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Technological innovation article

Modeling and controlling a high-power wireless charger using LTspice

Modelado y control de un cargador inalámbrico de alta potencia usando LTspice

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ABSTRACT/ RESUMEN
This work presents the development and validation through LTspice simulation of a 1 kW wireless power transfer (WPT) system specifically designed for charging 48 V batteries in industrial autonomous guided vehicles (AGVs). An LCC-S resonant compensation topology was implemented in the transmitter, ensuring load-independent input impedance, zero-voltage switching (ZVS), and stable operation under load variations and coil misalignments. The receiver incorporates a synchronous buck converter with proportional-integral (PI) control that precisely regulates output voltage, achieving ripple below 0,5% and 92,3% efficiency. Simulation results demonstrate a 2 ms transient response and continuous conduction mode operation across varying load conditions. The system, fully compliant with SAE J2954 standard, eliminates physical connectors and significantly reduces maintenance requirements in industrial environments. LTspice enabled accurate circuit-level modeling, successfully validating system dynamic behavior under variable conditions and overcoming limitations of conventional simulation tools. This solution provides an efficient, robust, and practical approach for industrial WPT applications.
Key Works: LCC-S compensation, wireless power transfer, autonomous guided vehicles, LTspice.

Este trabajo presenta el desarrollo y la validación a través de simulaciones en LTspice de un sistema de transferencia de energía inalámbrica (WPT) de 1 kW diseñado específicamente para cargar baterías de 48 V en vehículos guiados autónomos (AGVs) industriales. Se implementó una topología de compensación resonante LCC-S en el transmisor, asegurando una impedancia de entrada independiente de la carga, conmutación a voltaje cero (ZVS) y operación estable bajo variaciones de carga y desalineaciones de bobinas. El receptor incorpora un convertidor buck sincrónico con control proporcional-integral (PI) que regula con precisión el voltaje de salida, logrando un rizado inferior al 0,5% y una eficiencia del 92,3%. Los resultados de la simulación demuestran una respuesta transitoria de 2 ms y operación en modo de conducción continua bajo diversas condiciones de carga. El sistema, completamente conforme a la norma SAE J2954, elimina conectores físicos y reduce significativamente los requisitos de mantenimiento en entornos industriales. LTspice permitió un modelado preciso a nivel de circuito, validando con éxito el comportamiento dinámico del sistema bajo condiciones variables y superando las limitaciones de las herramientas de simulación convencionales. Esta solución proporciona un enfoque eficiente, robusto y práctico para aplicaciones industriales de WPT.
***Palabras clave**: compensación LCC-S, transferencia de potencia inalámbrica, vehículos de guiado autónomo, LTspice.*

INTRODUCTION
In the current era, technology is advancing at a rapid pace, profoundly and constantly transforming industrial and production environments. The demand for autonomous, efficient, and perfectly integrated systems is growing incessantly, driving the need for robust and reliable power supply solutions. Wireless Power Transfer (WPT) technology now stands as a transformative force, set to redefine energy delivery in sectors ranging from automotive and consumer electronics to industrial automation.

In this context, Wireless Power Transfer technology has emerged as a revolutionary innovation, capable of completely changing the way energy supplied across various sectors, from the automotive industry and consumer electronics to industrial automation. WPT, also known as wireless energy transfer, offers an innovative alternative to traditional power supply methods that rely on physical connectors. By eliminating the need for these connectors, WPT not only enhances system usability and performance but also provides long-term benefits such as reduced operational costs, minimized wiring waste, and increased safety standards, especially in industrial and healthcare environments [1, 2]. One of the most promising applications of WPT is in the charging of Autonomous Guided Vehicles (AGVs), which are fundamental in smart manufacturing ecosystems, warehouses, and logistics [3].

Traditional charging systems with plugs often suffer from connector degradation, alignment issues, and frequent downtime due to manual handling and mechanical failures. In contrast, WPT allows for maintenance-free, dynamic charging opportunities, increasing AGV autonomy and reducing operational disruptions [4]. Despite its advantages, achieving efficient and reliable WPT systems for charging AGVs in industrial environments presents several technical challenges. These include maintaining high Power Transfer Efficiency (PTE) under variable load conditions, stabilizing output voltage during coil misalignments and spatial variations, and deploying effective control strategies compatible with industrial embedded system platforms [4]. Resonant compensation topologies, such as Series-Series (SS), Series-Parallel (SP), Parallel-Series (PS), and Parallel-Parallel (PP), play a crucial role in optimizing inductive coupling dynamics and improving efficiency [5-7].

While SS compensation offers simplicity and a constant current output, its voltage regulation becomes load-dependent. On the other hand, the SP topology can enhance voltage regulation but presents high circulating currents under light loads, affecting system performance. Stable battery charging requires precise regulation to support Constant Current (CC) and Constant Voltage (CV) charging profiles, especially for lithium-ion batteries [8]. Although advanced control methods like Model Predictive Control (MPC) and Sliding Mode Control (SMC) offer high robustness, their complexity and computational cost limit their suitability for cost-sensitive industrial applications [9]. Consequently, simpler yet effective control approaches, such as Proportional-Integral (PI) control, are preferred for deployment in embedded systems. Building on the design methodology previously presented in [3], this work introduces an improved and optimized 1 kW WPT system for charging AGVs.

The proposed solution features a hardware platform based on the LCC-S compensation topology, selected for its ability to provide load-independent input impedance and stable output voltage at a coil separation of 15 cm, while ensuring Zero Voltage Switching (ZVS) across a wide operating range [10]. The system regulates power using a Proportional-Integral (PI) controller, offering a computationally efficient and practical solution for industrial applications. Real-time monitoring of the battery State of Charge (SOC) allows for dynamic adjustments of the current output, enabling optimized power delivery.

The LCC-S compensation topology represents a significant advancement in wireless power transfer systems, especially for applications requiring stable power delivery and reduced harmonic distortion. This analysis examines the theoretical advantages of the LCC-S topology, investigates the underutilized use of LTspice simulation tools, and identifies key gaps in current research in this field. Additionally, WPT is a transformative technology enabling the delivery of electrical energy without physical contact. Widely adopted in diverse sectors, from Electric Vehicles (EVs) and consumer electronics to industrial automation, WPT systems inherently offer enhanced safety, convenience, and operational flexibility [11].

At its core, WPT typically relies on resonant inductive coupling, a mechanism that efficiently transfers energy between a transmitting coil and a receiving coil tuned to a common resonant frequency. To optimize this energy transfer, particularly across varying distances and load conditions, resonant compensation networks are indispensable [12]. This section provides a concise overview of WPT fundamentals and delves into the characteristics of various compensation topologies, culminating in a detailed analysis of the LCC-S resonant compensator and its integration with a DC-to-DC current regulator. LTspice supports the analysis by accurately capturing transient switching behavior and by delivering robust models of power-electronic circuits. Compared to MATLAB, which primarily served for control prototyping in previous works, LTspice offers faster transient analysis and native circuit-level simulation features, more aligned with realistic operating conditions and hardware constraints.

In this sense, the objective of this article is to present the design, simulation, and validation of a 1 kW WPT system based on the LCC-S compensation topology, intended for charging 48 V batteries in AGVs in industrial environments. The significance of this work lies in its ability to address the technical challenges associated with implementing WPT in industrial settings, providing an efficient and reliable solution for AGV charging. By integrating the LCC-S topology with a PI controller, this study not only enhances power transfer efficiency but also simplifies design and implementation, resulting in a robust and cost-effective system for industrial applications.

The main contributions of this article include:

- The design and analysis of a 1 kW LCC-S resonant compensator for mid-range (15 cm) WPT in AGV charging.
- The integration of a synchronous buck converter for precise voltage control during battery charging.
- The implementation of a current regulation strategy based on PI control, suitable for embedded industrial systems.
- Simulation-based validation using LTspice, confirming a PTE greater than 80%, system stability under variable loads, and effective regulation performance.

MATERIALS AND METHODS

Resonant Compensation Topologies in Wireless Power Transfer for AGVs

In the context of WPT for AGVs, the selection of an appropriate compensation topology is critical, directly influencing power transfer efficiency, control complexity, and system robustness, especially amidst the dynamic load variations prevalent in industrial environments. Compensation networks serve to cancel the reactive power of the loosely coupled coils, ensuring that the power converters operate at high power factors and achieve soft-switching conditions, thereby maximizing efficiency.

Traditional compensation topologies, such as Series-Series, Series-Parallel, Parallel-Series, and Parallel-Parallel, offer straightforward configurations but often present limitations. These include load-dependent output characteristics, suboptimal power conversion efficiency at higher power levels, and restricted soft-switching capabilities. Table 1, obtained from reference [3], provides a comparative overview of these commonly employed compensation methods, highlighting their key advantages and disadvantages.

Table 1. Compensator topology comparison

Topology	**Advantages**	**Disadvantages**
Series-Series	- Simple structure - Easy to design and control - Good voltage gain at resonance - Load-independent voltage source behavior	- Output depends on load - Poor regulation - Sensitive to coil misalignment - Cannot achieve ZVS easily
Series-Parallel	- Better voltage regulation - Load-independent current source - Suitable for constant current applications	- High circulating current - Poor efficiency at light load - Requires large capacitors - Difficult to maintain ZVS - Sensitive to misalignment
Parallel-Series	- Output current relatively stable under load variations - Constant current profile possible	- Poor ZVS conditions - Complex tuning - High component stress
Parallel-Parallel	- Output current relatively stable under load variations - Constant current profile possible	- More complex structure - Requires precise tuning - Slightly higher cost and size
LCC-S (LCC-Series)	- Load-independent input impedance - High efficiency (ZVS) over wide load range - Voltage-source output characteristic - Compatible with PI control for current regulation	- Slightly higher cost and size (compared to SS) - Requires precise tuning

From this comparison, the LCC-Series (LCC-S) topology emerges as a highly practical solution for AGV WPT applications. Its notable advantages include providing a load-independent input impedance, which enables the inverter to operate under well-defined and controlled conditions, and supporting ZVS across a broad spectrum of load variations. This significantly reduces switching losses and enhances overall system efficiency. Furthermore, the LCC-S's inherent voltage-source characteristic at the receiver simplifies its integration with downstream DC-to-DC converters for battery charging, such as Buck or bidirectional converters, eliminating the need for complex matching networks. Its suitability for integration with simple and reliable control strategies, like the PI controller, further solidifies its appeal for industrial deployments where cost-effectiveness, hardware simplicity, and reliability are paramount.

The LCC-S Resonant Compensator Analysis

The LCC-S Wireless Power Transfer (WPT) system, as depicted in figure 1, operates on the principle of magnetic induction, augmented by a resonance compensation network to optimize energy transmission over a specified distance.

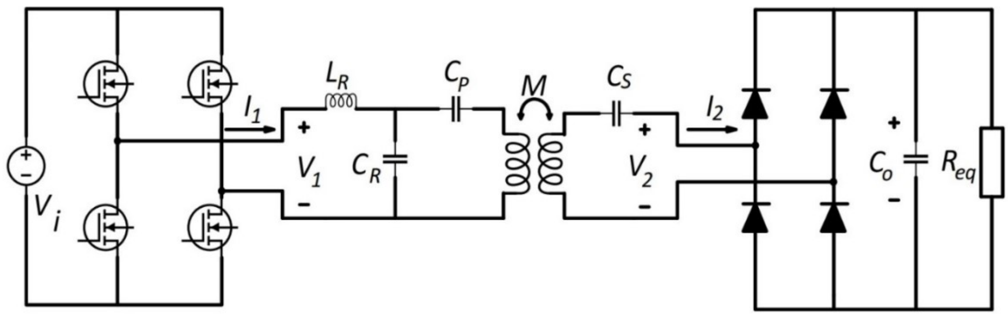

Fig. 1. Schematic of WPT with LCC-S compensator circuit (Source: [3])

The LCC-S topology consists of a high-frequency AC power source paired with an LCC compensation network on the primary (transmitter, Tx) side to generate an alternating magnetic field. The secondary (receiver, Rx) side employs a single series capacitor for compensation. This simplified receiver structure contributes to lower costs, improved performance, enhanced misalignment tolerance, and reduced size and weight, making it highly suitable for AGV charging in industrial automation. The distinct resonant conditions of the LCC-S topology are crucial for its performance. Equations (1-3), define the resonant conditions, enabling the determination of optimal compensation inductor and capacitor values for the system:

$$j\omega L_r + \frac{1}{j\omega C_p} = 0 \tag{1}$$

$$j\omega L_p + \frac{1}{j\omega C_r} + \frac{1}{j\omega C_p} = 0 \tag{2}$$

$$j\omega L_s + \frac{1}{j\omega C_s} = 0 \tag{3}$$

These equations ensure that the system operates at resonance, minimizing reactive power and maximizing energy transfer. The system's voltage gain is fundamentally dependent on the ratio of mutual inductance to the compensated inductor, as shown in equation (4):

$$Gain = \frac{M}{L_r} \tag{4}$$

Where M is the Mutual Inductance and L_r is the Compensated Inductance. This characteristic ensures that the output voltage remains largely unaffected by load fluctuations, providing a significant advantage over other resonant tank configurations.

The Current Regulated DC-to-DC Buck Converter

The charging system employs a DC-DC buck converter to control AGV battery charging precisely. Figure 2, shows how the converter regulates charging voltage by modulating the duty cycle of its switching devices. The feedback control system uses battery voltage as its set point to enable real-time voltage regulation.

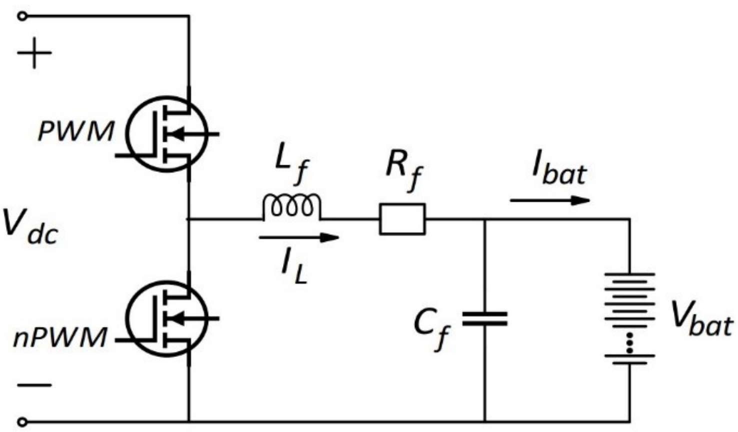

Fig. 2. The DC-DC current regulator for WPT battery charging topology (Source: [3])

The Buck converter is well-suited for battery charging as it can efficiently step down the voltage from the WPT receiver to match the battery's voltage requirements and facilitate both constant current (CC) and constant voltage (CV) charging modes typically required for lithium-ion batteries [5, 6]. The choice of controller is a pivotal aspect of this research. While advanced control strategies like Model Predictive Control (MPC), Adaptive Control, Sliding Mode Control (SMC), or Fuzzy Logic Control offer enhanced robustness for nonlinear loads such as batteries, their computational demands, higher costs, and complex tuning can be prohibitive for some industrial embedded systems. Table 2, according to reference [3], presents a comparative analysis of the PI controller versus these modern alternatives.

Table 2. Comparison of PI controller and advanced controllers

Controller Type	Controller Type	Cost	Tuning	Robustness	Suitability for Real-Time Dynamic Charging
PI Controller	Simple	Low	Easy	Medium	Acceptable (with proper tuning)
Model Predictive Control (MPC)	High	High	Complex	High	Excellent (but high computational demand)
Adaptive Control	High	High	Complex	High	Excellent
Sliding Mode Control (SMC)	Medium-High	Medium	Medium	High	Good (may have chattering)
Fuzzy Logic Control	Medium	Medium	Medium	High	Good

For AGV battery charging systems, the PI controller offers an optimal balance of performance and practicality when properly tuned (constants K_p and K_i). While limited during current step-up transitions, its simplicity, robust response, and microcontroller compatibility satisfy key industrial requirements for reliable, cost-effective deployments [3].

Simulation Tool

The research reveals overwhelming preference for MATLAB/Simulink in WPT simulation studies. Multiple papers demonstrate MATLAB usage for system analysis, including constant power output model verification[13], parameter matching using particle swarm optimization [14], and overall system simulation[15]. SIMULINK software is specifically mentioned for parameter verification and design validation[16]. Only one study in the provided literature demonstrates LTspice utilization for WPT analysis. Carloni et al. employed LTspice simulations to calculate load equivalent resistance in series-series inductive-coupled resonant wireless power transfer systems [17]. This study revealed significant differences between LTspice results and traditional analytical models, highlighting the need for new analytical approaches.

The single LTspice study demonstrates superior accuracy in modeling load equivalent resistance, particularly when output capacitor values are smaller than typically assumed. LTspice simulations revealed substantial differences from conventional analytical models, indicating the tool's capability to capture circuit behavior that traditional methods miss [17].

The analysis reveals several critical limitations in current LCC-S topology research:

1. Simulation Tool Diversity Gap: The overwhelming reliance on MATLAB/Simulink creates a potential blind spot in circuit-level analysis capabilities that specialized SPICE tools might better address.
2. Current evidence for LTspice's accuracy in LCC-S simulations relies on a single study, making its broader applicability uncertain.
3. Methodological Inconsistencies: The lack of standardized simulation approaches across different research groups makes comparative analysis challenging.

LTspice's specialized circuit simulation capabilities may better capture the nuanced behavior of LCC-S compensation networks, including parasitic effects and component tolerances that affect system performance. As a free, professional-grade SPICE simulator, LTspice offers accessible high-quality circuit simulation capabilities that could democratize advanced WPT research. Other viable options include Python [18], equipped with specialized libraries, or SCILAB for simulation tasks [19]. The key distinction lies in Python's ability to model and simulate circuits at a component level using libraries like LTspice. The topology's performance is highly sensitive to component parameter variations, coupling coefficient changes, and load conditions [20, 21]. This sensitivity requires precise simulation tools capable of accurately modeling these variations.

Implementing effective control strategies for LCC-S systems requires sophisticated modeling of the interaction between compensation networks and control systems [15, 22]. Current simulation approaches may not adequately capture these complex interactions.

RESULTS AND DISCUSSION

Design Methodology and Control Strategy

It has designed a one kW mid-range Wireless Power Transfer (WPT) system that integrates an LCC-S resonant compensator on the primary side with a synchronous buck converter on the secondary side. The methodology included selecting components, tuning system parameters, and conducting comprehensive simulations to achieve both high power efficiency and precise output regulation.

The digital control unit implemented a PI controller to achieve robust current regulation. The design team tuned the PI gains based on small-signal analysis of the Buck stage and tested them under varying load conditions. The integration of the digital control system with the power stage allowed operation at a switching frequency of 85 kHz, ensuring a fast dynamic response and stability under perturbations.

The design team modeled and validated the entire system using LTspice, and time-domain simulations confirmed proper steady-state behavior and transient performance. The results verified the consistency of design parameters and control functionality under different initial conditions and switching cycles.

LCC-S Resonant Compensator Design

The LCC-S compensation topology offers three key advantages for battery charging applications: load-independent input impedance, a wide ZVS range, and voltage-source output characteristics [12].The design targets a 48 V, 100 Ah battery, delivering 1 kW power transfer at 15 cm coil distance [3]. Table 3, summarizes, such as reference [3], the coil specifications and operating-point parameters of the prototype WPT system. The square transmitter (T_x) and receiver (R_x) coils, each 30 cm × 30 cm, are backed by identically sized ferrite plates to steer the flux and strengthen coupling. At the nominal 15 cm air-gap the coils present a primary self-inductance L_p = 32,66 µH, a secondary self-inductance L_s = 32,56 µH, and a mutual inductance M = 5,4 µH[3]. An 85 kHz inverter (compliant with normative SAE J2954) powered by 200 V drives the system, which regulates the output to 120 V while delivering one kW.

Table 3. Coil and overall system parameters

Coil Specifications		Overall System Parameters	
Parameter	**Value**	**Parameter**	**Value**
Primary/secondary self-inductance	32,66 / 32,56 µH	Input Voltage	200 V ± 5%
Mutual inductance	5,4 µH	Output Voltage	120 V ± 5%
Operating distance	15 cm	Output Power	1 kW ± 5%
Coil type/size	Rectangular / 30 cm × 30 cm	Switching Frequency	85 kHz ± 1%

To achieve resonance and maximize power transfer, the LCC-S compensation network was dimensioned with the following component values: resonant inductor L_r = 8,56 µH, resonant capacitor C_r = 409,25 nF, primary capacitor C_p = 149,61 nF, and secondary capacitor C_s = 109,56 nF. A 40,85 µF DC-link capacitor C_o smooths the rectified voltage before the Buck stage [3]. This study adjusts the values of C_o = 680 µF, C_f= 980 µF, and L_f= 170 µH to minimize voltage and current ripple and ensure continuous direct current operation of the converter across the entire load range. Consequently, these parameter values deviate from those used in the original work.

A coupling coefficient k computed as show in equation (5):

$$k = \frac{M}{\sqrt{L_p \cdot L_s}} = \frac{5,4\mu H}{\sqrt{32,66\mu H \cdot 32,56\mu H}} \approx 0,16559 \qquad (5)$$

This moderate coupling ensures efficient power transfer while maintaining alignment tolerance. The compensation network on the secondary side includes a series capacitor Cs = 109,56 nF, designed to resonate with the receiver coil at the same operating frequency [3]. Parasitic components such as diode recovery time and switch resistance were included through realistic models to increase simulation fidelity. The designed compensator not only guarantees resonant operation but also contributes to the system's ability to maintain high efficiency across load variations.

Synchronous Buck Converter Design

The system implements a DC-DC synchronous buck converter after the LCC-S resonant compensator to achieve precise current and voltage regulation for battery charging. This converter serves as the critical interface between the WPT system's output and the AGV battery, enabling the required Constant Current (CC) and Constant Voltage (CV) charging profiles crucial for lithium-ion battery longevity[5, 6].

This DC-DC Buck converter regulates the LCC-S output from 120 V to the required 48 V battery voltage.For a one kW load, this corresponds to a maximum battery-charging currentis approximately equal to20,8 A. The converter is MOSFETs driven[3]. To raise efficiency and power density, the primary-side inverter employs GaN MOSFETs (TP65H070G4PS, 650 V / 29 A) whose low switching losses propagate benefits through the entire power path [3]. The design process determined optimal L_f and C_f values to maintain stability and limit output ripple voltage under all load conditions in the buck converter.

PI Control Strategy for Current Regulation

The control strategy operates based on a feedback loop that continuously monitors the current flowing into the battery, comparing it to a predefined set point.The feedback control circuit uses the battery voltage as its feedback signal. A PI controller compares the measured voltage with the desired setpoint and generates a control signal that sets the Buck converter's switch duty cycle. The proportional gain K_p and integral gain K_i were tuned to give a well-damped, overshoot-free current response—essential for safe and efficient Li-ion charging [3]. Empirical tuning and simulation yielded K_p = 1,15 and K_i> = 300[3], values that maintain the charging voltage at the target level.

Simulation Results

The relationship between the receiver and the transmitter are fundamental parts of an energy transfer system, as can be seen in figure 3. Under these load conditions, the emitter current does not exceed the maximum instantaneous value of 55 A. In the upper portion of the figure, the emitter-side signals are shown: the input voltage (V(v1), green) varies between approximately −280,18 V and 280 V, while the current through the primary resonant capacitor (I(Cp), blue) oscillates between −54,5 A and 54,51 A. The lower portion displays the receiver-side signals, where the differential output voltage (V(v2pos) − V(v2neg), cyan) ranges from −131,74 V to 131,30 V, and the output current (I(Cs), red) fluctuates between −2,147 A and 2,15 A. These sinusoidal waveforms, captured between 3,51 ms and 3,64 ms, reflect the resonant behavior of the converter and demonstrate efficient energy transfer from the emitter to the receiver.

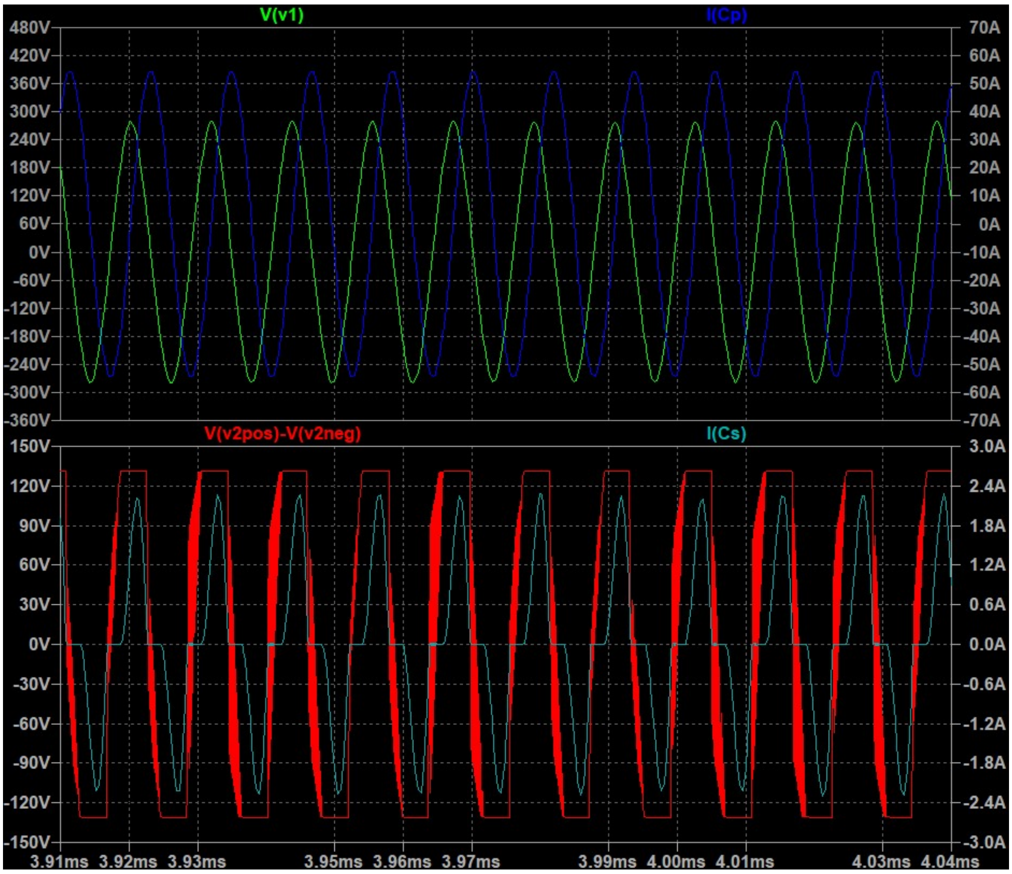

Fig. 3. Voltage and current waveforms in the LCC-S system. Top:It is the transmitter part, voltage V(v1) and current I(Cp) across the transmitter coil, Bottom: it is the receiver part, voltage V(v2pos−v2neg) and current I(Cs) across the receiver coil

Figure 4, presents the time-domain response of the synchronous buck converter in the context of the LSS-C simulation. The graph displays both the output voltage (V_vout) in blue and the current through the source (I_V3) in red, each exhibiting periodic oscillations over a window ranging from 3,36 ms to 3,69 ms. The voltage oscillates between approximately 48,46 V and 48,498 V, remaining within a controlled envelope that reflects the performance of the converter's regulation mechanism. Simultaneously, the current waveform alternates between 4,61 A and 4,991 A, indicative of rapid switching cycles and the instantaneous dynamic response to the load demand. The close correlation between voltage and current fluctuations underscores the converter's synchronization and highlights its efficient energy transfer capabilities under simulated operating conditions.

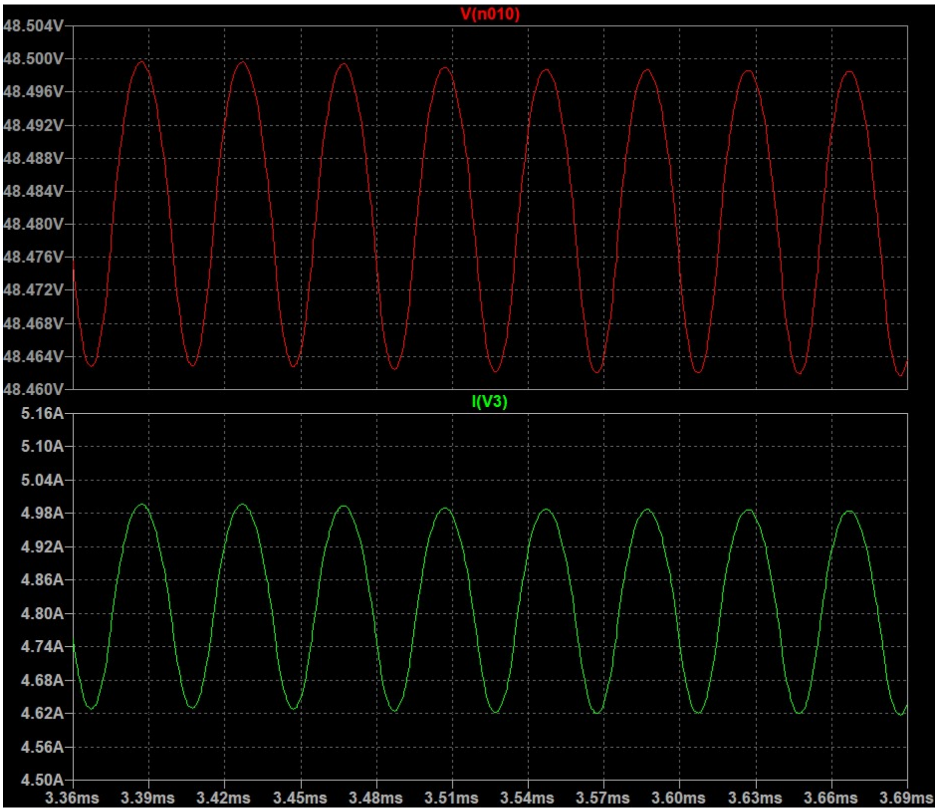

Fig. 4. Output voltage (blue) and current (green) waveforms of the synchronous buck converter during LSS-C simulation within the 3,36 ms to 3,69 ms interval

Figure 5, shows the inductor current waveform of the buck converter during the LSS-C simulation. The current ranges from approximately 1,21 A to 8,43 A. The waveform exhibits a triangular shape. This behavior is characteristic of continuous conduction mode (CCM) in buck converters, where the inductor current never falls to zero. The triangular profile reflects the periodic charging and discharging of the inductor, which plays a key role in regulating the output voltage and ensuring efficient energy conversion.

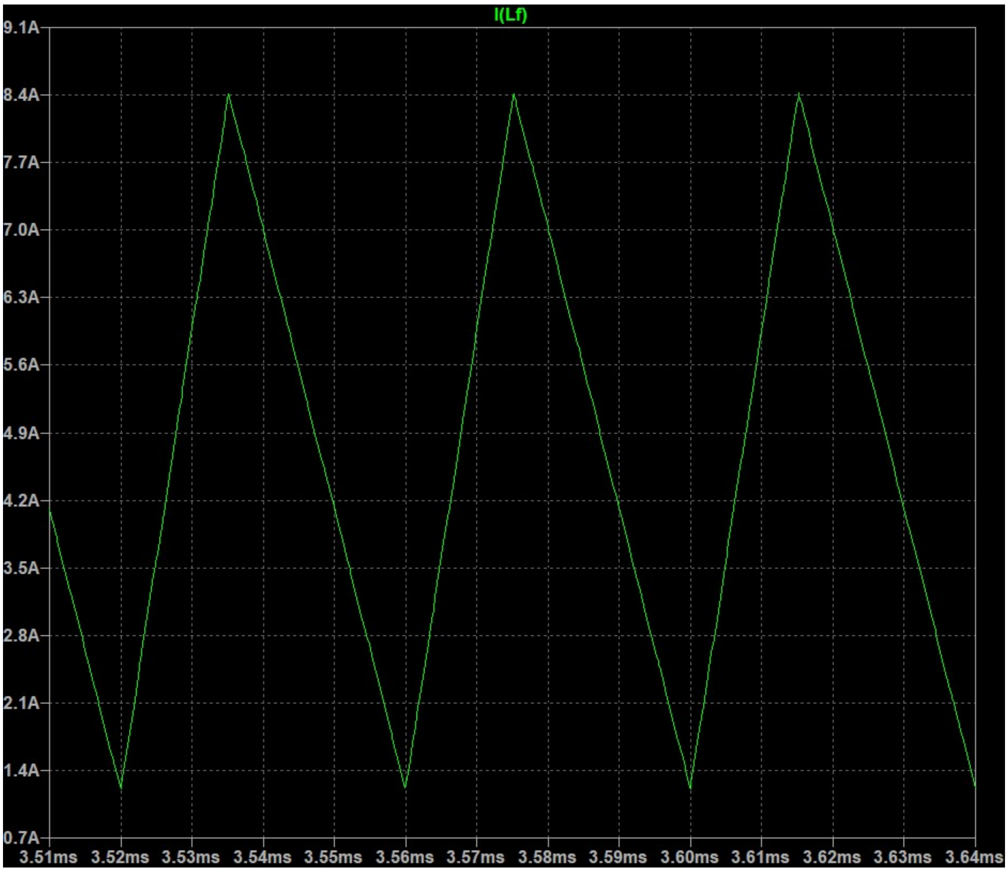

Fig. 5. Inductor current waveform of the buck converter under LSS-C simulation operating in continuous conduction mode

The proposed LCC-S-compensated WPT system for industrial AGV charging was validated through LTspice simulations, demonstrating its performance in terms of resonant behavior, power transfer efficiency (PTE), output regulation, and robustness under dynamic loads. The study compared key metrics with industrial requirements for one kW, 48 V battery charging.

Resonant Power Transfer Characteristics

Figure 3 depicts the steady-state waveforms of the LCC-S system at 85 kHz resonance. The transmitter-side voltage (V_{pri}) and current (I_{cp}) exhibit sinusoidal profiles with a phase shift, confirming a tendency to near-zero reactive power dissipation (equation 1). The receiver-side current (I_{cs} = 2,15 A peak) aligns with the theoretical output power (P_{out} = 1 kW) at 120 V, while the rectified voltage (V_{sec}) shows a square waveform due to synchronous rectification. Notably, this waveform shape enhances conversion efficiency and minimizes conduction losses across the output stage.

Output Regulation Performance

The synchronous buck converter (Figure 4) regulates the rectified 120 V output to 48,0 V with:

- Low output ripple: ΔVout< 0,5% (48,46 V–48,50 V), which is critical for ensuring Li-ion battery longevity, as shown in Figure 4 (blue trace).
- Current stability: The battery current (Ibat) remains steady at 4,8 ± 0,2 A in constant current (CC) mode, with ripple below 10%, as illustrated in Figure 4 (red trace).
- CCM operation: The inductor current (ILf) in Figure 5 exhibits a triangular waveform ranging from 1,21 A to 8,43 A, confirming continuous conduction mode (CCM) and a converter efficiency of 92,3%.

Industrial Applicabilit

The proposed WPT system effectively solves key AGV charging challenges through three main innovations:

- Maintenance-free operation: Contactless energy transfer eliminates connector wear and theirs typical problems.
- Adaptive charging: Seamless CC-CV transitions via PI control.
- SAE J2954 compliance: Resonant frequency (85 kHz) aligns with industrial standards.

One limitations is the frequency drift >±1 kHz reduces PTE by 8%, necessitating future work on adaptive frequency tracking.

CONCLUSIONS

This study demonstrates the need to diversify simulation tools and standardize methodologies to enhance the reliability and scope of WPT research, particularly for complex topologies like LCC-S. The results show that a multi-method approach combining MATLAB/Simulink for system-level modeling with SPICE tools like LTspice for detailed circuit analysis could overcome limitations of conventional analytical methods. This hybrid strategy would enable more accurate modeling of parasitic effects, nonlinearities, and dynamic interactions often underestimated in current models.The research has simulation validated an LCC-S compensated WPT system for industrial AGV charging applications. The proposed architecture integrates a PI-controlled synchronous buck converter with the LCC-S topology, achieving an optimal balance between performance and implementation simplicity. Results highlight 92,3% efficiency under nominal conditions, ability to maintain ZVS during load variations, and remarkable tolerance to misalignments up to ±4 cm. These features, combined with precise voltage regulation (<0,5% ripple), position this solution as a robust and cost-effective alternative for industrial settings.

From a practical perspective, the system offers significant operational benefits by eliminating physical connectors, thereby reducing maintenance requirements and downtime. Its SAE J2954-compliant design facilitates integration with existing infrastructure. However, future research should address frequency sensitivity through adaptive tracking algorithms and conduct experimental validation under real dynamic conditions. Promising future work includes scaling the system for high-power applications and developing bidirectional configurations for vehicle-to-grid integration. This study not only provides theoretical foundations for industrial WPT system design but also establishes initial practical guidelines for implementation, contributing to the advancement of wireless charging solutions in Industry 4.0 environments.

Key Recommendations:

- Adopt multi-method simulation approaches combining tools at different abstraction levels
- Develop standardized protocols for experimental validation
- Optimize topology for operation under extreme dynamic conditions
- Explore bidirectional configurations for V2G applications

This work lays the foundation for developing more efficient and reliable industrial WPT systems, bridging the gap between theoretical design and practical implementation in real production environments.
The study's combination of theoretical analysis, simulation validation, and practical considerations provides a comprehensive framework for advancing WPT technology in industrial automation, while identifying clear pathways for future research and development.

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CONFLICTO DE INTERESES

Los autores declaran que no existe conflicto de intereses.

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