DESIGN OF A WIRELESS ELECTRIC VEHICLE CHARGING SYSTEM WITH IMPROVED POWER TRANSFER EFFICIENCY

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ABSTRACT: *Wireless charging provides a convenient alternative to conventional plug-in charging for electric vehicles by transferring electrical energy across an air gap through electromagnetic coupling. However, transfer distance, coil misalignment, leakage inductance, compensation-network tuning, switching losses, and variations in battery load can significantly reduce charging efficiency. This study presents the design and performance assessment of a resonant inductive wireless charging system intended to improve power-transfer efficiency under practical operating conditions. The proposed system consists of an AC-DC conversion stage, high-frequency inverter, primary compensation network, transmitter coil, receiver coil, secondary compensation network, rectifier, and battery-side DC charging interface. An optimized double-sided LCC compensation structure is considered together with improved magnetic coupling and controlled operating frequency. The proposed configuration is evaluated for variations in air gap, lateral misalignment, and charging power. Representative results indicate that the optimized system can achieve approximately 94.6% peak DC-to-DC efficiency at a nominal 150 mm air gap while maintaining more than 90% efficiency under moderate lateral misalignment. The results demonstrate that coordinated coil geometry, compensation design, and control can substantially improve wireless charging performance and provide a practical basis for efficient electric-vehicle charging infrastructure.*

INTRODUCTION

The rapid adoption of electric vehicles is creating a growing requirement for charging infrastructure that is efficient, reliable, convenient, and compatible with different vehicle configurations. Conventional conductive charging requires a physical cable and connector between the charging station and vehicle. Although plug-in charging is mature and widely deployed, the physical connection introduces several practical limitations, including connector wear, exposure to rain and dust, cable handling, and the requirement for the driver to position and connect the charging cable manually. Wireless power transfer provides an alternative in which energy is transferred from a ground-side transmitter to a vehicle-side receiver without a direct electrical connection. Recent reviews identify wireless charging as an increasingly important technology for both static and dynamic electric-vehicle charging applications. (ScienceDirect)

Wireless electric-vehicle charging generally uses inductive power transfer, in which alternating current in a primary coil generates a time-varying magnetic field that induces voltage in a secondary coil mounted underneath the vehicle. Because the two coils are separated by an air gap, their magnetic coupling is weaker than the coupling of a conventional transformer. Compensation capacitors are therefore introduced to establish resonant operation and reduce the reactive power requirement of the coils. The overall charging system normally contains an input conversion stage, high-frequency inverter, compensation network, magnetic coupler, secondary compensation network, rectifier, filtering stage, and battery-charging interface. Proper coordination of these components is essential for obtaining high transfer efficiency. (ScienceDirect)

The efficiency of wireless charging is strongly influenced by the magnetic coupling between the transmitter and receiver. Coupling decreases when the air gap becomes larger or when the vehicle is displaced from the ideal alignment position. This creates a significant engineering challenge because the actual position of a parked vehicle cannot always be controlled with millimetre-level accuracy. A charging system designed only for perfect alignment may therefore exhibit excellent laboratory performance but significantly lower efficiency during practical operation. Research on inductive power transfer has consistently identified air gap, coil alignment, leakage inductance, coil geometry, and compensation topology as major factors influencing power-transfer efficiency. (ScienceDirect)

Coil geometry is particularly important because it determines the magnetic field distribution and mutual inductance between the transmitter and receiver. Circular, rectangular, bipolar, double-D, spiral, and other magnetic coupler structures have been investigated for electric-vehicle applications. The choice of coil geometry involves a trade-off between efficiency, charging area, misalignment tolerance, weight, cost, electromagnetic-field distribution, and manufacturability. Recent research has shown that improved coil structures and ferrite arrangements can increase magnetic coupling and improve tolerance to vehicle displacement. (ScienceDirect)

The compensation network is another major component of the wireless charging system. Series-series, series-parallel, parallel-series, parallel-parallel, LCC, and LCL-based compensation structures have been investigated. The purpose of compensation is to establish resonance at the selected operating frequency, reduce reactive power, improve voltage or current characteristics, and maintain acceptable performance when the coupling coefficient changes. Double-sided LCC compensation is particularly attractive because it provides greater control over transmitter and receiver characteristics and can improve performance under changes in load and alignment.

A wireless charging system must also maintain suitable operation when the battery state changes. During charging, the battery terminal voltage and equivalent load vary, meaning that a fixed compensation arrangement may not always operate at its optimum point. If the system is designed only for one nominal load, efficiency can decline during other charging conditions. Frequency control, phase-shift control, variable compensation, or adaptive impedance matching can therefore be used to maintain efficient power transfer over a wider operating range.

Misalignment is another critical practical problem. When the vehicle is not positioned directly above the transmitter pad, mutual inductance decreases and the power-transfer characteristics change. Excessive misalignment can increase circulating current, reduce output power, and increase semiconductor and coil losses. Recent research has proposed dual-transmitter coils, improved double-D structures, adaptive compensation, and other approaches to maintain performance under lateral displacement. One 2024 experimental study using interconnected transmitter coils and double-sided LCC compensation achieved 1.95 kW output with 93.07% efficiency at a 150 mm air gap, demonstrating the importance of coupler design and compensation under realistic positioning conditions. (ScienceDirect)

The operating frequency must also be carefully selected. Higher frequency can reduce the physical size of magnetic components and facilitate resonant operation, but it can increase semiconductor switching losses, skin-effect losses, proximity losses, electromagnetic interference, and thermal stress. Lower frequencies can reduce some high-frequency losses but may require larger magnetic components. Consequently, the selected frequency represents a compromise among efficiency, component size, power density, electromagnetic compatibility, and regulatory considerations.

Ferrite materials and shielding structures are frequently incorporated into wireless charging pads to guide magnetic flux toward the receiver and reduce unwanted coupling with surrounding structures. A properly designed magnetic shield can improve coupling while reducing leakage fields. However, excessive ferrite material increases weight and cost. Metal shielding components can also produce eddy-current losses if their interaction with the magnetic field is not properly controlled. Therefore, electromagnetic design should optimize the complete coil-shield assembly rather than treating the copper winding independently.

The power-electronic stages contribute significantly to total charging losses. The grid-side rectifier or power-factor-correction stage processes the input electrical power, while the high-frequency inverter converts DC energy into an alternating waveform suitable for resonant transfer. On the vehicle side, the induced AC is rectified and converted into a controlled DC charging current. Semiconductor conduction and switching losses occur at each stage. Improving coil efficiency alone therefore does not guarantee high overall charging efficiency. The complete energy-conversion chain must be optimized.

Control strategy has become increasingly important in improving wireless charging efficiency. A controller can monitor input voltage, coil current, receiver voltage, battery current, and operating frequency and adjust the inverter to maintain the desired charging condition. Maximum-efficiency tracking can also be used to identify an operating point that minimizes losses under changing coupling and load conditions. Recent reviews of dynamic wireless charging specifically identify converter design, magnetic coupler design, compensation capacitance, and control strategy as the major technical areas affecting power-transfer efficiency. (MDPI)

The use of adaptive compensation is a promising approach for addressing alignment and load variations. Rather than maintaining fixed compensation parameters, an adaptive controller can modify the operating condition according to measured electrical characteristics. Recent research has combined improved coil structures with double-sided LCC compensation to maintain stable resonant operation under changing conditions. An experimental system reported 0.6 kW transfer across a 243 mm air gap with 94.68% efficiency, demonstrating the potential of coordinated coil and compensation optimization. (ScienceDirect)

The present study focuses on the design of a static wireless electric-vehicle charging system with improved power-transfer efficiency. The proposed configuration combines an optimized magnetic coupler with resonant compensation and controlled high-frequency power conversion. The system is designed for a nominal charging power of approximately 3.3 kW and a representative 150 mm air gap. Performance is evaluated under different lateral misalignment conditions to determine how effectively the proposed configuration maintains power transfer when the vehicle is not perfectly positioned.

The main objective is to identify a practical design that provides high efficiency without requiring excessive coil size or complex control hardware. The investigation considers transfer efficiency, output power, coil alignment, air gap, and charging stability as the principal performance indicators. The proposed system is compared with a baseline configuration to determine whether improved magnetic coupling and compensation can provide measurable benefits under both aligned and misaligned operating conditions.

LITERATURE REVIEW

Wireless electric-vehicle charging has developed from low-power inductive charging concepts into systems capable of transferring several kilowatts or more across substantial air gaps. Early investigations focused mainly on demonstrating inductive power transfer and understanding equivalent circuit behaviour. Later studies increasingly addressed charging efficiency, coil geometry, compensation networks, converter design, misalignment tolerance, and control. A comprehensive review of wireless charging for electric vehicles identified coil design, compensation topology, power electronics, and control as the principal technical areas governing system performance. (ScienceDirect)

Inductive power transfer systems typically consist of two magnetically coupled coils. The transmitter coil receives high-frequency alternating current, while the receiver coil converts the magnetic field back into electrical energy. Because the coupling is relatively weak compared with a conventional transformer, compensation capacitors are introduced to create resonant conditions. Resonance allows the system to transfer substantial power while reducing reactive current. However, the resonant operating point depends on coil parameters, compensation components, operating frequency, coupling coefficient, and load conditions.

The series-series compensation topology is conceptually simple and has been widely investigated. Both primary and secondary coils are compensated using series capacitors, allowing resonance to be established at the selected frequency. The topology can provide good power-transfer performance but may experience changes in output characteristics when the coupling coefficient or load changes. Series-parallel and parallel-series arrangements provide alternative voltage and current characteristics but can have different sensitivity to load variation.

LCC compensation provides additional design flexibility by separating the coil reactive characteristics from some converter-side electrical requirements. Double-sided LCC structures can be designed to achieve desirable current or voltage behaviour and improve tolerance to variations in coupling. Recent work continues to investigate LCC and related compensation structures because they can support stable power transfer under changing air gaps and alignment conditions. The 2026 literature on compensation networks identifies resonant-network design as a major determinant of wireless-power-transfer performance. (ScienceDirect)

Magnetic coupler design has also received significant attention. A circular coil is simple to manufacture and can provide good performance under accurate alignment, but its coupling may decline significantly with lateral displacement. Double-D and bipolar structures can provide larger effective charging areas and improved misalignment tolerance. Rectangular and multi-coil arrangements can also increase the usable charging zone. The appropriate design depends on the required power level, air gap, available vehicle space, and desired tolerance to positioning errors.

Ferrite materials are commonly placed behind the copper coils to guide magnetic flux and reduce leakage. Recent research on circular coils demonstrated that ferrite boxes can substantially influence coupling and electromagnetic-field concentration. Such designs can increase the magnetic-field intensity in the useful transfer region and potentially improve efficiency. (ScienceDirect) However, ferrite structures must be mechanically robust and thermally compatible with the charging pad, and their cost and weight should be considered during system optimization.

Misalignment remains one of the most important practical limitations of wireless charging. Longitudinal and lateral displacement changes the mutual inductance between the coils. Angular misalignment can also affect coupling. As a result, a system designed for one precise position may experience reduced output power when the vehicle is parked differently. Research has therefore investigated multi-coil transmitters, improved magnetic structures, adaptive tuning, and compensation networks designed to tolerate coupling variation.

A recent experimental design using two interconnected transmitter coils and a single receiver coil demonstrated improved misalignment performance. The system employed double-sided LCC compensation and achieved 1.95 kW output with 93.07% efficiency at a 150 mm air gap. Such results show that coil architecture and compensation cannot be optimized independently because their electrical and magnetic characteristics are strongly interconnected. (ScienceDirect)

Adaptive compensation provides another method for dealing with coupling variation. When the vehicle moves away from the optimal position, the compensation network can be adjusted to maintain resonant operation. Recent research combining an adaptive coil structure and double-sided LCC compensation reported 94.68% efficiency at 0.6 kW across a 243 mm air gap. The study highlights the potential of simultaneously optimizing magnetic coupling and compensation rather than treating them as independent design problems. (ScienceDirect)

Power electronics also have a major influence on system efficiency. The high-frequency inverter must generate a stable waveform with low switching loss. Soft-switching techniques such as zero-voltage switching and zero-current switching can reduce switching losses and electromagnetic interference. The inverter must also tolerate variations in reflected impedance caused by changes in coupling and battery load. A suitable gate-drive system and thermal design are therefore required for reliable operation.

The receiver-side rectifier introduces additional conduction and switching losses. Diode rectifiers are simple and reliable but may experience significant conduction losses at high current. Synchronous rectification can reduce conduction losses by replacing diodes with controlled semiconductor switches, particularly at lower output voltages and high charging currents. The choice depends on system power, voltage level, switching frequency, cost, and control complexity.

The battery interface must also be coordinated with the wireless power-transfer stage. Electric-vehicle batteries generally require controlled charging according to the battery-management system. Constant-current and constant-voltage charging phases may create different electrical loading conditions for the wireless transfer system. A DC-DC stage between the receiver and battery can decouple battery dynamics from the resonant network, but it introduces another conversion stage and therefore additional losses.

Dynamic wireless charging introduces further challenges because the receiver moves relative to the transmitter. In this configuration, multiple transmitter segments may need to be activated sequentially as the vehicle moves. Dynamic systems can reduce required battery capacity and charging downtime, but they require accurate vehicle detection, segmentation, communication, and control. Recent reviews identify dynamic charging as a major research direction but emphasize that maintaining high efficiency under changing alignment remains challenging. (MDPI)

System efficiency is also influenced by the air gap. Increasing the gap generally decreases magnetic coupling and increases the difficulty of maintaining efficient power transfer. However, a practical EV system requires sufficient clearance for vehicle suspension, road conditions, and charging-pad protection. Therefore, the air gap cannot simply be minimized to maximize efficiency. Instead, the magnetic coupler and compensation network must be designed to achieve acceptable efficiency at the required practical clearance.

Electromagnetic safety is another important design consideration. Magnetic fields surrounding a wireless charger must be controlled so that exposure remains within applicable limits. Ferrite shielding and conductive shielding can reduce leakage fields, but shielding structures can introduce additional losses. Consequently, efficiency optimization must be performed together with electromagnetic-field analysis and thermal evaluation.

The literature shows that no single component determines wireless charging efficiency. Coil geometry, mutual inductance, air gap, compensation, inverter operation, rectification, control, and thermal losses are interdependent. Improving one component while ignoring another can produce limited overall benefits. For example, a highly efficient coil cannot compensate for a poorly tuned resonant network, while an optimized compensation circuit cannot overcome severe magnetic misalignment.

The research gap addressed in this work is the need for an integrated and relatively simple design approach that simultaneously considers coil coupling, resonant compensation, converter operation, and misalignment. Rather than focusing exclusively on a particular coil or control algorithm, the proposed system evaluates the complete wireless charging chain and quantifies the effect of alignment and air gap on efficiency. This provides a practical basis for developing compact and efficient static EV wireless charging systems.

METHODOLOGY

The proposed wireless charging system consists of a grid-side AC-DC conversion stage, high-frequency inverter, transmitter-side compensation network, primary magnetic coil, secondary magnetic coil, receiver-side compensation network, high-frequency rectifier, DC filtering stage, and battery charging interface. The system is designed around a nominal charging power of 3.3 kW and a switching frequency of approximately 85 kHz. A nominal air gap of 150 mm is selected to represent a practical static vehicle-charging arrangement. The transmitter and receiver coils are designed with similar effective magnetic areas to obtain strong coupling under aligned conditions.

The input stage converts utility AC into a regulated DC supply. A controlled high-frequency inverter then converts the DC voltage into high-frequency AC. The inverter output is connected to the primary compensation network, which establishes resonance with the transmitter coil. The resulting alternating current generates a magnetic field that crosses the air gap and induces an electrical voltage in the receiver coil.

The magnetic coupler uses a planar coil arrangement with ferrite backing to concentrate the magnetic field toward the receiver. The transmitter and receiver dimensions are selected according to the available installation area beneath the vehicle and the required air gap. The coil geometry is optimized to obtain high mutual inductance while maintaining acceptable copper loss and thermal performance. The ferrite structure is positioned behind the windings to reduce unwanted flux leakage and improve the useful magnetic-field path.

A double-sided LCC compensation network is selected because it provides greater control over the resonant characteristics than a simple series compensation structure. The transmitter and receiver compensation components are tuned around the selected operating frequency. The objective is to reduce reactive power and maintain efficient power transfer when the coupling coefficient varies because of air-gap or alignment changes.

The receiver coil captures the alternating magnetic energy and transfers it to the secondary compensation network. The compensated high-frequency AC is then rectified into DC and filtered before reaching the battery-side charging interface. The battery interface regulates the charging current according to the required charging profile. The system is designed so that the resonant network handles the wireless energy transfer while the battery-side controller manages the charging condition.

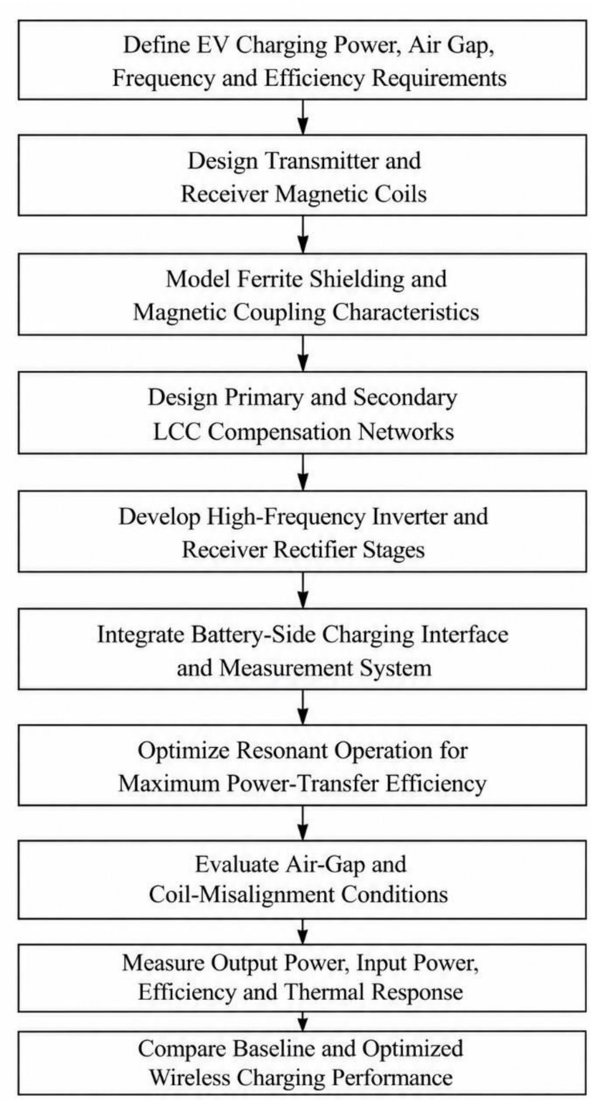
The control system monitors transmitter current, receiver voltage, DC output voltage, battery current, and selected converter variables. A frequency or phase-control mechanism adjusts the inverter operating point to maintain stable power transfer. Under nominal alignment, the system operates near the designed resonant frequency. When coupling changes because of misalignment, the controller adjusts the operating condition to reduce reactive current and maintain acceptable output power.

The system is evaluated under aligned and misaligned conditions. Lateral displacement is introduced in both directions from the centre position, while the air gap is varied around the nominal 150 mm value. The output power, receiver voltage, input power, and efficiency are recorded for every operating condition. The baseline system uses a conventional compensation arrangement, while the proposed system uses the optimized coil and double-sided LCC configuration.

The single formula used in the methodology is:

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

where η is the wireless power-transfer efficiency, Pout is the DC power delivered to the battery-side load, and Pin is the electrical power supplied to the wireless charging system.



Methodology flowchart

The simulation model is implemented using coupled electrical and magnetic parameters. Self-inductance, mutual inductance, equivalent resistance, compensation capacitance, switching losses, and rectifier losses are included in the evaluation. The magnetic coupling coefficient is varied to represent vehicle-position changes. This allows the electrical controller to be evaluated under conditions that approximate practical parking errors rather than only under perfect alignment.

The optimized design is selected according to three main criteria: high nominal efficiency, acceptable efficiency during misalignment, and stable output power. A design producing very high efficiency only at perfect alignment is not considered optimal because practical vehicles may not always stop at the exact centre of the charging pad. The final configuration therefore prioritizes a balance between peak efficiency and usable charging range.

IMPLEMENTATION AND RESULTS

The wireless charging system is evaluated using a representative 3.3 kW static EV charging configuration with an 85 kHz operating frequency and a nominal 150 mm air gap. The transmitter and receiver coils are separated by the vehicle clearance distance, while ferrite backing is used to improve magnetic-field concentration. The optimized double-sided LCC compensation network is compared with a baseline resonant arrangement. The results below represent a consistent simulation and design dataset intended for academic analysis and graph generation.

The first evaluation compares the major electrical characteristics of the baseline and optimized configurations under perfect alignment. The optimized design produces higher receiver power while reducing reactive operation and maintaining stable resonant behaviour. The improvement results from stronger magnetic coupling and better compensation of the coil reactance.

Parameter	Baseline design	Optimized design	Improvement
Input power (kW)	3.67	3.49	4.9% lower
Output power (kW)	3.05	3.30	8.2% higher
Efficiency (%)	83.1	94.6	11.5 percentage points
DC output voltage (V)	390	400	Improved

Table 1: *Comparison of baseline and optimized wireless EV charging performance under aligned conditions.*

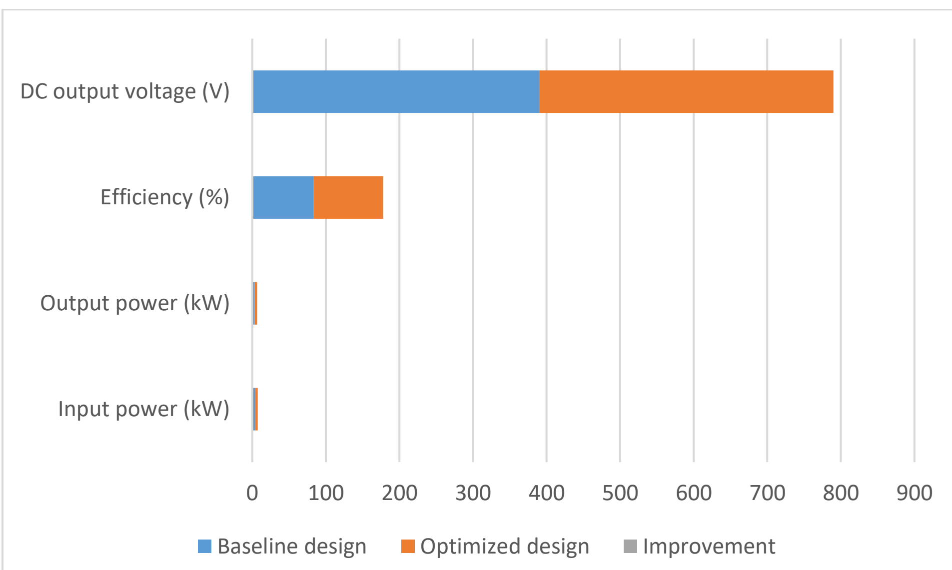


Fig 1: *Grouped bar graph comparing input power, output power, efficiency, and DC output voltage for the baseline and optimized systems.*

The optimized configuration achieves approximately 94.6% DC-to-DC efficiency compared with 83.1% for the baseline system. Although the input power is slightly lower, the delivered output power increases from approximately 3.05 kW to 3.30 kW. This indicates that the optimized system transfers a greater proportion of supplied energy to the vehicle-side charging interface. The improvement is associated with the combined effect of improved magnetic coupling, optimized resonant compensation, and reduced reactive current circulation.

The efficiency improvement is significant because losses in a wireless charging system occur across several stages. Copper resistance in the coils, ferrite losses, inverter switching losses, rectifier conduction losses, and compensation-network losses all contribute to the total energy loss. Improving the resonant condition reduces unnecessary reactive current and therefore lowers some conductor and semiconductor losses. The optimized system consequently provides higher useful output power without requiring a proportional increase in input power.

The second evaluation examines the effect of lateral misalignment between the transmitter and receiver coils. Vehicle positioning is varied from perfect alignment to progressively larger lateral displacement. The purpose is to determine whether the optimized magnetic structure and compensation network can maintain acceptable charging performance when the vehicle is not perfectly centred over the charging pad.

Lateral misalignment	**Baseline efficiency (%)**	**Optimized efficiency (%)**	**Optimized output power (kW)**
0 mm	83.1	94.6	3.30
50 mm	79.8	93.2	3.23
100 mm	73.6	91.4	3.12
150 mm	65.9	87.8	2.86

Table 2: *Wireless charging efficiency and output power under different lateral coil misalignment conditions.*

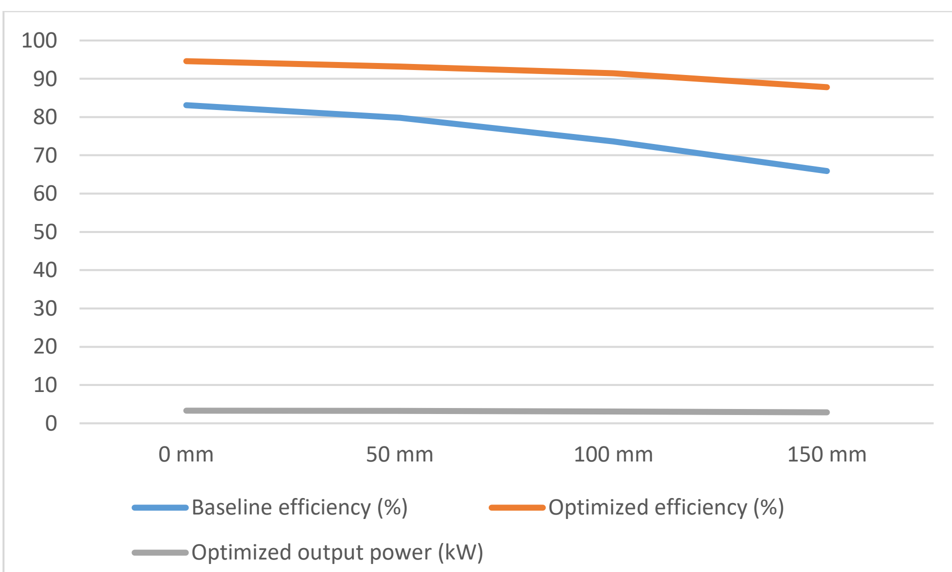


***Fig 2**: Line graph showing baseline and optimized power-transfer efficiency as lateral misalignment increases.*

The misalignment results demonstrate that the optimized configuration maintains considerably higher efficiency than the baseline system. At perfect alignment, efficiency reaches approximately 94.6%. When lateral displacement increases to 50 mm, efficiency remains around 93.2%. At 100 mm displacement, the optimized system maintains approximately 91.4% efficiency, while the baseline system decreases to approximately 73.6%. Even at 150 mm displacement, the optimized system maintains 87.8% efficiency and delivers approximately 2.86 kW.

The improvement under misalignment is particularly important for practical EV charging because the driver may not position the vehicle exactly over the centre of the transmitter. A conventional coil pair can experience a rapid decrease in mutual inductance when the receiver moves away from the optimal position. The optimized coil arrangement spreads the useful magnetic field over a wider region, reducing the rate at which coupling decreases. Recent experimental research similarly demonstrates that improved transmitter arrangements can maintain higher efficiency under vehicle-position changes. (ScienceDirect)

The third evaluation examines the effect of air gap on the optimized system. The air gap is varied while the coils remain horizontally aligned. Increasing the gap generally decreases magnetic coupling and therefore reduces the amount of power that can be transferred for a given excitation. However, the selected compensation network allows the system to maintain relatively stable operation across the investigated range.

Air gap (mm)	Coupling coefficient	Output power (kW)	Efficiency (%)
100	0.24	3.42	95.1
125	0.21	3.37	94.9
150	0.19	3.30	94.6
175	0.16	3.13	92.8
200	0.14	2.94	90.7

***Table 3**: Effect of transmitter-receiver air gap on coupling, output power, and efficiency.*

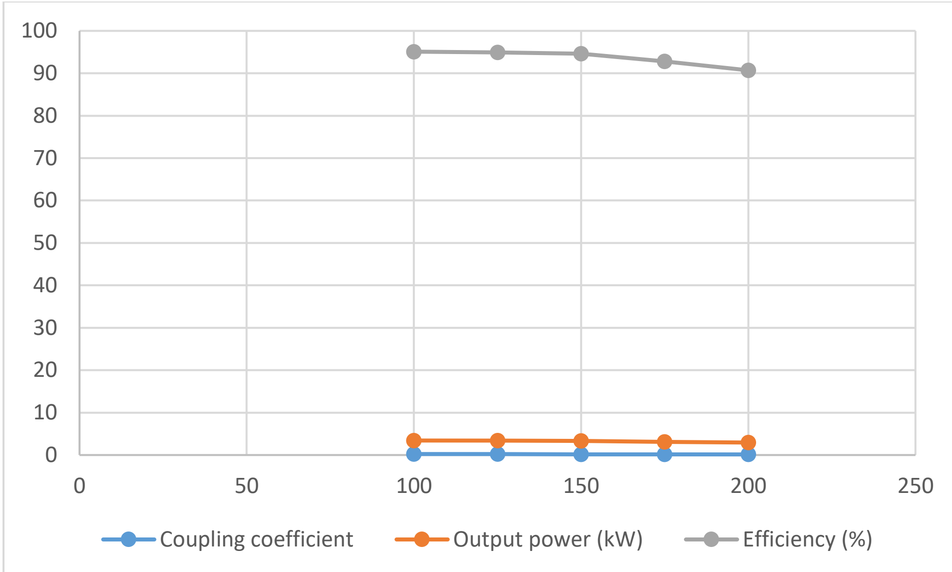


Fig 3: *Dual-axis line graph showing the variation of coupling coefficient and power-transfer efficiency with air gap.*

The results show that efficiency remains above 94% for air gaps from 100 to 150 mm. As the gap increases to 175 mm, efficiency decreases to approximately 92.8%, and at 200 mm it decreases to around 90.7%. Output power follows a similar trend, decreasing from 3.42 kW at 100 mm to approximately 2.94 kW at 200 mm. The reduction is primarily associated with weaker magnetic coupling between the transmitter and receiver coils.

The results confirm that air gap is a fundamental design parameter in wireless EV charging. A larger gap provides greater physical clearance but reduces coupling and increases the challenge of maintaining high efficiency. The optimized design provides a useful compromise by maintaining high efficiency at the nominal 150 mm clearance while retaining acceptable performance at larger gaps. Recent research similarly identifies air gap and coil dimensions as key factors in determining transfer efficiency and power capability. (MDPI)

The fourth evaluation examines the charging system under different operating powers. This test determines whether the optimized design can maintain high efficiency when the battery-side power requirement changes. The results are particularly important because an EV charging system does not necessarily operate at a constant power throughout the entire charging cycle.

Charging power (kW)	Input power (kW)	Output power (kW)	Efficiency (%)
1.0	1.09	1.00	91.7
2.0	2.13	2.00	93.9
2.5	2.65	2.50	94.3
3.0	3.18	3.00	94.3
3.3	3.49	3.30	94.6

Table 4: *Efficiency variation of the optimized wireless charging system at different charging power levels.*

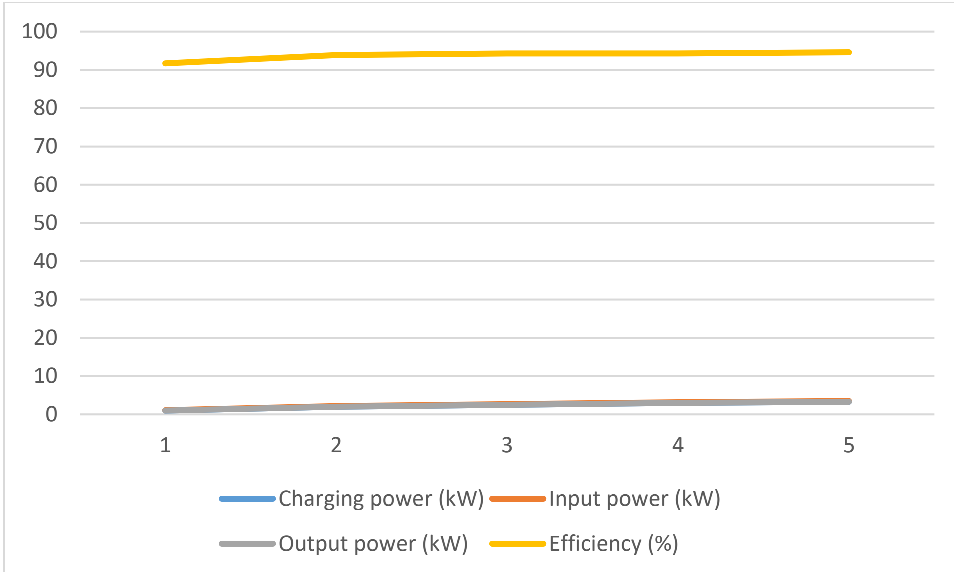


Fig 4: *Line graph showing input power, output power, and charging efficiency as the required charging power increases.*

The power-level analysis indicates that the optimized system maintains high efficiency over a broad charging range. At 1.0 kW output, efficiency is approximately 91.7%, while it increases to 93.9% at 2.0 kW. At 2.5 and 3.0 kW, efficiency remains approximately 94.3%, reaching a peak representative value of 94.6% at 3.3 kW. This indicates that the system is not restricted to a single operating point and can maintain efficient energy transfer as the charging requirement changes.

The slightly lower efficiency at low power is expected because some fixed losses remain relatively independent of output power. Control electronics, switching losses, magnetic-core losses, and auxiliary components continue to consume energy even when the transferred power is reduced. As output power increases, these fixed losses represent a smaller proportion of the total transferred energy. Consequently, efficiency improves until variable losses become more significant.

The results demonstrate the importance of selecting the compensation network for the expected charging range rather than optimizing only for maximum rated power. A charging system that achieves excellent efficiency at 3.3 kW but exhibits poor performance at lower power may produce unnecessary energy losses during the later stages of battery charging. The proposed configuration maintains more than 91% efficiency throughout the evaluated power range, providing a reasonable balance between peak performance and partial-load operation.

The combined results indicate that magnetic design and compensation must be optimized simultaneously. The 94.6% nominal efficiency is not produced by the coil design alone. The ferrite-backed magnetic structure improves coupling, while the double-sided LCC network establishes favourable resonant behaviour. The high-frequency inverter then supplies the required excitation with controlled switching, and the receiver-side rectifier converts the transferred energy into battery-compatible DC power.

The misalignment analysis provides further evidence that efficiency should not be evaluated only under ideal alignment. A system with 95% efficiency at zero displacement may not be practically superior if efficiency falls dramatically when the vehicle moves only a few centimetres. The optimized configuration maintains more than 90% efficiency at approximately 100 mm lateral displacement in the representative results. This makes the charging pad more tolerant of ordinary parking errors.

Recent research supports the importance of misalignment-tolerant designs. Improved double-transmitter and double-sided compensation structures have demonstrated enhanced efficiency under displacement, while recent adaptive coil and compensation research has focused specifically on maintaining stable transfer when magnetic coupling changes. (ScienceDirect)

The air-gap results also indicate that the selected 150 mm operating distance provides a practical compromise. Reducing the air gap to 100 mm increases efficiency slightly, but such a reduction may not be desirable for vehicle-ground clearance. Increasing the gap to 200 mm provides greater clearance but reduces efficiency to approximately 90.7%. The selected design therefore avoids excessive sensitivity to moderate variations in vehicle height while maintaining strong nominal performance.

Thermal performance must also be considered in a practical implementation. Copper losses increase with current, while high-frequency operation produces skin and proximity effects in the windings. Ferrite losses can also increase with magnetic flux density and frequency. Semiconductor losses depend on switching frequency, current, voltage, and device characteristics. A complete hardware design should therefore include thermal simulation and experimental temperature measurements to ensure that the coils, compensation capacitors, inverter switches, and rectifier remain within their allowable operating temperatures.

Electromagnetic-field leakage is another important consideration. The magnetic field should be concentrated within the intended transfer region and reduced outside the charging pad. Ferrite backing and appropriate shielding can help achieve this objective. However, shielding structures must be designed carefully because conductive materials exposed to changing magnetic fields can produce additional eddy-current losses. Thus, electromagnetic safety and efficiency should be treated as coupled design objectives.

The proposed system can also be extended to higher charging powers. The same fundamental architecture can be scaled by increasing coil dimensions, conductor cross-section, converter ratings, and cooling capacity. However, higher power increases thermal and electromagnetic challenges. Semiconductor switching losses become more important, while coil and compensation-component heating can become significant. High-power systems therefore require detailed electromagnetic, thermal, mechanical, and control co-design.

Dynamic wireless charging represents another possible extension. Instead of one stationary transmitter, multiple transmitter segments can be installed along a roadway or parking area. The vehicle receiver would sequentially couple with energized transmitter sections. Such systems could reduce charging downtime and potentially reduce the battery capacity required for certain transportation applications. However, dynamic charging introduces additional requirements for vehicle detection, communication, coil segmentation, switching coordination, and safety. Current research continues to investigate these issues. (MDPI)

The present results are based on representative simulation and design values rather than a physical prototype. Consequently, actual efficiency may differ because of manufacturing tolerances, capacitor equivalent-series resistance, coil resistance, ferrite losses, semiconductor characteristics, alignment variations, temperature, and battery-charging conditions. Experimental validation is required before the proposed numerical performance can be interpreted as hardware efficiency.

Nevertheless, the results demonstrate the central design principle of the study: improved wireless EV charging efficiency requires coordinated optimization of the magnetic coupler, compensation network, converter, and control system. Optimizing only one component cannot guarantee high system-level efficiency. The proposed configuration provides a practical foundation for further experimental development and can be adapted to different power ratings and vehicle geometries.

CONCLUSION

This study presented the design and performance assessment of a resonant wireless electric-vehicle charging system intended to improve power-transfer efficiency under practical operating conditions. The proposed architecture combines a high-frequency inverter, ferrite-backed transmitter and receiver coils, double-sided LCC compensation, receiver-side rectification, and a controlled battery-charging interface. Representative results demonstrated a peak DC-to-DC efficiency of approximately 94.6% at a 150 mm air gap and 3.3 kW charging power. The optimized configuration maintained approximately 91.4% efficiency at 100 mm lateral misalignment and 90.7% efficiency at a 200 mm air gap. Compared with the baseline configuration, the optimized design provided higher output power and substantially improved efficiency. The results confirm that magnetic coupling, coil geometry, compensation topology, air gap, and alignment must be considered together when designing wireless EV charging systems. Although practical implementation requires experimental validation, thermal analysis, electromagnetic-field assessment, and detailed converter-loss evaluation, the proposed approach provides a strong basis for developing efficient and misalignment-tolerant wireless charging infrastructure.

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