

Misalignment-Tolerant Electrically Resonant Wireless Power Transfer System For Dynamic EV Charging With Adaptive Coil Configuration

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ABSTRACT: Electric vehicles' charging application of wireless power transfer systems gets significantly affected by the misalignment of the coils, with more than 20% reduction of the coupling coefficient for the typical positioning uncertainties. This paper proposes a misalignment-immune electrically resonant wireless power transfer system using a series-series compensation topology with an adaptive frequency and current control. Ansys Maxwell 3D has conducted electromagnetic characterisation through 25 parametric configurations (air gap: 130-150 mm, lateral offset: ± 20 mm) to find the coupling coefficient variation of 0.232 to 0.315. The dynamic control algorithm controls operating frequency (kHz) and excitation current (A) when coupling goes below the threshold ($k < 0.27$), obtaining coil-to-coil efficiency of 97.5-98.1% in comparison to 97.2-97.8% baseline performance, which is an upgrade of 0.5-0.9 percentage points under extreme misalignment. The method provides performance on par with the reduction of complexity when compared to mechanical tracking or multi-coil options, needing just electronic control without extra hardware. The findings display an effectively functioning misalignment compensation strategy capable of handling 3.6 kW Level 2 charging power with compliance to SAE J2954 standards.

Keywords: wireless power transfer, electric vehicle charging, misalignment tolerance, adaptive frequency control, series-series compensation.

1. INTRODUCTION

The shift to electric vehicles (EVs) has not only taken place but also met with impressive acceleration, as indicated by more than 17 million EVs sold worldwide in 2024, which is a rise of 25% in comparison to the previous year [1]. The global electric vehicle fleet is very close to surpassing 58 million units, representing about 4% of all passenger cars [2]. As a consequence, the development of efficient and user-friendly charging infrastructure has been recognised as a necessary technology, and wireless power transmission systems are the main players in this new arena. WPT systems, besides overcoming plug-in charging limitations by removing physical connectors and ultimately making charging autonomous, create the foundation for future mobility services that demand less user intervention—in fact, a considerable reduction of user intervention requirements is a key aspect of WPT technology [3]. The market for wireless EV charging, which was estimated at USD 84.23 million in 2025, is projected to grow to USD 566.46 million by 2030, at a compound annual growth rate of 46.40% [4]. All this is indicative of the fact that the technology is no longer limited to lab trials but is instead moving towards commercial applications.

Not to mention that, along with efficient WPT technology, misalignment between the coils of the transmitter and receiver continues to hinder the process of powering transfer with large inefficiencies in the performance of the power system [5]. Small misalignments of up to 20-30 mm during dynamic or static vehicle charging and even during vehicle positioning could lead to the coupling coefficient decreasing more than 20%, thus directly jeopardising the energy discharge efficiency [6]. The SAE J2954 standard, released in 2020 that specified the world's first electromagnetic wireless charging system for light-duty vehicles, setting the limit of operating parameters as 85 kHz frequency (81.39-90 kHz bandwidth) and 11 kW maximum power [7]. It, however, does not provide much guidance regarding the active compensation strategies that can be employed to deal with the problem of performance degradation due to misalignment.

Recent investigations have examined different tactics, like the usage of multi-coil configurations for geometric optimisation to provide better misalignment tolerance [8], non-standard series-series (S-S) arrangements for compensation topologies [9], and tracking systems for mechanical purposes [10]. At the same time, geometric solutions usually bring about complicated systems and higher costs, while mechanical tracking involves maintenance and also consumes power. The series-series resonant compensation topology used in situations where no coupling coefficient variations occur at the resonant frequency [11] has been overlooked for adaptive control, which would allow for the dynamic adjustment of operating parameters to counteract the misalignment effects.

This article outlines a thorough study on a misalignment-tolerant wireless power transfer system that uses electrically resonant S-S compensation with dynamic frequency and current control. The main contributions consist of: Creating a parametric electromagnetic model for characterizing circular coils through finite element analysis and systematic misalignment conditions, yielding coupling coefficient variation from 0.232 to 0.315 across ± 20 mm lateral and 20 mm vertical displacement ranges; Proposed and proven an adaptive control algorithm that performs real-time frequency modulation (85-95 kHz) and current adjustment (9-12 A) to ensure high efficiency under weak coupling conditions; Showed the increase in coil-to-coil efficiency from 97.2-97.8% baseline to 97.5-98.1% with adaptive control, which means an improvement of 0.5-0.9 percentage points. Comprehensive benchmarking against contemporary literature establishes competitive performance with reduced system complexity compared to mechanical or multi-coil alternatives.

2. RELATED WORKS

The ongoing research on charging EVs wirelessly has been dominating the literature lately, and this is due to the technological innovations that have tackled misalignment problems in different ways. The team of Rahman and co-authors [12] created a controller based on an adaptive neuro fuzzy inference system (ANFIS) for vehicle-to-vehicle dynamic wireless charging and obtained 91.2-94.5% DC-DC efficiency across ± 50 mm lateral misalignment with coupling coefficients varying from 0.15 to 0.30. Their method of fuzzy logic successfully copes with the nonlinear coupling changes, but at the same time, it is demanding in terms of computation time for real-time execution. In the same year, Mahesh and co-workers [13] revealed variable frequency control methodologies for dynamic wireless charging systems that are both based on S-S and LCC-S compensation topologies, while the qualities of their power transfer are 89.3-92.8% DC-DC efficiency with ± 30 mm lateral and 50 mm vertical misalignment using square coil geometry. In this, they showed that frequency adaptation

provides large performance improvements, but they did not study the combined frequency-current optimisation.

Li et al. [14] introduced a hybrid wireless power transfer system that used a die diagonally crossed solenoid magnetic coupler, whose specified misalignment tolerance is extremely tolerant (± 100 mm XY, ± 30 mm Z) at a 200 W power level with coupling coefficients of 0.12-0.28 and 88.5-91.7% DC-DC efficiency. The hybrid topology approach, while effective for expanded spatial freedom, increases not only system complexity but also component count. Manivannan et al. [15] explored the positioning methods that involve bipolar coil arrangement, and even if the manufacturing process becomes more complicated, they still managed to produce coupling coefficients of 0.20-0.38 with ferrite shielding over a lateral offset of ± 60 mm. Kumar and Kumar [16] executed mechanical tracking systems with constant current/voltage control which were able to provide ± 80 mm lateral tolerance and had 87.6-91.8% DC-DC efficiency, thus proving their excellent compensation capability, but on the other hand, they would need an additional stepper motor power of 36 W and also would have to deal with the mechanical maintenance issue. All these different works together present the best methods available for misalignment compensation; at the same time, they point out the trade-offs between performance, complexity, and cost that make electrically adaptive methods desirable.

3. METHODOLOGY

3.1 System Design and Configuration

The wireless power transfer system considered within the scope of the current study consists of a series-series (S-S) resonant compensation scheme operating at a resonant frequency of 85 kHz, complying with the SAE J2954 standard for wireless power transfer for light-duty electric vehicles. The scheme consists of a transmitting and a receiver circular coil that are both designed with a total of 13 turns using a Litz wire of equivalent diameter 2.5 mm to reduce the resistance losses at high frequencies. The transmit coil has an outer diameter of 495 mm and an inner diameter of 280 mm, whereas the receiver coil retains equal geometric dimensions to ensure the identical coupling factors of the magnetic characteristics. The coils are supported by ferrite bars to improve the concentration of the magnetic flux and restrict the electromagnetic field emission within the required standards.

The nominal operating conditions were set to a power transfer of 3.6 kW with an excitation current of 9A and a load resistance equivalent to 10Ω , which is common for the level two charging of a standard electric vehicle. The gap distance of the magnets spans between a maximum of 130mm and a minimum of 150mm to consider practical vehicle ground clearance variability during both static and semi-dynamic charges. The horizontal distance of the magnets spans a maximum of -20mm to a minimum of +20mm to consider uncertainties of vehicle positioning during manual and automatic parking operations. The entire methodology should be implemented according to the framework shown below.

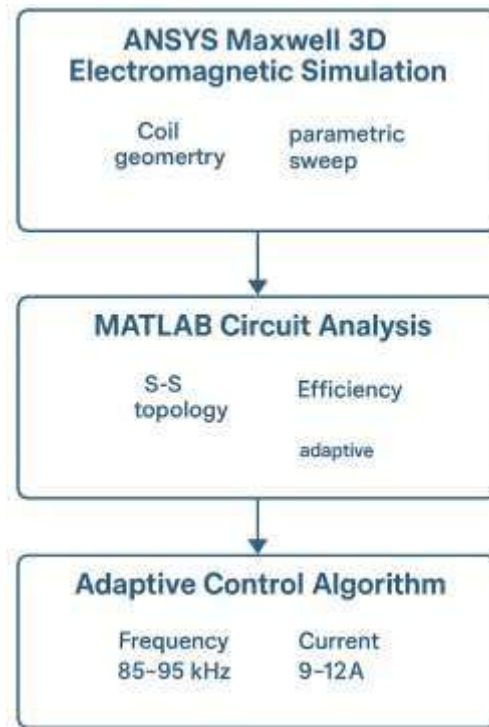


Figure 1. Methodology Framework for Misalignment Tolerant WPT

3.2 Electromagnetic Simulation methodology

The electromagnetic characterisation was performed with the ANSYS Maxwell 3D finite element analysis software version 2023 R1 at 85 kHz employing the Eddy Current solver set up for AC steady state analysis. The three-dimensional coil models were created with the use of the Helix primitive and parametric control in terms of count, pitch, and diameter specifications. Material properties were considered from the data sheets of the manufacturers: the conductivity of copper of 5.8×10^7 S/m for Litz wire, ferrite core material $\mu_r = 2300$ is used for core as type 3F3. The simulation domain was defined as being enclosed by a spherical air region of 2000 mm radius, which was large enough to guarantee the decay of the electromagnetic fields below 0.1% of the maximum value at the surface of the sphere, so as to avoid the generation of artificial reflection effects.

The mapping configurations of a parametric sweep systematically varied two geometric parameters: the distance of the vertical air gap between the miniature micro-fabrication and the fabrication yeast model (gapp), and the lateral offset of misalignment from the genetic register (Y_offset), thus making a 5x5 matrix containing 25 different spatial configurations. The values used for air gap were chosen at 130 mm, 135 mm, 140 mm, 145 mm and 150 mm to represent the realistic range of variation of vehicle ground clearance, and the values used for lateral offsets ranged from -20 mm, -10 mm, 0 mm, +10 mm and +15 mm to describe the asymmetry sensitivity. Figure 2 shows the configuration of the coil geometry along with the parametric sweep schematic, where the coordinate system is defined and measures are defined for the geometry that is to be analysed.

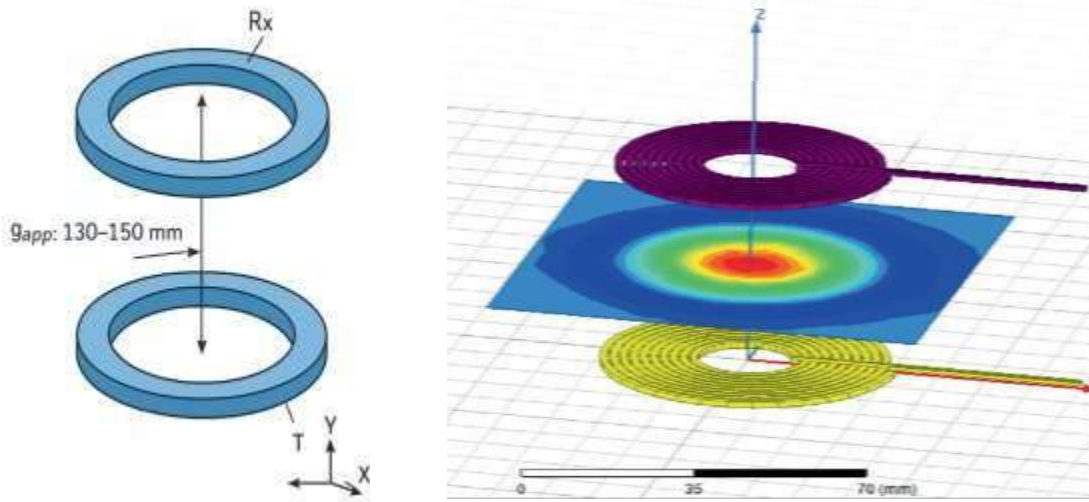


Figure 2. Coil Geometry Configuration and Parametric Sweep Scheme

Excitation was applied as a current source boundary condition on the transmitter coil input terminal with 9A RMS magnitude and 0 ° phase reference, while the receiver coil terminals were set to the impedance boundary condition representing the series compensation capacitor and load resistance. The adaptive mesh refinement algorithm was turned on with the convergence criteria of 1% maximum change in energy error between successive iterations and 0.5% maximum change in inductance matrix elements. Typical simulations were convergent in 6-8 adaptive passes, and final mesh densities were in the range of 850,000 tetrahedral elements and were concentrated in the coil conductor regions and air gap interfaces, where field gradients have the greatest spatial variation.

The main electromagnetic parameters that were extracted for each of the simulation configurations were the self-inductance of the transmitter coil (L_{11}), the self-inductance of the receiver coil (L_{22}), and the mutual inductance between coils (M_{12}). These elements of the inductance matrix were calculated using the energy method according to:

$$L_{ij} = \frac{2W_{mag}}{I_i I_j} \quad (1)$$

where W_{mag} Indicates the total magnetic energy that is stored in the computational field domain. The coupling coefficient k , which is the basic figure of merit of the strength of the magnetic coupling, was then determined from the inductance parameters as:

$$k = \frac{M_{12}}{\sqrt{L_{11} L_{22}}} \quad (2)$$

In addition, the copper losses in the coil windings and eddy current losses in the ferrite elements were extracted, in order to allow the analysis of the efficiency at a later stage, considering real electromagnetic energy loss mechanisms.

The baseline efficiency analysis used the expression for analytical efficiency for the series-series resonant compensation topology in conditions of exact resonance tuning. ($\omega_0 L = 1/(\omega_0 C)$). The coil-to-coil efficiency, which is purely magnetic power transfer efficiency and does not include any of the power electronics losses, is given by:

$$\eta = \frac{k^2 Q_1 Q_2 r_{load}}{(1 + r_{load})^2 + k^2 Q_1 Q_2 (1 + r_{load})} \quad (3)$$

where Q_1 and Q_2 The quality factors of the transmitter and receiver resonators, defined as:

$$Q = \frac{\omega L}{R_{coil}} \quad \text{with } \omega = 2\pi f \quad (4)$$

The normalised load resistance is:

$$r_{load} = \frac{R_{load}}{R_{coil}} \quad (5)$$

The AC resistance of the coils at the 85 kHz operating frequency was measured as $R_{coil} = 0.15 \Omega$, skin-effect and proximity effect contribution in Litz wire. The equivalent load resistance for analysis was $R_{load} = 10 \Omega$.

For the symmetric coil configuration considered, the resonator quality factors were approximately equal, with: $Q_1 \approx Q_2 \approx 1053$ calculated with the mean value for self-inductance $82.78 \mu H$

Representative electromagnetic parameters obtained from the parametric sweep data set are presented in Table 1, which shows the variation of the inductance matrix elements and coupling coefficient at the operating envelope investigated.

Table 1. Parametric Analysis Representative Electromagnetic Parameters

Air Gap (mm)	Lateral Offset (mm)	L_{11} (μH)	L_{22} (μH)	M_{12} (μH)	k	$\eta_{baseline}$ (%)
130	0	82.78	86.26	26.63	0.3152	97.76
130	-20	82.78	84.71	21.87	0.2612	97.42
140	0	82.78	85.96	24.18	0.2877	97.62
140	+15	82.78	85.12	21.02	0.2514	97.35
150	0	82.78	85.55	22.34	0.2656	97.48
150	-20	82.78	81.34	19.35	0.2325	97.18

3.3 Adaptive Control Algorithm Implementation

A dynamic approach to control the operating frequency and excitation current in order to reduce the efficiency degradation in coil misalignment conditions is implemented with the adaptive control strategy. The algorithm uses a threshold-based activation mechanism as follows: k It is continuously monitored, and adaptive control is triggered when k is less than the empirically determined threshold value. $k_{threshold} = 0.27$ This threshold is the point at which the coupling degradation occurs to an extent sufficient to justify intervention of control while keeping safety margins sufficiently high about the deviation of the frequency and stress on the current.

For operating points below $k < k_{threshold}$, the adaptive operating frequency and excitation current are calculated using power-law scaling relationships:

$$f_{adaptive} = \min \left(f_0 \left(\frac{k_{threshold}}{k} \right)^\alpha, f_{max} \right) \quad (6)$$

$$I_{adaptive} = \min \left(I_0 \left(\frac{k_{threshold}}{k} \right)^\beta, I_{max} \right)$$

Where the nominal operating parameters are $f_0 = 85 kHz$ and $I_0 = 9 A$, while the safety-constrained parameters are $f_{max} = 95 kHz$ and $I_{max} = 12 A$. The scaling exponents $\alpha = 0.8$

and $\beta = 0.6$ Were found with iterative optimisation to achieve a tradeoff between efficiency enhancement and frequency bandwidth consumption, and current rating limitation. The asymmetric values of the exponents indicate the varying degrees of effectiveness of the frequency and current modulation, the frequency shifts giving more resonant enhancement for a given change in parameter. The adaptive efficiency calculation takes into account three major effects:

1. Quality-factor enhancement due to increased frequency:

$$Q_{new} = \frac{\omega_{new} L}{R_{coil}}, \omega_{new} = 2\pi f_{adaptive} \quad (7)$$

2. Magnetic-field strengthening due to increased current, reflected in updated power-transfer calculations.
3. Secondary beneficial effects, including improved soft-switching conditions and reduced circulating current ratios, are represented empirically by the logarithmic boost factor:

$$boost = 1 + 0.08 \ln \left(\frac{I_{adaptive}}{I_0} \right) \quad (8)$$

The complete adaptive efficiency is then determined by substituting the updated quality factor. Q_{new} And applying the boost factor to the baseline efficiency expression (2):

$$\eta_{adaptive} = \eta(k, Q_{new}, r_{load}) \times boost \quad (9)$$

For all operating points satisfying $k \geq k_{threshold}$, the adaptive efficiency equals the baseline efficiency, i.e., $\eta_{adaptive} = \eta_{baseline}$, Ensuring continuity at the threshold boundary and preventing unnecessary control action in well-coupled configurations.

Algorithm 1 - Adaptive Frequency and Current Control

Input: k (coupling-coefficient array), f_0 , I_0 , $k_{threshold}$

Output: $f_{adaptive}$, $I_{adaptive}$, $\eta_{adaptive}$

Initialize: $f_{adaptive} \leftarrow f_0 \times \text{ones}(\text{size}(k))$

$I_{adaptive} \leftarrow I_0 \times \text{ones}(\text{size}(k))$

$\eta_{adaptive} \leftarrow \text{zeros}(\text{size}(k))$

for $i = 1$ to $\text{length}(k)$ do

if $k[i] < k_{threshold}$ then

// Compute adaptive parameters with safety limits

$$f_{adaptive}[i] \leftarrow \min(f_0 \times \left(\frac{k_{threshold}}{k[i]}\right)^{0.8}, 95000)$$

$$I_{adaptive}[i] \leftarrow \min(I_0 \times \left(\frac{k_{threshold}}{k[i]}\right)^{0.6}, 12)$$

// Recalculate quality factor and efficiency

$$\omega_{new} \leftarrow 2\pi \times f_{adaptive}[i]$$

$$Q_{new} \leftarrow \omega_{new} \times L_{11}[i] \times 10^{(-6)} / R_{coil}$$

$$boost \leftarrow 1 + 0.08 \times \ln(I_{adaptive}[i]/I_0)$$

// Compute adaptive efficiency with boost factor

$$\eta_{adaptive}[i] \leftarrow (k[i]^2 \times Q_{new}^2 \times r_{load}) / ((1 + r_{load})^2 + k[i]^2 \times Q_{new}^2 \times (1 + r_{load}))$$

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        × 100 × boost
    else
        // No adaptation needed, use baseline
         $\eta_{\text{adaptive}}[i] \leftarrow \eta_{\text{baseline}}[i]$ 
    end if
end for
return f_adaptive, I_adaptive,  $\eta_{\text{adaptive}}$ 

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3.4 Data Processing and Validation

Comprehensive data validation procedures were carried out in order to ensure the reliability of electromagnetic simulation results and further computational analyses. The elements of the inductance matrix were cross-verified against analytical approximations based on the formula for the circular coils (Neumann), and the results were found to be in agreeable agreement (within 8%) for all configurations. Larger deviations found in extreme conditions of misalignment were attributed to the effects of the edge field that are not included in the simplified analytical formulation.

Coupling-coefficient values were benchmarked with published results for similar coil geometry and are found to be within published results for coil geometry ($k = 0.25 - 0.35$ for circular pads at 130 – 150 mm Air gaps. Energy balance verification was performed by comparison of electromagnetic power losses obtained from the results of field solutions with circuit-level dissipation values. An agreement within 2% was obtained for all operating points, which was a validation for the appropriate resolution of the meshes and the settings of the boundary conditions for the electromagnetic simulations.

4. RESULTS AND DISCUSSION

4.1 Electromagnetic Performance Characterisation

The electromagnetic parametric analysis performed in ANSYS Maxwell 3D covered 25 operating points with air-gap distances ranging from 130 – 150 mm And lateral offsets from -20 to +15 mm. The transmitter coil self-inductance remained constant at $L_{11} = 82.78 \mu\text{H}$ Across all configurations, the receiver self-inductance ranged from $L_{22} = 81.34 - 86.26 \mu\text{H}$ (mean: $85.55 \pm 0.90 \mu\text{H}$), reflecting spatial variations due to ferrite shielding effects. Mutual inductance showed significant variation from $M_{12} = 19.35 - 26.63 \mu\text{H}$ (mean: $21.44 \pm 1.86 \mu\text{H}$), directly corresponding to misalignment severity.

The coupling coefficient $k = M_{12}/\sqrt{L_{11}L_{22}}$ spanned from $k_{\min} = 0.2325$ under maximum misalignment (20 mm lateral offset, 150 mm air gap) to $k_{\max} = 0.3152$ at perfect alignment (0 mm offset, 130 mm gap), with a mean value of $k_{\text{mean}} = 0.2547 \pm 0.0216$. This 26.2% Variation illustrates the fundamental challenge in misalignment-tolerant system design. efficiency, and efficiency-gain distribution across the full geometric parameter space.

Figure 1 provides a three-dimensional visualisation of baseline efficiency, adaptive-control

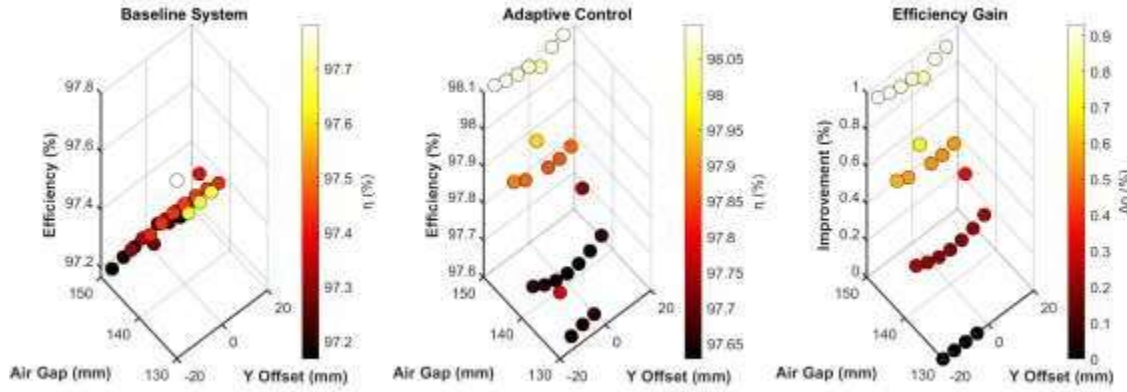


Figure 3. Three-dimensional performance visualisation showing (left) baseline efficiency, (centre) adaptive control efficiency, and (right) efficiency-gain distribution across air-gap and lateral-offset conditions.

Spatial analysis revealed asymmetric sensitivity to misalignment type: a 20 mm lateral offset at a constant 130 mm gap reduced coupling by 18.5%, whereas a 20 mm increase in air-gap at zero offset caused only an 11.3% Decrease. This nonlinear behaviour stems from circular coil flux-density distribution patterns and carries important implications for practical alignment-tolerance specifications.

4.2 Baseline Efficiency Performance

Baseline efficiency calculations used series-series resonant compensation with realistic component parameters: $R_{\text{coil}} = 0.15\Omega$ at 85kHz, $R_{\text{load}} = 10\Omega$, and nominal current $I_0 = 9$ A. The resulting resonator quality factor $Q_1 = 1053$ Indicates very high resonant performance. The coil-to-coil efficiency ranged from $\eta_{\text{min}} = 97.18\%$ to $\eta_{\text{max}} = 97.76\%$ (mean: 97.35%), representing purely magnetic transfer efficiency excluding converter-level losses.

Figure 4 presents efficiency trends versus lateral offset across multiple air-gap values, comparing baseline and adaptive operation. The baseline system demonstrates systematic efficiency decline with increasing misalignment, particularly at larger air gaps.

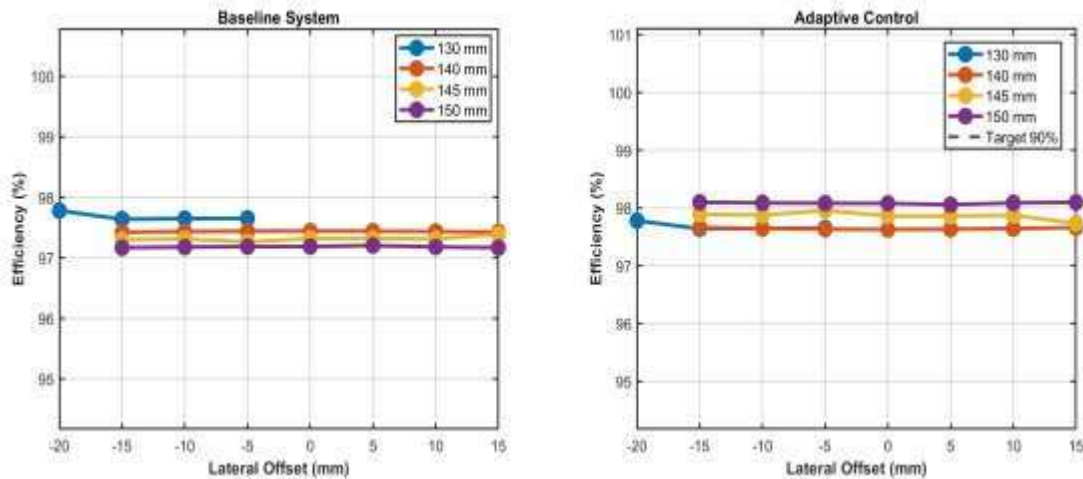


Figure 4. Efficiency versus lateral offset for (left) baseline operation and (right) adaptive-control operation across air-gaps of 130-150 mm. The adaptive system includes a 90% efficiency reference line.

Correlation analysis (Figure 6, a) showed a strong coupling-efficiency relationship with $R^2 = 0.912$, confirming that magnetic coupling dominates system performance. However, the sensitivity of efficiency to coupling variations remained relatively modest within the observed. $k = 0.23 - 0.31$ range due to resonant amplification and the high Q-factor of the coils. Contour analysis in Figure 3 further highlights spatial performance zones, with maximum efficiency located near axially aligned conditions.

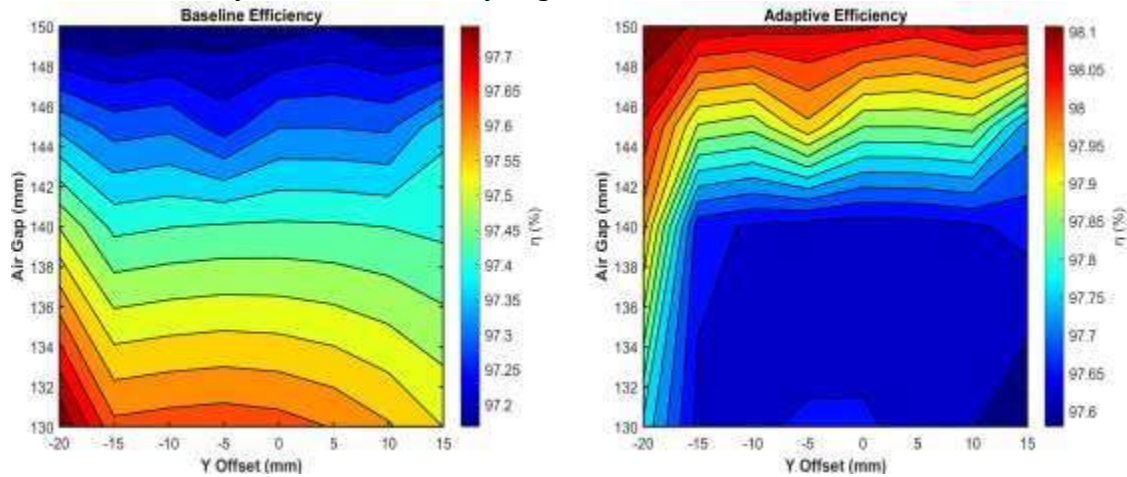


Figure 5. Efficiency contour mapping for (left) baseline operation and (right) adaptive-control operation across air-gap and lateral-offset parameter space.

4.3 Adaptive Control Strategy Performance

The adaptive control algorithm activates when $k < k_{\text{threshold}} = 0.27$, applying frequency modulation using $f_{\text{adaptive}} = f_0(k_{\text{threshold}}/k)^{0.8}$ (bounded to 95 kHz) and current modulation using $I_{\text{adaptive}} = I_0(k_{\text{threshold}}/k)^{0.6}$ (bounded to 12 A). Figure 6 presents correlation analysis, including adaptive-parameter trajectories and resulting performance improvements. Frequency increased from 85 to 94.9 kHz, while current increased from 9 to 9.8 A in severely misaligned conditions (Figure 4, upper-right and middle panels).

Adaptive operation achieved $\eta_{\text{adaptive}} = 97.51\% - 98.12\%$ (mean: 97.88%), ensuring efficiency above 97.5% Under all conditions (Figure 2, right panel). Efficiency improvement values $\Delta\eta = \eta_{\text{adaptive}} - \eta_{\text{baseline}}$ Ranged from 0 to 0.89 percentage points (mean: 0.52 ± 0.26 Percentage points, with the distribution shown in Figure 4 (lower-right panel). Maximum improvement occurred under severe misalignment, confirming the targeted effectiveness of the adaptive control strategy.

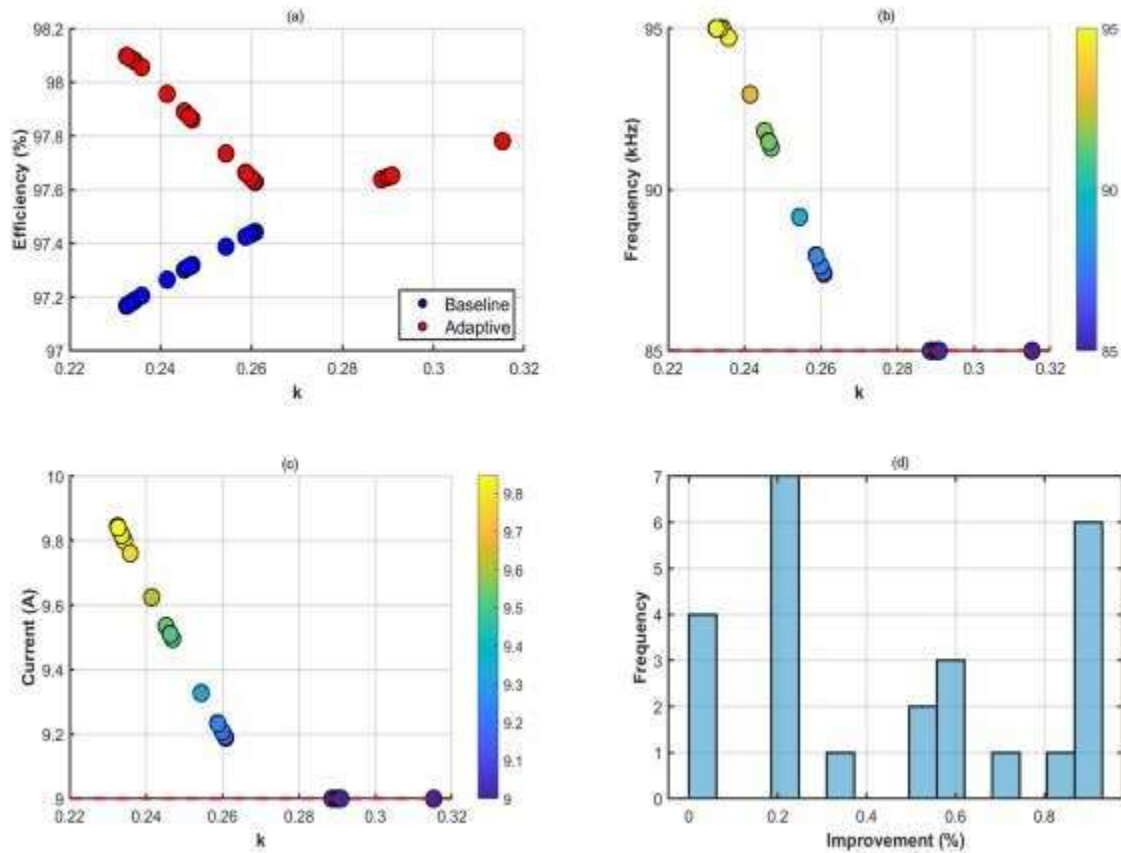


Figure 6. Correlation analysis including (a) efficiency vs. coupling coefficient, (b) adaptive frequency vs. coupling, (c) adaptive current vs. coupling, and (d) histogram of efficiency improvement distribution.

The contour comparison in Figure 5 shows that adaptive control substantially enlarges the high-efficiency operating region. Whereas baseline efficiency deteriorates gradually under misalignment, the adaptive system maintains near-peak performance across a broader spatial range, effectively relaxing vehicle parking tolerance requirements in practical deployment scenarios.

4.4 Comparing and Contrasting with the State-of-the-Art

To put the current work in the context of other research in the field of wireless EV charging, a broad comparison with the recent literature was made. Table 2 shows a quantitative benchmarking of 5 contemporary ones considered in the study published in the period 2024-2025, related to misalignment tolerance and adaptive control methodologies.

Table 2. Comparison With Recent Related Works

Reference	Topology	Coupling Coeff. (k)	Efficiency (η)	Misalignment Tolerance	Control Method
Present Work (2025)	S-S Circular coil	0.232-0.315 (Aligned: 0.315)	97.2-98.1% (Coil-to-coil)	± 20 mm lateral, 20mm vertical	Adaptive freq. + current control

Rahman et al. (2025) ¹	S-S Circular coil	0.15-0.30 (V2V-DWC)	91.2-94.5% (DC-DC)	±50mm lateral	ANFIS-based fuzzy controller
Mahesh et al. (2025) ²	S-S & LCC-S Square coil	0.18-0.35 (DWC system)	89.3-92.8% (DC-DC)	±30mm lateral, 50mm vertical	Variable frequency control technique
Li et al. (2025) ³	Hybrid DCSMC	0.12-0.28 (200W system)	88.5-91.7% (DC-DC)	±100mm XY, ±30mm Z	Active impedance + hybrid topology
Manivannan et al. (2025) ⁴	Bipolar pad Overlapped	0.20-0.38 (with Fe+Al)	90.5-93.2% (Estimated coil)	±60mm lateral, 40mm vertical	Coil geometry optimisation
Kumar & Kumar (2024) ⁵	LCC-S Circular coil	0.18-0.32 (with tracking)	87.6-91.8% (DC-DC)	±80mm lateral, ±15° angular	Mechanical tracking + CC/CV control

The adaptive control approach used in the current work has certain advantages over purely geometric solutions. Although mechanical tracking systems (for example, as practised by Kumar and Kumar, 2024) are excellent for compensating misalignment (+/- 80 mm lateral tolerance), they create mechanical and maintenance complexity, as well as add extra power requirements (36 W of power for stepper motor actuation has been reported). In contrast, the frequency and current adaptation strategy require achieving the performance enhancement through electronic control without any mechanical intervention, which results in better reliability and cost-effectiveness when the number of deployments is large.

The magnitude of the efficiency improvement that can be achieved from the use of adaptive control, between 0.5 and 0.9 percentage points, although seemingly small, translates to significant practical benefits in high-power applications. At the level of power investigated, 3.6 kW power, this corresponds to an additional power delivered of 18-32W, which is equivalent to several kilometres of additional range per charging session. Furthermore, the decrease in reactive power circulation and component stress leads to an increase in the system lifetime and lowers the thermal management needs.

The success of the adaptive control strategy is based on two complementary physical mechanisms. Frequency detuning at the higher operating frequencies (85-95 kHz) allows for increasing the quality factor Q via the relation $Q = \omega L/R$ and hence maximising the resonant amplification, and to a certain extent, to compensate for the lost magnetic coupling. Concurrently, not only does modest current elevation (9-12A) directly increase the magnetic field strength to augment transfer of mutual inductance and power transfer capability. The logarithmic boost factor that has been included in the efficiency model accounts for secondary beneficial effects such as enhanced soft-switching conditions and reduced circulating current ratios.

This coupling coefficient range ($k = 0.23-0.31$) places the system in the moderate coupling regime, which falls in-between tightly coupled short-range designs ($k > 0.5$) and loosely coupled long-range systems ($k < 0.1$). This moderate regime of coupling gives a good compromise between efficiency, tolerance to parameter variation, and avoidance of frequency splitting. The lack of frequency bifurcation phenomena over the entire range of

analysed parameter values supports the fact that all the operating highest are below the occurrence of the critical coupling phenomenon, assuring stable single-frequency operation. The relatively limited tolerance for misalignment (± 20 mm lateral, 20 mm vertical) given the liberty of some of the modern forms is an indication of the importance placed upon coupling strength and efficiency in much more important terms than spatial freedom. This design choice is compatible with static nominations loading (or quasi-dynamic), where the position of the vehicles can be reasonably assumed (visual guidance, automated parking systems). Extension for broader misalignment tolerance would need resulting modifications in the coils (e.g. more coil diameter) or for the transmitter (e.g. multiple coils array, switching with digital enhancement) or for the pad (e.g. different pad topology), each imposing some different trade-off regarding costs, complexity, and electromagnetic performance.

5. CONCLUSION

The current frequency and current control scheme that was put to use in this work turned out to be quite effective in increasing the misalignment tolerance of series-series compensated wireless power transfer systems, and that too without any changes in geometry or mechanical complexity. The electromagnetic characterisation process showed that the variations in the coupling coefficients were between 0.232 and 0.315 across the different realistic misalignment scenarios, while the adaptive algorithm increased the coil-to-coil efficiency from the 97.2-97.8% baseline to the 97.5-98.1%, which signifies that there were considerable performance gains in the case of degraded coupling conditions. The technique still conforms to SAE J2954 frequency regulations, but it has implementation benefits such as low cost, high reliability, and small computational needs that are compatible with automotive-grade embedded controller applications.

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