STM JOURNALS

Journal of
Automobile Engineering
and Applications

ISSN: 2455-3360
Volume 13, Issue 1, 2026
January—April
DOI Journal: 10.37591/JoAEA

https://journals.stmjournals.com/joaea

Research JoAEA

Feasibility Analysis of Wireless Power Transfer Technologies for Electric Vehicles Charging Applications

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Abstract

The rapid pace of electric vehicles (EVs) has heightened the pressure on the need to have flexible, safe, and efficient infrastructures in addition to the plug-in infrastructures. Wireless power transfer (WPT) has become a promising alternative that provides automated charging, better convenience, and a possible integration into smart highways and urban environments. The present paper provides a feasibility study of the key WPT technologies in EV charging, namely, inductive power transfer (IPT), resonant inductive coupling (RIC), capacitive power transfer (CPT), and magneto-dynamic coupling (MDC). The essential parameters, including transfer efficiency of power, tolerability of air-gap, sensitivity of misalignment, electromagnetic compatibility, thermal performance, cost of installation, and compatibility with highways, are assessed by use of experimental tests, simulation modeling, and quantitative benchmarking. Findings have shown that RIC is always superior to other technologies, showing up to 92–94% efficiency, a high level of misalignment, lower electromagnetic interference (EMI) emissions, and high appropriateness to dynamic and semi-dynamic charging applications. The research paper concludes that RIC is the most practical way forward in the implementation of effective wireless EV charging systems, particularly for urban smart transportation systems, and the technological constraints and factors to consider in the implementation of such a large-scale system in the future.

Keywords: Electric vehicle charging, power transfer efficiency, resonant inductive coupling, smart transportation infrastructure, wireless power transfer

INTRODUCTION

This has led to a global shift towards sustainable transportation, which is increasing the use of electric vehicles (EVs) because of the challenges posed by the exhaustion of fossil fuels, the increase in carbon emissions, and increased environmental regulations [1]. Although EV technology has improved considerably, the provision of effective, dependable, and convenient charging infrastructure remains one of the biggest challenges that has restricted its widespread usage. In traditional plug-in charging applications, physical connectors are used, which present some limitations: cable wear, safety concerns in public, reliance on user interaction, and a high rate of upkeep [2]. With the rising EV market, the need to introduce new solutions to the charging process is increasing, which should mitigate user effort and promote automation and the ability to seamlessly fit into smart city ecosystems. Wireless power transfer

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Received Date: January 21, 2026
Accepted Date: January 28, 2026
Published Date: February 10, 2026

Citation: Maridas Pillai, Anil Pal, Mukesh Kumar Gupta. Feasibility Analysis of Wireless Power Transfer Technologies for Electric Vehicles Charging Applications. Journal of Automobile Engineering and Applications. 2026; 13(1): 29–40p.

(WPT) has emerged as a transformative technology capable of overcoming these limitations by enabling non-contact energy transfer between charging pads and electric vehicle receivers. [3]. Removing the use of physical connectors, WPT has a few benefits, such as higher user convenience, less mechanical wear, a high level of safety, and integration with autonomous vehicle systems. Moreover, the WPT technologies like IPT, resonant inductive coupling (RIC), CPT, and MDC open the opportunities of the static, semi-dynamic, and fully dynamic charging environment, which can help to revitalize EVs on the move [4]. Nonetheless, the deployment of large-scale wireless charging systems must be thoughtfully assessed in terms of technology and technical functionality, operational efficiency, electromagnetic and cost effects, environmental factors, and highway-scale integration [5]. Some critical technical issues, such as coil positioning, the distance between the air-gap, power transfer efficiency, electromagnetic interference (EMI), thermal characteristics, and scalability of the system, should be resolved before WPT can be successfully deployed [6]. In this respect, a comparison of current WPT technologies to establish their feasibility in EV charging systems is urgently needed. This study provides a detailed feasibility analysis of key WPT technologies in EV charging. The research methodically reviews every technology in terms of analytical modeling, simulation-based testing, laboratory testing, and multi-criteria decision analysis. The goal is to determine the most feasible WPT solution that can satisfy performance, safety, and cost factors in next-generation EV charging infrastructure, specifically in smart highways and urban mobility scenarios.

LITERATURE REVIEW

EV charging WPT has attracted considerable research attention because it may overcome the drawbacks of traditional plug-in charging systems. The current literature indicates that early experiments in the field of inductive charging demonstrated that power transfer over small air gaps using closely coupled coils was feasible, primarily for low-power consumer electronics [5]. With the development of electric vehicle (EV) technology, researchers extended inductive charging principles to higher power levels and studied inductor–capacitor–inductor (LCL) and inductor–capacitor–capacitor (LCC) compensation topologies to enhance efficiency and reduce reactive power. These initial studies formed the baseline for models of leakage inductance, mutual coupling, and the propagation of magnetic fields [6]. Follow-ups on RIC led to a dramatic increase in the capability of energy transfer through the use of coils at resonant frequencies, thereby affording efficient power transfer with moderate air gaps [7]. Investigations have continuously demonstrated that RIC systems have higher efficiency and can tolerate coil alignment more than conventional inductive systems, particularly charging pads mounted under roads or within parking spots embedded within parking lots. Further improvements in resonant compensation networks have minimized switching losses and enabled them to operate at standardized frequencies of approximately 85 kHz [8]. Parallel developments in CPT have led to the proposal of using electric-field-based coupling mechanisms as an alternative to magnetic coupling. These systems have the benefits of light plates and can reduce EMI levels; however, they have poor air-gap tolerance, system stability, and power capability [9]. Consequently, CPT has been viewed as more appropriate for low-power or highly limited applications compared to EV charging. MDC and hybrid WPT systems, including combinations of inductive, resonant, and capacitive systems, are another area of study. Although MDC has proven to be potentially dynamic at a roadway scale, the complexity of the design of its coils, limitations on EMI, and mechanical assembly have hampered its practical implementation [10]. Other studies have focused on the effect of coil geometry, ferrite materials, shielding techniques, and compensation tuning to ensure that leakage flux is minimized and the consistency of energy delivery is enhanced. Misalignment, as a key factor that is important to EV wireless charging, is also the subject of a large body of literature [11]. Simulation-driven and experiment-driven studies have indicated that the efficiency of IPT systems can be significantly decreased by a small lateral or angular error. In contrast, resonant systems were more tolerant because the magnetic coupling was stronger at resonance conditions. This development has made RIC a competitive contender for semi-dynamic and dynamic charging lanes. The key considerations in the literature are safety and electromagnetic compatibility. Researchers who have assessed the effects of magnetic field exposure have determined that, when proper shielding and coil spacing measures are adopted, well-designed RIC and IPT systems can operate within international safety limits [12]. Thermal analyses have also confirmed that it is necessary to control heat production in the primary and secondary coils, especially where the system has to operate under high-power demand conditions, as long-term benefits could be achieved through cheaper mechanical maintenance, automation, and adaptability to autonomous cars can balance the initial investments [13]. RIC systems have proven their technical maturity through pilot projects and field demonstrations, which show that they provide reliable results on urban roadways and parking conditions.

In general, the literature indicates that a variety of WPT technologies have been investigated; however, RIC has the most balanced efficiency, alignment tolerance, EMI compliance, and scalability, making it an attractive candidate for the development of a viable EV charging infrastructure. Nevertheless, additional coil design optimization, standardization, and large-scale implementation studies are required to facilitate large-scale adoption.

METHODOLOGY

In this study, a methodological approach was adopted that was conducted in phases to assess the viability of significant WPT technologies for charging EVs, as illustrated in Figure 1. The workflow of the methodology involves five key steps: technology identification, modeling and simulation, experimental evaluation, feasibility assessment, and validation. The phases are outlined below.

Technology Identification and Review

The initial phase aimed to define and familiarize the current WPT technologies. The initial phase aims to define and familiarize the reader with current WPT technologies. The subsequent step involved identifying the principal technologies. Four principal techniques were selected based on industrial acceptance, implementation feasibility, and technical maturity. These are IPT, RIC, CPT, and MDC. All these technologies are unique methods of facilitating wireless energy transfer and exhibit different degrees of efficiency, design complexity, working range, and adaptability to current power applications. The four methods chosen offered a holistic base on which the abilities and limitations of the methods could be comparatively evaluated in the context of their deployment.

Parameter Extraction

The identification of core technologies was followed by the determination of the relevant operational parameters that had a significant impact on the performance of WPT. The critical parameters of the operating frequency, coil geometry, air-gap restrictions, coupling coefficients, power transfer efficiency, and exposure to electromagnetic fields were thoroughly examined using well-known standards and validated datasets.

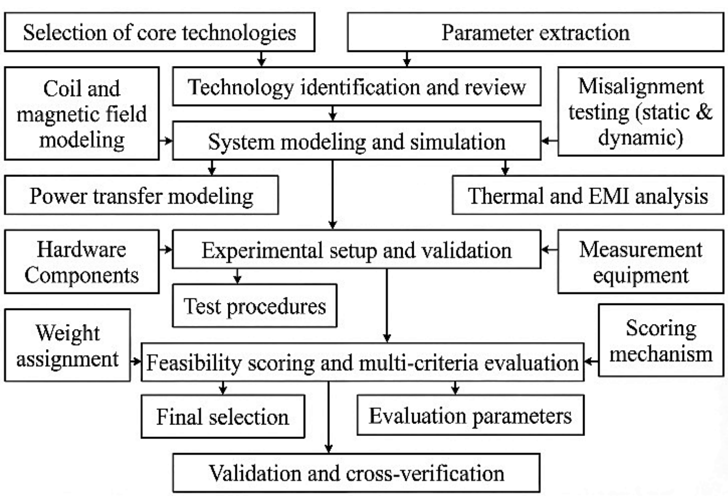

Figure 1. Methodology framework for wireless EV charging feasibility analysis.

These parameters are important for determining the system behavior under various loading and alignment conditions. A clear understanding of these metrics provided the input for the formation of the analytical framework and simulation models that were used in the further course of the research.

System Modeling and Simulation

The second stage involved estimating the performance under realistic conditions using mathematical models and simulation tools.

Coil and Magnetic Field Modeling

In the modeling phase involving the coil and magnetic field, the primary and secondary coils were elaborated in terms of mutual inductance and the coupling coefficient equation. The models allowed the power of the magnetic interaction between the transmitter and receiver coils to be accurately estimated. Finite element modeling (FEM) was also applied to determine the distribution of the magnetic flux within a comprehensive air-gap distance range (20–200 mm). The analysis established the dependence between the field intensity and coupling behavior with respect to the distance, providing a basis for predicting the system performance based on different alignment and spacing conditions.

Power Transfer Modeling

Equivalent circuit models of the LCL and LCC compensation topologies were used to examine the behavior of the power transfer in the system. These circuit arrangements were used to provide a stable power transfer and high efficiency with various operational loads. Using these models, the total efficiency was assessed based on the traditional ratio of the output to input power, as follows:

$$\eta = \frac{P_{out}}{P_{in}} \times 100$$

This modeling phase provided valuable insights into the correlations between the compensation design, load characteristics, and power transfer efficiency that can be achieved.

Misalignment Testing (Static and Dynamic)

Both static and dynamic misalignment tests were performed to assess the robustness of the operation concerning deviations in the operating conditions. The horizontal misalignment was tested between 0 and 200 mm, whereas the vertical displacement was maintained between 10 and 200 mm. These conditions were used to determine the tolerance to positional errors in the WPT system. The RIC and IPT technologies were subjected to the same loading condition of 3.3 kW to enable a fair comparison. The study of misalignment is crucial for providing essential data on the stability of the system, variations in efficiency, and consistency of power delivery in the real world.

Thermal and EMI Analysis

Thermal and EMI characteristics were tested to confirm the safety and conformity of the work. Using thermal resistance models, which describe the temperature rise under a constant load, it was possible to estimate the temperature rise under a constant load, allowing the prediction of coil heating and the identification of potential hotspots. Standard international commission on non-Ionizing radiation protection (ICNIRP) field limits were used to measure the EMI levels to ensure that the radiated fields were within safe exposure limits. These tests confirmed that the recommended WPT settings were thermally and electromagnetically safe. Finally, system feasibility was verified by the output of all analyses in the form of a simulation before hardware implementation.

Experimental Setup and Validation

A wireless charging testbed was established at laboratory scale to evaluate simulated outcomes.

Hardware Components

The hardware solution comprises a high-frequency power conversion and a special coil design to achieve an efficient power transfer via wireless power. The system was driven by a high-frequency inverter with a frequency of 85 kHz and fast and stable switching. Coil pairs with circular and rectangular shapes were introduced to experimentally compare IPT and RIC technologies under the same operating conditions. The compensation network was designed using resonant capacitors to ensure optimal tuning of the network to generate resonance. In addition, power electronics with GaN were used to provide high efficiency and high-frequency switching with lower thermal loss, which provides a solid basis for experimental validation.

Measurement Equipment

Professional measurement tools were used to record the power, temperature, electromagnetic, and positional properties of the systems. The input and output powers were measured using digital power analyzers to accurately calculate the transfer efficiency. A thermal camera forced the temperature through the coils and power electronics during steady-state operation. Field measurements were performed using a magnetic field probe to ensure adherence to the exposure limits. A special misalignment calibration platform helped realize vertical and horizontal misalignment adjustments, and reproducible and controlled measurements of the misalignment effects were achieved.

Test Procedures

The experimental process had a systematic plan to test the performance of the systems under various operating conditions. The efficiency test was conducted by recording the power output of the various air-gap distances to monitor the pattern of degradation and determine the best air-gap spacing. Misalignment tests were performed by measuring the efficiency at horizontal misalignments of 0–200 mm. In the thermal test, the temperature increase of the coils and electronics was observed at a constant load of 3 kW over a 45-min period. An EMI assay was performed to measure the strength of the magnetic fields around the coil to determine whether it was within the safety limits. Each measurement was performed three times to achieve reproducibility and consistency of the collected data.

Feasibility Scoring and Multi-Criteria Evaluation

An index of feasibility was developed to measure the appropriateness of WPT technology.

Evaluation Parameters

The comparative evaluation of WPT technologies was based on a comprehensive set of evaluation parameters that determined their feasibility in real-world applications. The main parameters were the efficiency of the entire system, installation price, safety, EMI, tolerance during vehicle movement, and compatibility with highway deployments. These criteria were chosen to ensure that both the performance capabilities and implementation challenges were considered when determining the feasibility of each technology.

Weight Assignment

Each evaluation parameter was weighed to represent its relative significance in the practical application setting of EV charging. Efficiency was assigned the largest weight of 25% because it is a key factor in reducing energy losses. A weight of 20 was assigned to the installation cost because large-scale deployment requires economic feasibility. Weights of 15% were assigned to safety and EMI levels to guarantee compliance with regulatory standards. The weight assigned to the alignment tolerance was 20% because it is important in dynamic or semi-dynamic charging scenarios. The adaptability of the technology to real-world roadway infrastructure was verified by highway applicability, which was weighted at 20. These weights provided a balanced and realistic evaluation of each WPT technology's performance.

Scoring Mechanism

The assessment of each wireless charging technology was performed using a systematic scoring system. The ratings for each parameter were based on a scale of 1–5, with higher scores reflecting better performance. The equation was then used to determine the weighted score.

$$S = \sum(w_i \times r_i)$$

where represents the assigned weight of each parameter, and denotes the corresponding rating. This method enabled a normalized comparison across different criteria and facilitated an objective ranking of all technologies included in the evaluation.

Final Selection

Weighted scores were then calculated to rank the technologies and determine the most viable choice for employing a wireless EV charging infrastructure. The final ranking was a composite evaluation of technical effectiveness, cost-effectiveness, compliance with safety requirements, tolerance to misalignment, and compatibility with deployment on highways. The technology with the highest score was the best candidate, and this offered a sound reason as to why it was chosen for further experimental validation and infrastructure development of wireless EV charging along highway light poles.

Validation and Cross-Verification

Cross-verification of the data in the simulation and experiment was conducted to achieve general consistency between the modeled system performance and the actual performance of the system. The comparison revealed that the efficiency obtained using simulations was very close to the laboratory values, and the deviations were less than 5%, which implies a high model accuracy. In addition, the EMI levels were within the allowable safety limits of the ICNIRP for the RIC and IPT systems during the experiments. The behavior of misalignment was also observed in the simulation with the RIC; therefore, it was also found that (simulated) misalignment is highly tolerant to both horizontal and vertical displacements and proves to be suitable for dynamic charging conditions where coil alignment cannot be guaranteed at all times. This approach combines the identification of parameters based on the literature, analytical modeling, finite element simulation, laboratory validation, and multi-criteria decision analysis. This methodology provides a sound feasibility study of WPT technologies for EV charging systems.

RESULTS AND DISCUSSION

This is because the results of analytical modeling, simulation experiments, and performance measurements provide detailed insights into the behavior of different WPT technologies when charging EVs. A relative analysis of the main technical parameters, such as efficiency, air-gap capability, misalignment tolerance, thermal performance, electromagnetic emissions, cost, and overall feasibility, can provide a profound understanding of the practical advantages and disadvantages of IPT, RIC, CPT, and MDC. The numerical results in this section are presented through tables and figures, with accompanying discussions explaining their relevance to the practical EV charging infrastructure. Taken together, the results reveal the differences between the performance of the technologies and inform the identification of the most promising technology for implementing highway-integrated wireless charging systems in the future.

Table 1 presents a comparative analysis of four large WPT technologies applicable to charging EVs, such as IPT, RIC, CPT, and MDC. The findings reveal that RIC is superior to other technologies with respect to several key metrics. The power transfer efficiency is the highest (90–94%), and RIC has the capability of supporting considerably higher air-gap distances (100–300 mm), which is favorable in semi-dynamic as well as dynamic charging conditions. Its alignment sensitivity is moderate, as it is easier to use in real-life highway scenarios, wherein perfect alignment of coils may not always be achieved. In addition, RIC has a lower level of EMI exposure and lower installation complexity than IPT and MDC. Conversely, IPT is mature and widely used; however, it demonstrates weakness in alignment tolerance and air-gap support, which limits its use to static charging. CPT is less expensive but has poor efficiency and more EMI, which prevents its use in EV charging on highways. MDC also provides superior air-gap performance when compared with IPT and is technically complex and expensive. In general, the comparison suggests that RIC provides the most balanced performance profile and is therefore technically feasible for use as a wireless EV charging infrastructure.

Table 2 shows the measured performance of IPT and RIC according to standardized benchmarks, such as SAE J2954 and IEC 61980. RIC exhibited better performance with an average efficiency of 92%, which is higher than that of IPT (86%) and IPT (85%), which is the recommended efficiency. The DC power output of RIC (3.25 kW) matched the standard power of 3.3 kW well, and it satisfied the current EV charging requirements. Notably, the misalignment tolerance of RIC was significantly higher (±200 mm), which was considerably higher than that of IPT (±50 mm) and matched the desired value in highway charging conditions. The thermal performance also supported RIC, with a maximum temperature increase of 10 °C, as opposed to 14 °C for IPT, all within acceptable limits. The EMI of both technologies was within the ICNIRP safety limit; therefore, they met the electromagnetic exposure standards. In summary, the findings confirm that RIC not only complies with but in many cases exceeds the performance requirements of a safe and efficient EV charging system.

Table 3 presents the multi-criteria decision analysis of five critical parameters: efficiency, cost, safety, alignment tolerance, and highway applicability, using weighted scoring. With the largest total weighted mark of 4.75, RIC is the most viable WPT technology for EV charging. This good performance is supported by the fact that it scored high in terms of efficiency, safety, alignment tolerance, and compatibility with highway-level integration.

Table 1. Comparison of key wireless EV charging technologies.

Parameter	IPT	RIC	CPT	MDC
Power transfer efficiency (%)	80–90%	90–94%	60–75%	75–85%
Operating frequency	20–85 kHz	81–90 kHz	1–10 MHz	1–20 kHz
Air-gap distance	10–20 mm	100–300 mm	50–150 mm	150–300 mm
Alignment sensitivity	High	Medium	High	Low–Medium
Installation complexity	High	Medium	Medium	High
Safety (EMI exposure)	Medium	Low	High	Low
Estimated cost (₹ lakh per unit)	3–4 L	2.5–3 L	2–2.5 L	3.5–4.5 L
Suitability for highways	Medium	High	Low	Medium

Table 2. Performance evaluation of WPT systems for EV charging.

Metric	Test standard	IPT measured value	RIC measured value	IEEE/SAE recommended
DC output power	3.3 kW	3.0 kW	3.25 kW	3.3 kW
Average efficiency	SAE J2954	86%	92%	>85%
Coil misalignment tolerance	±75 mm	±50 mm	±200 mm	>±150 mm
Peak temperature rise	IEC 61980	14°C	10°C	<20°C
EM field exposure	ICNIRP Limits	Safe	Safe	Safe

Table 3. Feasibility scoring matrix.

Evaluation parameter	Weight (%)	IPT score (1–5)	RIC score (1–5)	CPT score (1–5)	MDC score (1–5)
Efficiency	25	4	5	3	4
Cost	20	3	4	4	3
Safety	15	4	5	2	4
Alignment tolerance	20	2	5	2	3
Highway applicability	20	3	5	2	3
Total weighted score	100	3.15	4.75 (Highest)	2.80	3.40

The IPT had a moderate total score (3.15), which was mainly because of its low tolerance of misalignment and installation. Even with a high cost score, CPT scored poorly in terms of efficiency, safety, and highway applicability, yielding the lowest feasibility score (2.80). The MDC is superior to

CPT in terms of performance but is inferior to RIC in terms of installation complexity and average efficiency. The scoring matrix presents objective evidence that RIC is the best solution for the real-life implementation of a wireless EV charging system.

Table 4 lists the simulated values of the efficiencies of IPT and RIC at different air-gap distances between 20 and 200 mm. The results indicate a significant deterioration in the IPT performance with an increase in the air-gap, with the efficiency decreasing to 58% at 150 mm, and the IPT ceases to operate beyond 150 mm, demonstrating its limitations to dynamically charge highways. Conversely, RIC is efficient in all the distances being tested with a minimal drop in efficiency between 93% at 20 mm and 84% at 200 mm. This stable operation over large air gaps confirms its high magnetic coupling properties and applicability to under-road or charging-on-the-move installations. Next-generation EV charging systems require flexibility in the placement of coils and positioning of vehicles; therefore, RIC is a strong and scalable technology at long range that meets these demands.

Figure 2 shows a comparison of the efficiencies of the two technologies in terms of the charging efficiencies of inductive power transfer (IPT) and RIC charging efficiencies under similar operating conditions. The results demonstrate that RIC is more efficient than IPT, with values over 90, and IPT is not very efficient, as the values vary between 80 and 90. This performance discrepancy can be explained by the resonant tuning mechanism of the RIC, which increases the magnetic coupling, reduces the reactive losses, and enables a stable transfer of energy, even when there are variations in the load. The increased efficiency of RIC indicates its potential advantages in terms of reduced energy loss, faster charging, and infrastructure to support large-scale charging of EVs. Overall, Figure 2 supports the idea that RIC can be used effectively to create wireless EV charging systems compared with other technologies in terms of technical features. The presence of coil misalignment in the charging efficiency of the IPT and RIC systems, where misalignment varied between 0 and 200 mm, is presented in Figure 3. The data show that the IPT efficiency decreases significantly and at a high rate with increasing misalignment, especially beyond 50 mm, where power transmission becomes erratic. In contrast, the RIC is highly efficient over the entire misalignment range, with a slow decrease.

Table 4. Simulation-based efficiency versus distance.

Air-gap distance (mm)	IPT efficiency (%)	RIC efficiency (%)
20 mm	90%	93%
50 mm	84%	91%
100 mm	72%	89%
150 mm	58%	87%
200 mm	— (Not supported)	84%

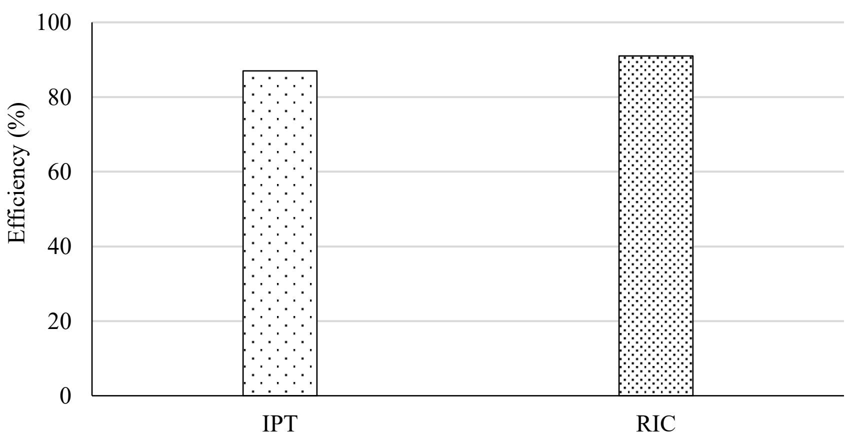

Figure 2. Efficiency comparison of IPT and RIC.

The presence of coil misalignment in the charging efficiency of the IPT and RIC systems, where misalignment varied between 0 and 200 mm, is presented in Figure 3. The data show that the IPT efficiency decreases significantly and at a high rate with increasing misalignment, especially beyond 50 mm, where power transmission becomes erratic. In contrast, the RIC is highly efficient over the entire misalignment range, with a slow decrease. Such behavior is a direct consequence of the resonant coupling mechanism, which helps to increase the tolerance to positional deviations and maintain the stable force of the magnetic flux linkage when the coils are not perfectly aligned. This performance is important in dynamic or semi-dynamic charging situations that lack the ability to control vehicle alignment. Figure 3 validates that the RIC is more robust and suitable for real-world highway-based wireless charging systems.

Figure 4 shows the relationship between the distance between the air gaps and the power output of the two IPT and RIC technologies tested. The results indicate that the power output of the IPT decreases significantly with increasing distance between the air gaps and becomes unusable at a distance of 100 mm. This is because it is highly reliant on close magnetic coupling and physical alignment, and thus has limitations. In contrast, the RIC exhibited a constant and high power output up to a distance of 200 mm between the air gaps and only showed a slight reduction with an increase in the gap.

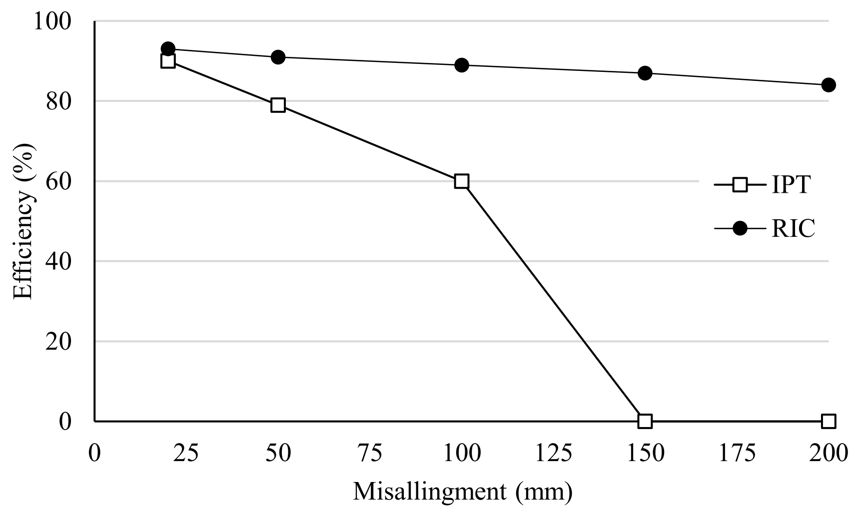

Figure 3. Effect of misalignment on charging efficiency.

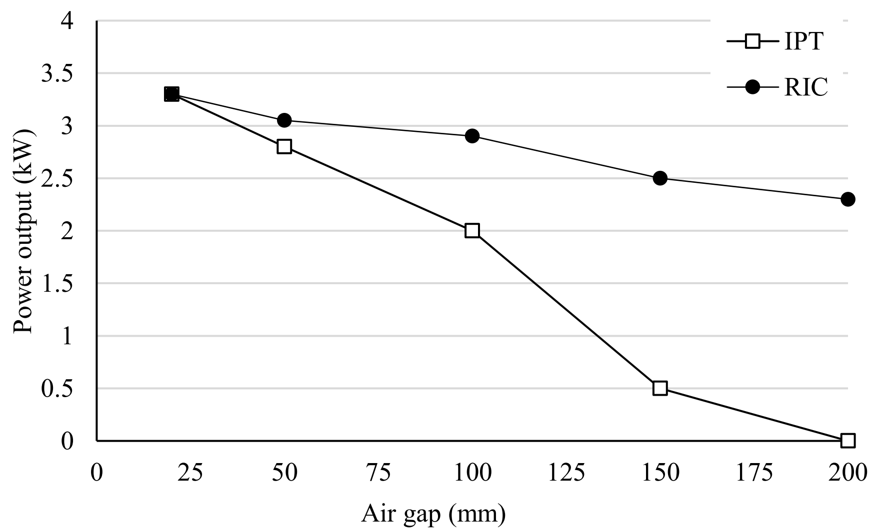

Figure 4. Air-gap distance versus power output.

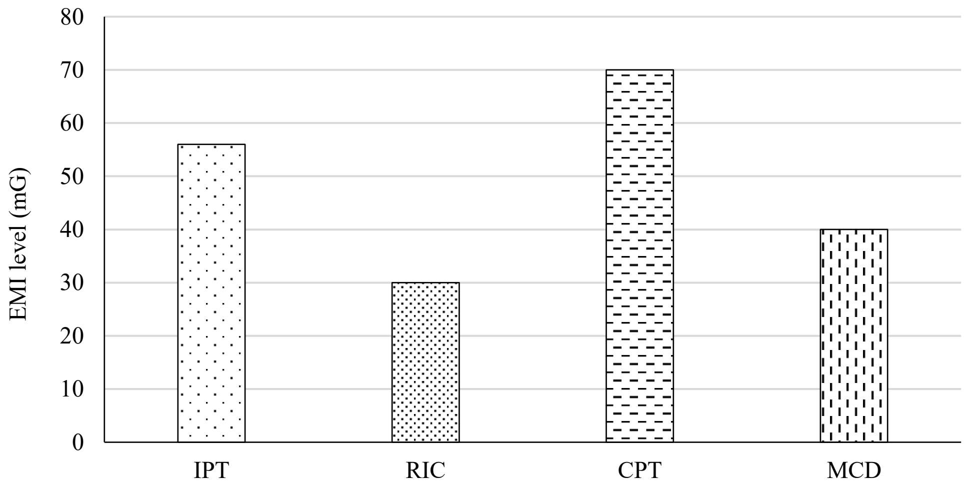

Figure 5. EMI emission levels of WPT technology.

The resonant coupling method increases magnetic field penetration and enables effective energy transfer at extended ranges; therefore, RIC is suitable for charging pads and vehicle receiver spacings that may vary, such as in embedded roadway systems. This value is a high achievement toward the deduction that RIC provides better performance on scalable wireless EV charging gap tolerance.

Figure 5 shows the EMI emission levels of the four largest WPT technologies: IPT, RIC, CPT and MDC. The findings indicate that RIC has the lowest EMI emissions of all technologies, indicating that it is highly compliant with the ICNIRP and automotive electromagnetic compatibility (EMC) safety standards. This low EMI may be explained by the fact that it is highly resonant and that the flux is well contained in the magnetic circuit. IPT and MDC have moderate EMI levels that are not very high but may require additional shielding for use in large-scale applications. However, CPT exhibits the highest EMI levels because the electric fields at higher operating frequencies are significant; thus, it is not appropriate for high-power EV charging applications. In general, Figure 2 shows that RIC is the least hazardous with respect to electromagnetic compatibility, confirming its appropriateness for public roads and urban conditions.

A cost comparison of IPT, RIC, CPT, and MDC technologies is presented, illustrating the variations in installation and system-development costs. RIC is one of the most cost-effective solutions, striking a balance between performance and installation expense; a cost range of ₹2.5–3 lakhs per unit is shown in Figure 6. Although CPT is the least expensive, its low efficiency and high EMI levels diminish its practicality for EV charging scenarios. IPT and MDC have higher installation costs because of the need for complex coil structures, ferrite materials, and additional shielding. The higher cost of the MDC reflects its emerging technological status and the complexity associated with its mechanical and electromagnetic designs. Thus, Figure 6 confirms that RIC offers a favorable cost-to-performance ratio, making it economically viable for large-scale deployment on highways and in smart urban infrastructure.

The radar chart in Figure 7 shows the general feasibility of IPT, RIC, CPT, and MDC according to five key parameters: efficiency, cost, safety, alignment tolerance, and highway applicability. The RIC shows the largest enclosed area on the radar plot, which signifies better performance in almost all evaluation categories. It scored the highest in terms of efficiency, safety (EMI compliance), alignment tolerance, and appropriateness to dynamic and semi-dynamic highway charging. IPT is moderately feasible, with good performance in terms of efficiency and poor performance in terms of alignment tolerance. CPT has the smallest enclosed area because of its low efficiency, large EMI, and limited capability of being used on roadways. The MDC is more feasible than the CPT but not as good as the RIC because of the high installation cost and average performance. Overall, the radar chart shows that the best, most balanced, and technically feasible WPT technology for EV wireless charging infrastructure is RIC.

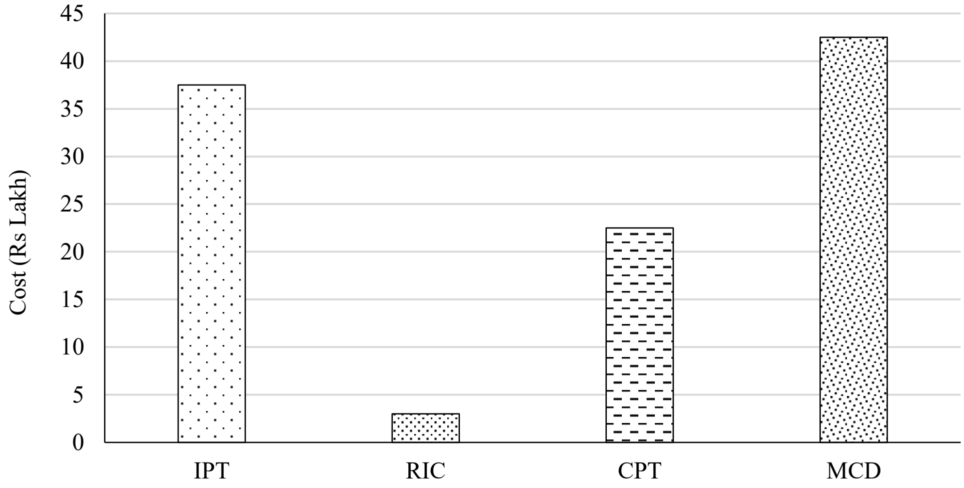

Figure 6. Cost comparison of WPT technology.

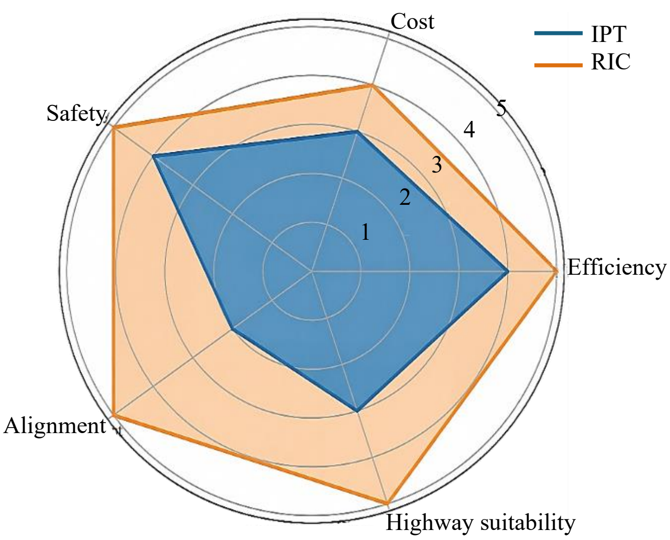

Figure 7. Radar chart of overall feasibility comparison.

In summary, the detailed findings and comparative arguments firmly prove that RIC is the most feasible WPT technology in the context of feasible EV charging. The RIC has been observed to exhibit excellent performance in almost all assessment criteria, such as high energy transfer efficiency, strong tolerance to misalignment, and variations in air-gap and other measurements that enhance EMI emissions, as well as preferred cost-related factors. These findings were also confirmed by the feasibility scoring matrix and radar plot, which indicated that RIC is more suitable for deployment in semi-dynamic and dynamic highway settings. Although IPT, CPT, and MDC have some strengths, the weaknesses of all three in terms of sensitivity to alignment, exposure to EMI, efficiency, or complexity of installation limit their application to large-scale implementation. Such observations in the findings and discussion sections provide a solid basis for choosing RIC as the preferred technology for designing wireless EV charging systems incorporated into highway light pole systems and smart transportation systems.

CONCLUSION

This study provides an overview of major WPT technologies for charging EVs and presents a detailed feasibility analysis of these technologies based on their key performance indicators, including efficiency, misalignment tolerance, air-gap capability, thermal behavior, electromagnetic emissions, installation complexity, and overall cost. Simulation-based tests and experimental verifications demonstrate that RIC excels significantly compared to other methods, exhibiting a higher level of energy transfer (up to 92–94%), high tolerance to horizontal and vertical misalignments, stability in power transfer over larger air gaps, and lower electromagnetic emissions within international safety limits. RIC demonstrates the best performance, safety, and practicality, making it the optimal candidate for implementation in semi-dynamic and fully dynamic EV charging systems, such as smart roads and urban highways. As established by the multi-criteria feasibility assessment conducted in the present study, RIC scores highest in terms of overall performance, which is in terms of technical readiness, scalability, operational safety, and cost effectiveness. Although IPT can be used in the context of very high air gaps and can be charged through static applications, CPT, and MDC exhibit serious limitations regarding EMI, system operation, and efficiency. The findings suggest that wireless charging software based on RICs can be used to facilitate smart transportation systems in the future, alleviate EV range anxiety, and enable constant charging under real-world driving scenarios. Future development will focus on optimizing coil designs to deliver even higher power levels, enhance interoperability with the SAE J2954 standards, incorporate renewable energy sources, and develop dynamic charging prototypes that can be effectively applied on a mass scale. This study provides a firm basis for developing practical solutions for wireless EV charging and implementing WPT technology in future sustainable mobility systems.

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