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

Maridas Pillai[1,*], Anil Pal[2], Mukesh Kumar Gupta[3]

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. The Wireless Power Transfer (WPT) has become a promising alternative that provides automated charging, better convenience, and a possible integration into the smart highways and urban environment. 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 include 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 Resonant Inductive Coupling is always superior over other technologies showing up to 92–94 percent efficiency, high level of misalignment, lower 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 to the 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 grown to be the global shift towards sustainable transportation which is increasing the use of EVs due to the challenges posed by exhaustion of fossil fuel, increase in carbon emissions, and increased environmental laws [1]. Although EV technology has improved greatly, provision of effective, dependable, and convenient charging infrastructure remains one of the biggest challenges that have restricted its widespread usage. In traditional plug-in charging applications, physical connectors are used, which present some limitations: cable wear, safety concerns in the public, reliance on user interaction, and a high rate of upkeep [2]. With the rising EV market, the necessity to introduce new solutions to the charging process is rising, which should mitigate user effort and propel automation and the ability to seamlessly fit into the smart city ecosystems. WPT has become a disruptive technology that can overcome these constraints by allowing the transfer of energy

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between charging pads and EV receivers non-contactlessly [3]. Removing the use of physical connectors, WPT has a few benefits such as higher user convenience, less mechanical wear, high level of safety, and integration with autonomous vehicle systems. Moreover, the WPT technologies like IPT, 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 like coil positioning, the distance between the air-gap, power transfer efficiency, electromagnetic interference (EMI), thermal characteristics and scalability of system should be resolved before WPT could be deployed successfully [6]. In this respect, the comparison of current WPT technologies, to establish their feasibility in the EV charging systems in the reality, is in urgent need. This paper will give a detailed feasibility study 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 be able to satisfy performance, safety, and cost factors when it comes to the next-generation EV charging infrastructure, specifically in smart highway 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 points out that initial experiments in the field of inductive charging established that transfer of power over small air gaps using closely coupled coils was possible, mainly low-power consumer electronics [5]. With the development of EV technology, scientists expanded the inductive charging principles to higher power levels and studied LCL and LCC compensation topology to enhance efficiency and reduce reactive power. These initial works have formed the baseline of models of leakage inductance, mutual coupling, and 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, and therefore afforded efficient power transfer with moderate air gaps [7]. Investigations have continuously demonstrated that RIC systems have a greater level of efficiency and can tolerate coil alignment more than conventional inductive systems, particularly charging pads mounted under-road or within parking spots embedded within parking lots. Further improvements in resonant compensation networks also minimized switching losses and enabled them to operate at standardized frequencies around 85 kHz [8]. Parallel developments In similar work on CPT, it was proposed to use electric-field-based coupling mechanisms as an alternative to magnetic coupling. These systems had the benefits of light plates and there could be a reduction in EMI levels but had poor air-gap tolerance, system stability and power capability [9]. Consequently, CPT has been viewed to be more appropriate in low-power or highly limited applications as opposed to EV charging. MDC and hybrid WPT systems including combinations of inductive, resonant, and capacitive systems were another line of study. Although MDC proved to be potentially dynamic at roadway scale, the complexity of the design of its coils, limitations on EMI and mechanical assembly hampered its practical implementation [10]. Other studies were on the effect of the 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 large body of literature [11]. Simulation-driven and experiment-driven studies indicated that the efficiency of IPT systems can be significantly decreased by a small lateral or angular error. Resonant systems in contrast were more tolerant because magnetic coupling was stronger at resonance conditions. This development made RIC a competitive contender of semi-dynamic and dynamic charging lanes. The key consideration of the literature is safety and electromagnetic compatibility. The researchers who have assessed the effects of magnetic field exposure determined that when proper shielding and coil spacing measures are adopted, well-designed RIC and IPT systems can operate within the international safety limits [12]. Thermal analyses 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

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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 it provides reliable results in the urban roadways and parking conditions.

In general, the literature indicates that a variety of WPT technologies have been investigated, but Resonant Inductive Coupling has the most balanced efficiency, alignment tolerance, EMI compliance, and scalability, which makes it an attractive candidate in the development of a viable EV charging infrastructure. Nevertheless, additional coil design optimization, standardization, and large-scale implementation studies are needed to facilitate its large-scale adoption.

METHODOLOGY

This paper has adopted a methodological approach that will be conducted in phases with the objective of assessing the viability of significant WPT technologies to charge EVs as illustrated in Figure 1. The workflow of the methodology involves five key steps, namely, technology identification, modeling, and simulation, experimental evaluation, feasibility assessment, and Validation. Each phase is outlined below.

Technology Identification and Review

The initial phase is aimed at defining and familiarizing with the current WPT technologies. The following steps were undertaken: Identification of Major Technologies. The four key approaches have been chosen based on the assessment of their adoption on an industrial level, their ability to be implemented, and their technical maturity. These are IPT, RIC, CPT, and MDC. All these technologies are unique ways of facilitating a wireless energy transfer and portray 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 the deployment of these methods. Parameter Extraction The identification of core technologies was followed by the determination of the operational parameters that were relevant and 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 the well-known standards and well-validated datasets. These parameters are important in the condition of the system behavior under various loading and alignment conditions. The clear knowledge of these metrics provided the input to the formation of the analytical framework and simulation models that were to be used in the further course of the research.

System Modeling and Simulation

The second stage involved the estimation of performance under realistic conditions in the form of mathematical models and simulation tools.

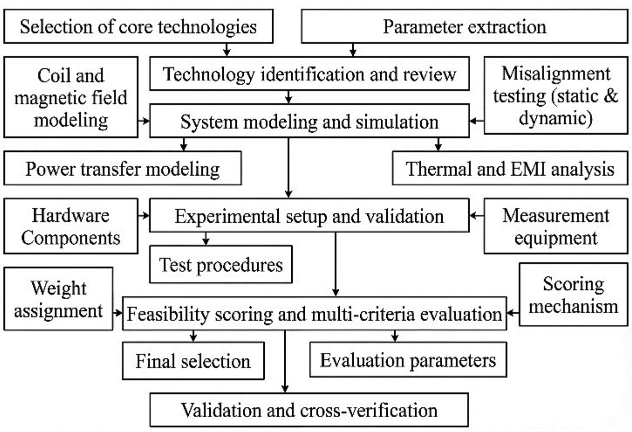

Figure 1. Methodology framework for wireless EV charging feasibility analysis.

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Coil and Magnetic Field Modeling

The modeling phase with coil and magnetic field involved the elaboration of the primary and secondary coils in terms of mutual inductance and equation of coupling coefficient. The models allowed the magnetic interaction power between the transmitter and the receiver coils to be estimated correctly. The Finite Element Modeling (FEM) was also applied to determine the distribution of the magnetic flux within a comprehensive air-gap distances range (20–200 mm). The analysis helped establish the dependence between field intensity and coupling behavior with distance, coming up with the basis of prediction of system performance based on different alignment and spacing conditions.

Power Transfer Modeling

Equivalent circuit models of LCL and LCC compensation topologies were used to examine the behavior of the power transfer of the system. These circuit arrangements were done to provide stable power transfer and high efficiency with various operational loads. With such models, the total efficiency was assessed based on the traditional ratio of output to input power and that is:

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

This modeling phase provided a proper insight into the correlation between compensation design, load characteristics, and power transfer efficiency that can be achieved.

Misalignment Testing (Static & Dynamic)

Both static and dynamic misalignment tests were done to assess the robustness of the operation with deviation of operating conditions. Horizontal misalignment was tested between 0–200 mm whereas the vertical displacement was taken between 10–200 mm. These situations were used to determine the tolerance to positional errors in the WPT system. RIC and IPT technologies were put under the same loading condition of 3.3 kW to make a fair comparison. The study of misalignment was crucial in offering essential data on 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 provide the safety and conformity of working. Through thermal resistance models, which are temperature rise under constant load, it was possible to estimate temperature rise under constant load allowing prediction of coil heating as well as the identification of the possible hotspots. Standard ICNIRP field limits were used to measure the EMI levels to ensure that radiated fields were under the safe exposure limits. These tests made sure that the recommended settings of WPT were thermal and electromagnetic safety conforming. Finally, system feasibility was checked by the output of all the analyses in the form of simulation before hardware implementation took place.

Experimental Setup and Validation

Wireless charging testbed A testbed was developed in laboratory scale to test simulated results.

Hardware Components

The hardware solution comprised of high frequency power conversion and special coil design to achieve efficient power transfer on wireless power. The system was driven by a high-frequency inverter with a frequency of 85 kHz, with which the switching is fast and stable. The coil pairs of circular and rectangular shapes were introduced in order to compare both IPT and RIC technologies experimentally under the same operating conditions. The compensation network was designed with resonant capacitors to ensure the tuning of the network to optimally generate resonance. As well, power electronics with GaN were used to provide high-efficiency, high frequency switching with less thermal loss, which provides a solid basis of experimental validation.

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Measurement Equipment

Professional measurement tools were used to record power, temperature, electromagnetic, and positional properties of the system. Input and output power was measured using digital power analyzers so that transfer efficiency could be calculated accurately. A thermal camera forced the temperature through coils and power electronics in steady state operation. Field measurement was done by a magnetic field probe to ensure adherence to exposure limits. The special misalignment calibration platform helped in the realization of the 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 in a variety of operating conditions. Test of efficiency was conducted by recording the power output of the various air-gap distances in order to monitor the pattern of degradation and determine the best air-gap spacing. Misalignment tests were done by measuring the efficiency at horizontal misalignments of 0–200 mm. In the thermal testing, the temperature increase of coils and electronics was observed at constant load of 3 kW over a 45 minutes period. EMI assay was done to measure the strength of magnetic fields at the surrounding of the coil to determine whether it was within safety limits. Each of the measurements was done three times in order to achieve reproducibility and consistency of collected data.

Feasibility Scoring and Multi-Criteria Evaluation

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

Evaluation Parameters

The comparative evaluation of technologies of wireless power transfer was grounded on a comprehensive arrangement of evaluation parameters that determine feasibility in the real world. The main parameters were the efficiency of the entire system, installation price, safety, and EMI, tolerance during the movement of vehicles and its compatibility in the deployment along highways. The criteria were chosen to make sure that skill in performance as well as the challenges in implementation are taken into consideration in finding out the feasibility of every technology.

Weight Assignment

Each of the evaluation parameters was weighted to represent its relative significance in the practical applications setting of EV charging. Efficiency was assigned the largest weight of 25 percent as it is a key factor in ensuring reductions in energy losses. A weight of 20 was given to the installation cost because the large-scale deployment requires the economic feasibility. A weight of 15% was given on safety and EMI levels to guarantee the level of compliance with the regulatory standards. The weight assigned to alignment tolerance was 20 because it is important in dynamical or semi-dynamical charging scenario. The adaptability of the technology to real-world roadway infrastructure was checked by highway applicability, which was weighted at 20%. These weights provided a balanced and realistic evaluation of every WPT technology.

Scoring Mechanism

The assessment of every wireless charging technology was performed based on a systematic scoring system. The rating on every parameter was based on a scale of 1–5 with higher scores reflecting excellence. The equation was then used to arrive at weighted scores.

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

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.

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Final Selection

The weighted scores were then calculated before ranking the technologies to come up with the most viable choice to employ wireless EV charging infrastructure. The last ranking was a composite evaluation of the technical effectivity, cost-effectiveness, compliance with safety and tolerance to misalignment, and compatibility with deployment on highways. The technology with the highest score became the best candidate and this offered a sound reason as to why it was chosen in the further experimental validation and infrastructure development of the wireless EV charging along highway light poles.

Validation and Cross-Verification

The cross-verification of data in simulation and the experiment was done to achieve the general consistency of the modeled system performance with the actual performance of the system. The comparison revealed that the efficiency that was obtained using simulations was very close to the laboratory values, and the deviations were less than 5 percent, which implies the high model accuracy. In addition, EMI levels were within the allowable safety limits of ICNIRP of RIC and IPT systems in the course of experiments. The behavior of misalignment was also seen in simulation, with RIC; therefore, it was also found that (simulated) misalignment is highly tolerant to both horizontal and vertical displacement and proves to be suitable to dynamic charging conditions where coil alignment cannot be guaranteed at all times. The approach combines the identification of the parameters on the basis of the literature, analytical modeling, FEM simulation, laboratory validation, and multi-criteria decision analysis. This methodology will provide a sound feasibility study of Wireless Power Transfer technologies regarding EV charging systems.

RESULTS AND DISCUSSION

This is due to the fact that the results of the analytical modeling, simulation experiments, and performance measurements give a detailed insight on the behavior of different WPT technologies when used in charging electric vehicles. The relative analysis of the main technical parameters of efficiency, air-gap capability, misalignment tolerance, thermal performance, electromagnetic emissions, cost, and overall feasibility can provide profound understanding of the practical advantages and drawbacks of IPT, RIC, CPT, and MDC. The quantitative results in this section are summarized by table and Figure and the discussions related to them interpolate on the implications of these findings on real-world 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 to implement highway-integrated wireless charging systems.

Table 1 presents the comparative analysis of four large WPT technologies that are applied in charging electric vehicles such as IPT, RIC, CPT, and MDC. The findings reveal clearly that RIC has been found superior to the other technologies on a number of key metrics. The power transfer efficiency is the highest (90–94 percent) and RIC has the capability of supporting much higher air-gap distances (100–300 mm), which is very favorable in semi-dynamic as well as dynamic charging conditions. Its alignment sensitivity is moderate hence is easier to use in the real-life highway whereby the perfect alignment of coils may not always be achieved. In addition, RIC has a lower level of EMI exposure and lower-instalment complexity than IPT and MDC. Conversely, IPT is mature and widely used, but demonstrates a weakness in alignment tolerance and air-gap support, which limits its use to mostly static charging. CPT is less expensive, but with poor efficiency and more EMI, which cannot be used in EV charging on highways. MDC also provides superior air-gap performance when compared to IPT and is technically complex and expensive. In general, the comparison suggests that RIC provides the most balanced performance profile, which is why it is technically possible to use as the wireless EV charging infrastructure.

Table 2 shows the measured performance of IPT and RIC concerning the standardized benchmarks like SAE J2954 and IEC 61980. RIC shows better performance with an average efficiency of 92 which is higher than IPT (86) and the lowest efficiency of 85 which is the recommended efficiency. The DC

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power output of RIC (3.25 kW) matches the standard power of 3.3 kW very well, and the fact that it fits the current EV charging requirements very well. Notably, the misalignment tolerance of RIC is significantly higher (±200 mm), which is much higher than that of IPT (±50 mm) and matches the desired value in highway charging conditions. Thermal performance also provides an added support to RIC with maximum temperature increase of 10 °C as opposed to 14 °C on IPT, all well within acceptable limits. The EMI of both technologies is within the ICNIRP safety limit and therefore they meet the electromagnetic exposure standards. Combined, the findings can be used to confirm that RIC does not only comply with but in many cases exceeds the set performance requirements of a safe and efficient EV charging.

Table 3 presents a multi-criteria decision analysis of five critical parameters, efficiency, cost, safety, alignment tolerance, and highway applicability using weighted scoring. Having the largest total weighted mark of 4.75, RIC becomes the most viable WPT technology to use in 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. IPT has a moderate total score (3.15), which is mainly because of the low tolerance of misalignment and installation. Even with a high score in cost, CPT scores poorly in efficiency, safety, and highway applicability, giving the lowest feasibility score (2.80). MDC is superior in its performance compared to CPT but is inferior to RIC in the complexity of the installation and average efficiency. The scoring matrix presents the objective evidence of RIC as the best solution to the real-life implementation of the wireless EV charging system.

Table 4 shows the simulated values of the efficiency of IPT and RIC at different air-gap distances between 20–200 mm. The findings indicate a significant deterioration in the IPT performance with the enlargement of the air-gap with the efficiency decreasing to 58% at 150 mm only and the IPT ceases to work after 150 mm, which shows its limitations to dynamically charge highways. Conversely, RIC is efficient in all the distances being tested with minimal drop in efficiency between 93 percent at 20 mm to 84 percent 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. The next-generation EV charging systems need flexibility in placement of coils and positioning of vehicles which is why RIC is a strong and scalable technology at long range which meets the demands.

Figure 2 shows comparative efficiency of two technologies in terms of charging efficiency of the Inductive Power Transfer (IPT) and Resonant Inductive Coupling (RIC) in similar operating conditions. The findings make it clear that RIC is always more efficient than IPT, having values over 90, and IPT is also not so efficient, as the values vary between 80 and 90. This performance discrepancy could be explained by resonant tuning mechanism of RIC that increases magnetic coupling, reduces the reactive losses and enables stable transfer of energy even when there are variations in load. The increased efficiency of RIC indicates its possible advantages in the loss of energy, faster charging, and the infrastructure to support the large-scale charging of EVs. On the whole, the figure supports the idea that RIC can be used effectively in creating wireless EV charging when compared to other competitors in terms of technical features.

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

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Figure 4 indicates the relationship between the distance between the air-gaps and power output of the two IPT and RIC technologies. The findings indicate that the power output of IPT reduced drastically with the distance between the air-gaps and is almost unusable at a distance of 100 mm. This is because it is highly reliant on close magnetic coupling and close physical alignment and thus its limitation. As compared to that, RIC exhibits constant and high-power output up to the distance of 200 mm between air-gaps, and only shows slight reduction with an increase in the gap. Resonant coupling method increases magnetic field penetration and enables effective energy transfer at extended ranges and RIC is therefore good where the charging pad and the vehicle receiver are likely to vary in spacing like embedded roadway systems. This value is a high achievement toward the deduction that RIC provides better performance on scalable wireless EV charging gap tolerant.

Figure 5 shows the EMI emission levels of the four largest WPT technologies such as IPT, RIC, CPT, and MDC. The findings indicate that, RIC has the lowest EMI emissions of all technologies, meaning that the technology is highly compliant with the ICNIRP and automotive EMC safety standards. This low EMI may be explained by the fact that it is highly resonant and the flux is well contained in the magnetic circuit. IPT and MDC have moderate EMI levels that are not very high but can need extra shielding to be used in large-scale applications. CPT, however, exhibits the greatest EMI levels since the electric fields at higher operating frequencies are great, and thus is not appropriate in high power applications of EV charging. In general, the figure shows that RIC is the least hazardous with respect to the electromagnetic compatibility, which confirms its appropriateness to the public roads and city conditions.

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

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Table 4. Simulation-based efficiency vs. 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%

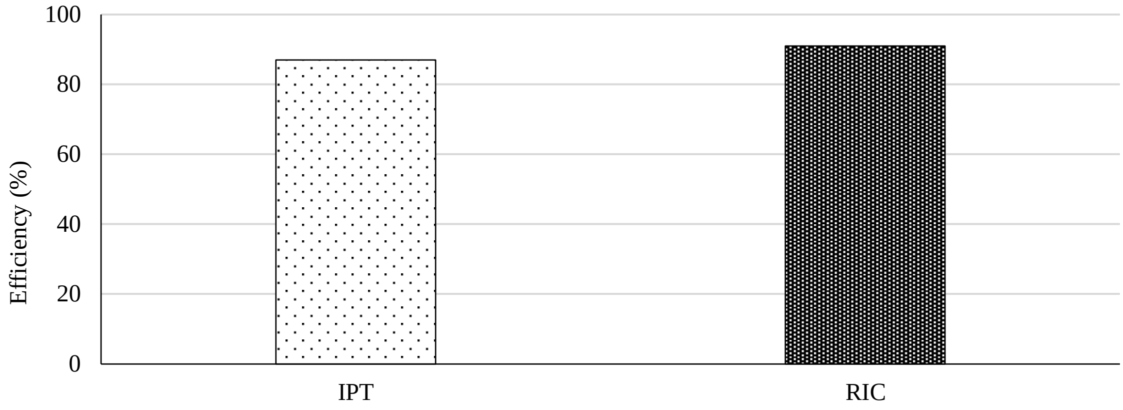

Figure 2. Efficiency comparison of IPT and RIC.

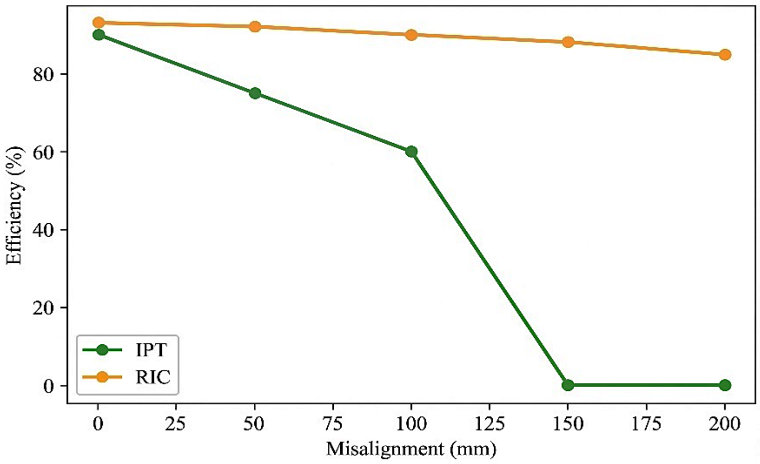

Figure 3. Effect of misalignment on charging efficiency.

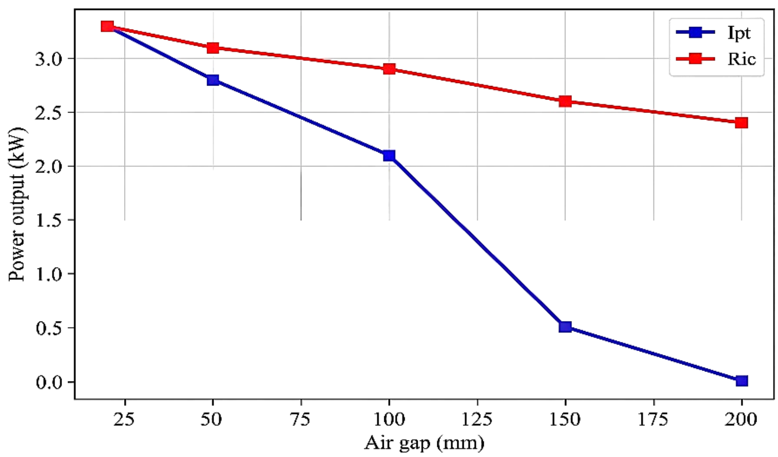

Figure 4. Air gap distance vs power output.

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

The radar chart in Figure 7 shows the general feasibility of IPT, RIC, CPT, and MDC as per five key parameters, namely, efficiency, cost, safety, alignment tolerance and highway applicability. RIC shows the biggest enclosed area on the radar plot that signifies the better performance in almost all evaluation categories. It scores the highest in 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 least enclosed area because of low efficiency, large EMI and small capability of being used in roadways. MDC is more feasible than CPT but not as good as RIC due to the expensive cost of installation and average performance. All in all, the radar chart shows the best and most balanced and technically feasible WPT technology in EV wireless charging infrastructure is RIC.

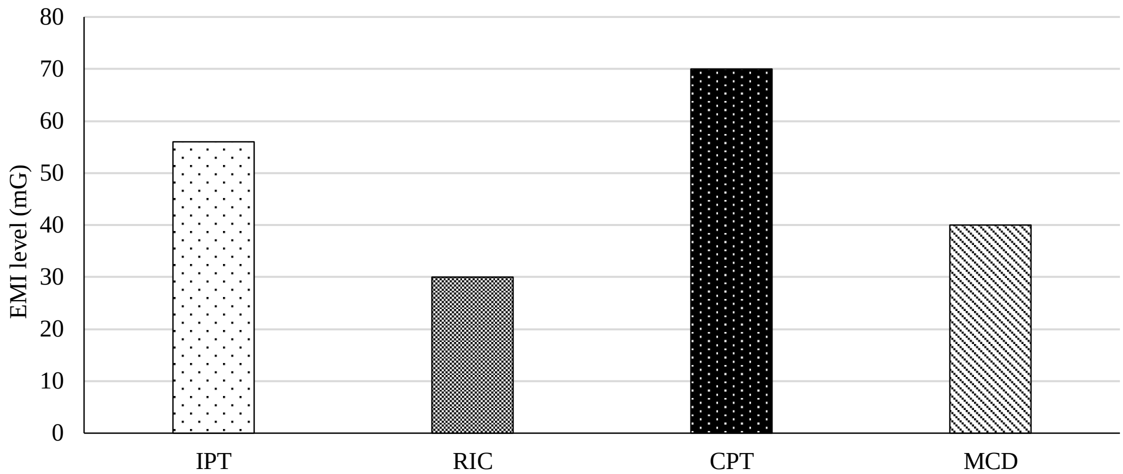

Figure 5. EMI emission levels of WPT technology.

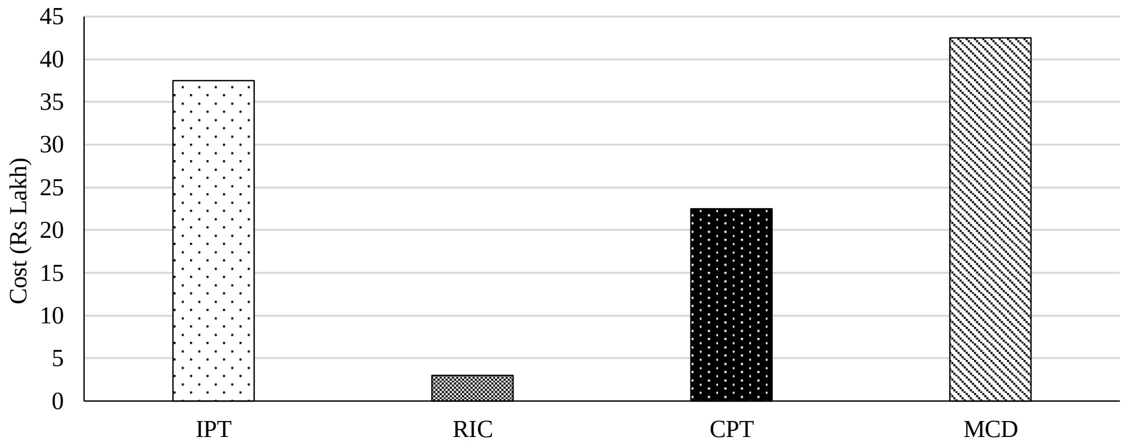

Figure 6. Cost comparison of WPT technology.

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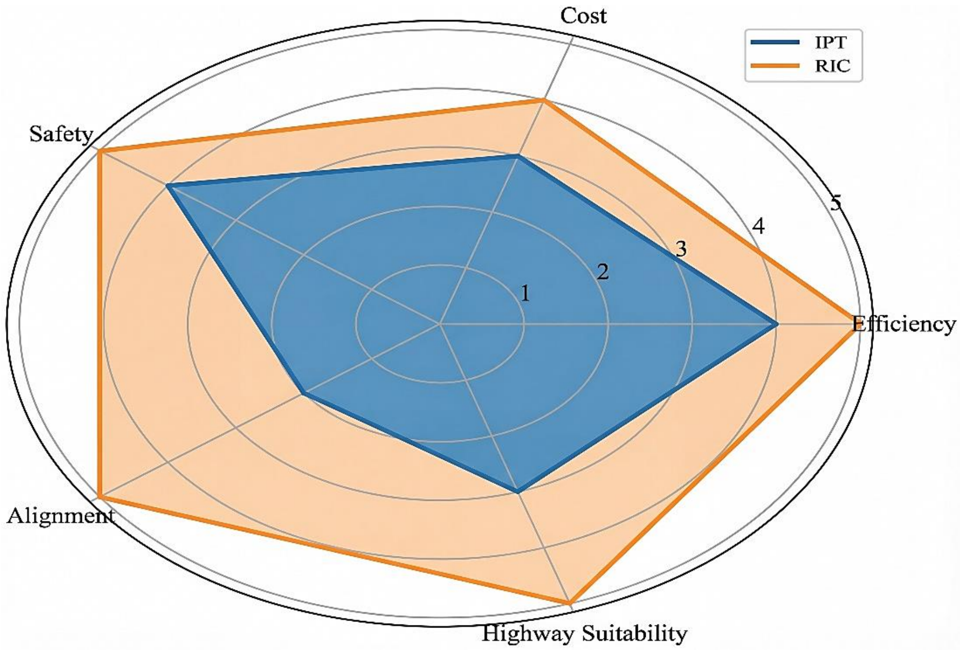

Figure 7. Radar chart of overall feasibility comparison.

All in all, the detailed findings and comparative arguments firmly prove that Resonant Inductive Coupling (RIC) can be the most feasible WPT technology in the context of feasible EV charging. RIC has been observed to exhibit excellent performance in almost all the assessment criteria such as high energy transfer efficiency, strong tolerance to misalignment, and variation of air-gap and other measurements that enhance EMI emissions as well as preferred cost-related factors. These findings are also confirmed by the feasibility scoring matrix and radar plot as it indicates that RIC is more suitable to be deployed on semi-dynamic and dynamic highway settings. Although IPT, CPT, and MDC have some strengths, the weaknesses of all three in sensitivity to alignment, exposure to EMI, efficiency, or complexity of installation limit their application to large scale implementation. Such observations of the findings and discussion section provide a solid basis upon which RIC is chosen as the technology to prefer in designing wireless EV charging systems incorporated into highway light pole systems, and smart transportation systems.

CONCLUSION

The paper has provided an overview of major WPT technologies in charging electric vehicles and has given a detailed feasibility analysis of these technologies based on their key performance indicators, including efficiency, misalignment tolerance, air-gap capability, thermal behavior, electromagnetic emissions, complexity in installation, and overall cost. Simulation-based tests and experimental verifications proved that RIC excels much higher than other methods with a higher level of energy transfer (up to 92–94%), high tolerance to horizontal and vertical misalignments, stability in the power transfer over larger air-gaps, and lower electromagnetic emissions in international safety limits. RIC has the best performance, safety, and practicality, and hence it is the best candidate to be implemented in semi-dynamic and fully-dynamic EV charging systems like smart roads and urban highways. As the multi-criteria feasibility assessment conducted within the context of the present study established, 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 level of air-gaps and can be charged through static application, CPT, and MDC show serious limitations with regards to 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 anxiety as a result of a range, and allow constant charging under real-world driving scenarios. Future development will be aimed at making the coils designs optimal to deliver even higher power levels, enhance the interoperability with the SAE J2954 standards, incorporate renewable energy sources, and

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come up with dynamic charging prototypes that can be effectively applied on a mass-scale basis. The paper provides a firm base to develop the practical solutions in wireless EV charging and helps to implement the WPT technology in future sustainable mobility systems.

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