehicle Applications

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ABSTRACT: Wireless Power Transfer (WPT) has emerged as a transformative technology for Electric Vehicle (EV) charging, promising enhancements in convenience, autonomy, and driving range by circumventing physical plugs. Pre-2019 developments encompass both **stationary** and **dynamic (in-motion)** charging methods, mainly through **inductive coupling** and **magnetic resonance**. Early trials such as Plugless Power's inductive pads at Google (2011), Utah State University's induction-charging Aggie Bus, and Korea's moving-charger systems (60 kW over 17 cm, later 83% efficiency over 20 cm) validate feasibility. The theoretical framework highlights three WPT modalities: inductive, capacitive, and far-field techniques. Inductive coupling, including coupled magnetic resonance systems (CMRS), remains dominant. Innovations in coil design, EM shielding, multi-coil setups, and system topology have improved transfer range, efficiency, and safety. Dynamic charging corridors, such as Korea and Germany trials, demonstrate the potential for continuous power during motion. Safety considerations led to EMF shielding practices. This paper presents a unified methodology for designing EV-compatible WPT: from method evaluation and coil topology to shielding and infrastructure alignment. Key findings show stationary systems are mature with high efficiency (>90%), whereas dynamic systems face infrastructure challenges and cost barriers, despite range and battery size benefits. Wireless charging reduces user intervention and enables smaller batteries, but suffers from alignment sensitivity, infrastructure cost, and electromagnetic safety concerns. The paper concludes that non-radiative near-field methods (inductive, resonant) offer optimal trade-offs, with growth potential in dynamic implementations. Future work should address standardization, infrastructure cost-effectiveness, interoperable coil designs, and safe, scalable deployments.

KEYWORDS: Wireless Power Transfer (WPT); Electric Vehicle (EV); Inductive Charging; Magnetic Resonance; Stationary Charging; Dynamic Charging; Plugless Power; Aggie Bus; Coil Design; Electromagnetic Shielding

I. INTRODUCTION

Wireless Power Transfer (WPT) is surfacing as a vital enabler for next-generation Electric Vehicle (EV) charging, offering seamless, contactless solutions that diminish reliance on cables and improve user convenience. As EV uptake grows, overcoming limitations like range anxiety and charging friction is paramount. WPT addresses this by providing both **stationary charging**, through inductive or resonant pads, and **dynamic charging**, where moving vehicles receive continuous energy—potentially reducing onsite battery capacity and infrastructure maintenance.

Early examples include Plugless Power's inductive pads trialed at Google in 2011 WIREDWikipedia, Utah State University's Aggie Bus that achieved 25 kW at 90% efficiency even with misalignment up to 6 inches WIRED, and South Korean dynamic charging experiments delivering up to 60 kW over a 17 cm gap, later improved to 83% efficiency at 20 cm ScienceDirect. This paper surveys foundational WPT modalities—inductive coupling, magnetic resonance, capacitive, and far-field—and evaluates their suitability for EVs. We highlight recent technical advances in coil design, power transfer efficiency, safety measures, and economic feasibility. The proposed methodology guides designers through selecting WPT approaches, designing coil systems, implementing shielding, and aligning infrastructure strategies with vehicle dynamics. By synthesizing pre-2019 milestones, the paper serves as a compendium of progress and a roadmap for future scalable, safe, and efficient wireless EV charging systems.

II. LITERATURE REVIEW

1. WPT Fundamentals & Modalities

Mou & Sun (2015) classify WPT into inductive coupling, magnetic resonance (CMRS), and electromagnetic radiation. Inductive and resonant methods dominate due to non-radiative, near-field safety and efficiency arXiv.

2. Early EV-Specific Implementations

- Plugless Power deployed inductive charging pads in 2011 with ~84–90% efficiency WIREDWikipedia.

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- Utah State's Aggie Bus achieved in-motion charging: 25 kW, 90% efficiency, with misalignment tolerance WIRED.
- Korea developed dynamic chargers with 60 kW, 17 cm gap, later extended to 83% at 20 cm ScienceDirect.
- Bombardier's tram systems reached 250 kW transfer via three-phase setups in Germany ScienceDirect.

3. Coil Design & Shielding Techniques

Musavi & Eberle (2014) discussed feasibility, coil geometry, compensation topologies, and EMF suppression methods, including reactive cancellation loops for safe in-road systems ResearchGate.

4. Reviews & Roadmaps

Mou & Sun (2015) laid out current trends and research needs; Xiao Lu et al. (2015) survey charging standards and network implications arXiv+1.

This literature cements the viability of near-field WPT for EVs, evidencing efficiency gains and real-world trials, while highlighting challenges in dynamic infrastructure and EMF management.

III. RESEARCH METHODOLOGY

We propose a generalized workflow for WPT system design in EV contexts:

1. **Define Use-Case Mode**
2. Choose stationary (parking) or dynamic (in-motion) charging based on application needs.
3. **Select WPT Technology**
4. Evaluate inductive vs. resonant vs. capacitive, prioritizing safety, efficiency, and distance capabilities arXivMDPI.
5. **Coil & Compensation Design**
6. Model primary and secondary coil geometries, compensation networks, and multiple coils to optimize coupling and alignment ResearchGate.
7. **EMF Safety Design**
8. Implement shielding and resonant cancellation techniques to meet exposure limits ResearchGate.
9. **Prototype & Testing**
10. Fabricate a pilot pad or track; measure power transfer, efficiency (targeting >80%), misalignment tolerance, and system losses.
11. **Infrastructure Integration**
12. For dynamic systems, design embedded power tracks; for stationary, align pad placement and communication for billing/parking.
13. **Economic and Energy Analysis**
14. Compute cost-benefit, charging speed, infrastructure investment, battery sizing trade-offs ScienceDirect.
15. **Iterate & Optimize**
16. Refine coil layout, frequency, shielding, and controls to maximize performance in real-world conditions.

IV. KEY FINDINGS

- **Stationary charging systems** (e.g., Plugless Power) achieve efficiencies between 84–90% Wikipedia and offer user convenience without handling cords.
- **Dynamic charging** (Aggie Bus, Korea trials) demonstrates feasibility, with up to 25 kW at 90% efficiency and over 60 kW at 83% efficiency at 20 cm gaps WIREDScienceDirect.
- **Coil and shielding design** advancements enable improved misalignment tolerance and reduced EMF leakage via reactive cancellation and multi-coil systems ResearchGate.
- **Economic implications** suggest significant battery size reductions and operational flexibility with dynamic systems, though at high infrastructure cost ScienceDirect.

V. WORKFLOW

1. **Mode Selection**: Stationary or dynamic depending on urban infrastructure and user behavior.
2. **Method Determination**: Inductive resonant coupling favored for safety and mid-range; capacitive/far-field less common.
3. **Coil Design**: Use multi-coil, resonant networks; simulate misalignment and coupling.
4. **Shielding Implementation**: Apply passive or active EMF shielding techniques.
5. **Prototype Fabrication**: Build pad or track segment.
6. **Performance Testing**: Measure efficiency, power delivered, misalignment tolerance.

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7. **Economic Evaluation**: Analyze cost vs. battery sizing and user convenience.
8. **Infrastructure Planning**: Determine pad deployment or road embedding layout.
9. **Iterative Refinement**: Optimize for alignment, cost, safety, and efficiency.

VI. ADVANTAGES & DISADVANTAGES

Advantages

- **Convenience**: Plugless operation.
- **Reduced Battery Size**: Dynamic charging supports smaller batteries.
- **Safety**: Non-radiative near-field limits hazard.

Disadvantages

- **High Infrastructure Cost**: Especially for dynamic deployments.
- **Alignment Sensitivity**: Requires precise alignment or multi-coil solutions.
- **EMF Safety**: Must manage exposure.
- **Standardization Gaps**: Multiple systems risk incompatibility.

VII. RESULTS AND DISCUSSION

Wireless EV charging via near-field WPT is viable and advancing rapidly. Stationary systems deliver high efficiency and user comfort. Dynamic systems promise transformative benefits in range and battery demand, but face hurdles of infrastructure cost and system complexity. Technical improvements in coil design, resonance control, and EMF mitigation enhance performance. For widespread adoption, interoperability, cost-sharing models, and safety standards are required. Users experience improved convenience and operational flexibility, yet benchmarks in charging speed and cost per kWh equivalence with wired systems remain adoption barriers.

VIII. CONCLUSION

Pre-2019 advancements in WPT for EVs underscore compelling gains: stationary systems deliver high efficiency and ease, while dynamic charging holds promise for seamless operation. Near-field inductive and resonant coupling strikes the best balance of safety and performance. Infrastructure and cost remain key challenges. The field requires standard frameworks, further economic analysis, and safe, interoperable designs to advance adoption.

IX. FUTURE WORK

- **Standardization Efforts**: Align WPT pads and EV receiver interfaces.
- **Infrastructure Cost Reduction**: Modular pad systems, retrofit-friendly designs.
- **Improved Alignment Tolerance**: Adaptive multi-coil and sensor feedback.
- **EMF Exposure Modeling**: Advanced shielding and safety protocols.
- **Energy Efficiency Optimization**: Idle power reduction, bidirectional V2G WPT.
- **Long-term Field Trials**: Large-scale network and user behavior studies.

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