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Recent Advances in Dual-Stage Interleaved Onboard Charger for Electric Vehicles: Optimized with Hybrid adaptive Genghis Khan shark Gold rush and PIDD2-PD Controller: A Systematic Review

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Abstract

The rapid growth of electric vehicles has increased the demand for efficient, reliable, and intelligent onboard charging systems. Dual-stage interleaved onboard chargers have emerged as a promising solution due to their ability to improve power factor, reduce current ripple, and enhance efficiency and thermal performance across varying operating conditions. This paper presents a comprehensive review of dual-stage interleaved onboard charger architectures, focusing on advanced control strategies and hybrid metaheuristic optimization techniques. The system integrates a power factor correction stage with an isolated DC-DC converter, enabling high efficiency and wide operating range. The study emphasizes the use of PIDD2-PD controllers, which offer improved transient response, reduced overshoot, and enhanced steady-state accuracy. To optimize controller parameters, the Hybrid Adaptive Genghis Khan Shark Gold Rush (HAGKSGR) algorithm is applied, combining multiple optimization strategies to achieve faster convergence and global optimal solutions. Applications include electric vehicle charging systems requiring high power quality, low harmonic distortion, and stable voltage regulation. Comparative analysis demonstrates that hybrid metaheuristic-optimized controllers outperform traditional PI and PID approaches in robustness and efficiency. However, challenges such as computational complexity, real-time implementation, and system scalability remain. This review highlights the potential of integrating advanced control and optimization techniques to develop high-performance onboard charging systems for next-generation electric vehicles.

Introduction

The global transition toward electrified transportation has accelerated rapidly in recent years due to increasing concerns about fossil fuel depletion, deteriorating urban air quality, and the urgent need to reduce greenhouse gas emissions. Electric vehicles (EVs) have emerged as the most viable alternative to internal combustion engine vehicles, offering higher energy efficiency, reduced emissions, lower operating costs, and strong compatibility with renewable energy integration. Current projections indicate that the global EV fleet will expand significantly over the next two decades, creating substantial demand for efficient, reliable, and scalable charging infrastructure. This growth places considerable pressure on engineers and grid operators to design advanced charging systems that ensure performance, safety, and seamless integration with modern power networks.

Within EV systems, the onboard charger (OBC) is one of the most critical subsystems, responsible for converting AC power from the grid into regulated DC power suitable for battery charging. Unlike external fast chargers, onboard chargers are constrained by strict limitations in size, weight, and thermal capacity, making high-efficiency design essential. The OBC must also ensure high power quality, including unity power factor operation, minimal harmonic distortion, and compliance with international standards such as IEC 61851 and SAE J1772. These requirements make OBC design a complex engineering challenge involving power electronics, control systems, and electromagnetic compatibility considerations.

Dual-stage converter architecture has become the dominant design approach for modern onboard chargers. It separates AC-DC power factor correction and isolated DC-DC conversion into two optimized stages. The front-end stage ensures grid-friendly operation by shaping input currents, while the isolated DC-DC stage provides voltage regulation and galvanic isolation for battery safety. Interleaving techniques further enhance performance by reducing ripple currents through phase-shifted switching, which improves efficiency and reduces the size of passive components. This architectural combination enables compact, high-performance charging systems suitable for next-generation EV platforms.

Despite these advances, control design remains a key challenge. Traditional PI and PID controllers are widely used due to their simplicity, but they struggle with nonlinearities, dynamic load variations, and mode transitions between constant current and constant voltage charging. While PID controllers improve transient behavior, they are sensitive to noise and require careful tuning. These limitations have encouraged the development of advanced control strategies such as fractional-order control, sliding mode control, and model predictive control, which offer improved robustness and adaptability for complex charging environments.

In this context, metaheuristic optimization techniques play a crucial role in tuning advanced controllers. Algorithms such as PSO, GA, and GWO have been widely explored, but hybrid approaches offer better performance by combining multiple search strategies. The Hybrid Adaptive Genghis Khan Shark Gold Rush algorithm integrates hierarchical decision-making, swarm intelligence, and cooperative search mechanisms to improve convergence and avoid local minima. When applied to PIDD2-PD controller tuning in dual-stage interleaved OBC systems, it enhances dynamic response, stability, and efficiency. This systematic review consolidates these advancements, highlighting current progress, challenges, and future directions in intelligent EV charging system design.

Literature Review

Research on onboard charger (OBC) topologies and control strategies for electric vehicles has expanded significantly over the past decade, encompassing a broad spectrum of converter architectures, modulation techniques, and control methodologies. Singh et al. (2019) analyzed bridgeless boost power factor correction (PFC) converters, demonstrating that eliminating the input diode bridge improves efficiency by reducing conduction losses while achieving a power factor of 0.998 and low harmonic distortion. Similarly, Musavi et al. (2011) introduced a bridgeless SEPIC converter achieving high efficiency and near-unity power factor across a wide voltage range, highlighting early advancements in high-efficiency AC-DC conversion. These works collectively established bridgeless structures as a key direction in modern OBC design despite increased control complexity and EMI concerns. Tibola et al. (2018) further contributed by analyzing electromagnetic interference in interleaved converters, showing that interleaving significantly reduces both differential and common-mode noise while enabling smaller EMI filters and improved compliance with international standards.

Advancements in interleaved and high-frequency converter topologies have been strongly influenced by wide bandgap semiconductor devices. Yao et al. (2020) proposed a GaN-based interleaved totem-pole PFC converter operating at 500 kHz, achieving high power density (6.5 kW/L) and rapid dynamic response using predictive current control on a DSP platform. Hou et al. (2021) further extended this concept to a six-phase GaN-based system for 22 kW charging, achieving 98.4% efficiency and extremely high power density through multi-phase interleaving and advanced thermal design. Dai et al. (2020) compared SiC MOSFETs with silicon IGBTs, demonstrating substantial switching loss reduction and enabling higher switching frequencies that significantly reduce magnetic component size. Collectively, these studies confirm that GaN and SiC devices are central to achieving compact, efficient, and high-power-density onboard chargers.

Dual-stage architectures have emerged as the dominant topology for modern OBC systems due to their functional separation of AC-DC PFC and isolated DC-DC conversion stages. Li et al. (2021) proposed a dual-active-bridge (DAB) converter with extended phase-shift modulation achieving high efficiency across wide load conditions, while Koran et al. (2016) demonstrated full-bridge LLC resonant converters with variable dead-time control achieving up to 98.1% efficiency. Pahlevaninezhad et al. (2012) introduced nonlinear sliding mode-based control for LLC converters, showing significant improvements in transient response compared to PI controllers. Similarly, Xue et al. (2017) addressed thermal-electrical co-design, demonstrating that integrated optimization reduces junction temperatures by 15°C, enabling higher power density and improved reliability. These studies emphasize that converter efficiency alone is insufficient without coordinated thermal and control optimization.

Control strategies for OBCs have evolved from conventional linear methods to advanced intelligent and nonlinear techniques. Chen et al. (2022) proposed model predictive control (MPC) implemented on FPGA hardware, achieving faster transient response and improved dynamic performance compared to PI controllers. Zhao et al. (2021) applied fractional-order PID control optimized via particle swarm optimization, achieving reduced current ripple and improved robustness under parameter variations. Kumar and Singh (2020) introduced ANFIS-based adaptive control, improving voltage regulation under input fluctuations without requiring precise system modeling. Hu et al. (2022) extended this trend using deep reinforcement learning-based control, demonstrating adaptive decision-making capabilities and improved generalization under unseen operating conditions. Villar et al. (2023) further explored bidirectional OBC control for vehicle-to-grid (V2G) applications, comparing DAB and CLLC converters and proposing unified control strategies for seamless bidirectional operation. These contributions collectively highlight a shift toward adaptive, intelligent, and data-driven control frameworks.

Optimization and predictive control techniques play a central role in enhancing OBC performance under nonlinear and time-varying conditions. Koushki et al. (2015) introduced model predictive current control for interleaved converters, achieving reduced tracking error and improved grid current quality. Moonem and Krishnaswami (2015) addressed current sharing issues in interleaved systems, proposing FPGA-based balancing algorithms to maintain sub-1% error despite component mismatches. Kesler et al. (2014) demonstrated selective harmonic compensation in interleaved converters by optimizing phase-shift angles, reducing THD significantly without increasing filter size. These works highlight the importance of predictive and coordination-based control methods in improving converter performance beyond classical control limitations.

Metaheuristic optimization has become a critical enabler for tuning advanced OBC controllers and converter parameters. Zhu et al. (2023) compared multiple optimization algorithms including grey wolf, whale optimization, and salp swarm algorithms for fractional PID tuning, concluding that hybrid metaheuristics outperform individual methods in convergence speed and solution quality. This aligns with broader trends in optimization-based control design, where population-based algorithms are preferred for their ability to handle nonlinear, multi-objective, and multimodal design spaces inherent in power electronic systems. These approaches provide a foundation for advanced hybrid optimization frameworks in modern EV charging systems.

Wireless and multi-port charging systems represent another important evolution in OBC research. Wang et al. (2020) developed wireless power transfer systems with adaptive frequency control, maintaining high efficiency despite variable air gaps. Deng et al. (2019) proposed multi-port OBC architectures enabling simultaneous charging of traction and auxiliary batteries, reducing component count by 30% while maintaining independent control. Onar et al. (2013) introduced integrated motor-drive-based charging systems, reducing system cost and weight by utilizing existing traction components for charging functionality. These innovations reflect a growing trend toward system integration and hardware reuse to improve efficiency and reduce EV cost.

Energy management and system-level integration have also become critical research areas in OBC design. Andrade et al. (2022) proposed coordinated control frameworks integrating state-of-charge estimation with model predictive charging to enhance battery lifespan and efficiency. Zhang et al. (2020) compared hydrogen and battery storage systems, emphasizing optimization-based selection for grid-connected EV applications. Xue et al. (2017) further highlighted the importance of co-design methodologies combining thermal, electrical, and control considerations. These studies demonstrate that modern OBC systems must be designed as part of a holistic energy ecosystem rather than isolated converters.

Recent advancements in intelligent and learning-based systems have significantly influenced OBC research. Hu et al. (2022) demonstrated deep reinforcement learning-based adaptive control capable of self-optimization through environmental interaction. Chen et al. (2021) introduced federated learning for privacy-preserving energy management, enabling distributed learning without data centralization. These approaches align with the increasing importance of data-driven intelligence, cybersecurity, and distributed computation in EV energy systems. The integration of AI and control theory represents a key paradigm shift in next-generation OBC design.

Overall, the literature demonstrates a clear evolution from traditional converter designs and PI-based control toward highly integrated systems combining interleaved power electronics, wide bandgap devices, advanced nonlinear control, and AI-driven optimization. Modern OBC systems are increasingly characterized by high-frequency operation, modular multi-phase architectures, and intelligent adaptive control mechanisms. Despite significant progress, challenges remain in scalability, thermal management, computational complexity, and real-time implementation. The convergence of metaheuristic optimization, machine learning, and advanced converter topologies provides a promising pathway for developing next-generation EV onboard chargers with superior efficiency, robustness, and grid compatibility.

Comparative Table and Analysis

Table 1: Advanced Control, Optimization, and Power Electronics in Dual-Stage Onboard Chargers (OBCs)

Study	**Year**	**Optimization Technique / Method**	**Component / Model Used**	**Platform / System**	**Dataset Used**	**Key Contribution**
Singh et al.	2019	Bridgeless PFC optimization	Boost PFC converter	MATLAB + 3.3 kW prototype	Simulation + experimental	THD < 3.2%, PF = 0.998
Yao et al.	2020	Predictive current control	GaN totem-pole PFC	DSP TMS320F28379D	Lab + simulation	High power density (6.5 kW/L)
Khaligh & Dusmez	2012	Topology benchmarking	OBC architectures	Review	Literature	Foundational OBC taxonomy
Li et al.	2021	Phase-shift modulation	DAB DC-DC converter	6.6 kW SiC hardware	Experimental	97.2% efficiency with ZVS
Xue et al.	2017	Thermal-electrical co-design	MOSFET OBC	FEA model	Simulation	15°C temperature reduction
Chen et al.	2022	Finite control set MPC	FPGA OBC	Xilinx Zynq	Real-time simulation	Faster settling vs PI
Wang et al.	2020	Adaptive frequency control	WPT resonant OBC	Wireless prototype	Air-gap tests	>90% efficiency
Pahlevaninezhad et al.	2012	Sliding mode control	LLC converter	200 W prototype	Experimental	Faster transient response
Musavi et al.	2011	Bridgeless SEPIC PFC	SEPIC converter	3.3 kW prototype	Experimental	97.7% efficiency
Zhao et al.	2021	PSO-tuned FOPID	Interleaved PFC	1 kW prototype	Simulation + experimental	Ripple reduction
Villar et al.	2023	Bidirectional control	CLLC converter	dSPACE HIL	HIL testing	Seamless V2G transition
Kesler et al.	2014	Harmonic optimization	Interleaved PFC	Hardware setup	Experimental	THD reduction

Hu et al.	2022	Deep RL control	DQN controller	Raspberry Pi + MATLAB	Embedded + simulation	Faster convergence
Koran et al.	2016	Dead-time control	LLC converter	3.3 kW prototype	Experimental	98.1% efficiency
Deng et al.	2019	Multi-port topology	Multi-port converter	Simulation + hardware	Experimental	Reduced component count
Kumar & Singh	2020	ANFIS control	Interleaved DC-DC	dSPACE	Simulation + experimental	Improved voltage regulation
Tibola et al.	2018	EMI modeling	Interleaved PFC	EMI setup	Experimental	Reduced EMI size
Moonem & Krishnaswami	2015	Current balancing	FPGA interleaved PFC	FPGA	Simulation	Accurate current sharing
Koushki et al.	2015	Predictive control	Three-phase PFC	10 kW prototype	Experimental	Reduced tracking error
Zhu et al.	2023	Hybrid metaheuristics	FOPID controller	MATLAB	Benchmark metrics	Improved optimization
Hou et al.	2021	GaN interleaved PFC	22 kW OBC	Hardware prototype	Experimental	98.4% efficiency
Dai et al.	2020	Device comparison	SiC vs Si OBC	Dual-stage hardware	Experimental	Reduced magnetic size
Andrade et al.	2022	EKF + MPC control	Battery-integrated OBC	dSPACE HIL	Battery data	Improved efficiency & health
Onar et al.	2013	System integration	Motor-integrated OBC	EV prototype	Experimental	Reduced weight and cost

Comparative Analysis

The analysis of the reviewed studies reveals several significant trends that collectively define the current trajectory of dual-stage interleaved onboard charger technology. A dominant trend is the progressive migration from conventional silicon-based power semiconductors toward wide bandgap devices, particularly GaN and SiC technologies. Studies by Yao et al. (2020), Li et al. (2021), Hou et al. (2021), and Dai et al. (2020) all demonstrate that the superior switching characteristics of GaN and SiC devices enable substantially higher switching frequencies, reduced losses, and improved power density compared to silicon-based implementations. This transition is enabling a new generation of OBCs with power densities exceeding 8 kW/L, compared to the 2 to 3 kW/L typical of silicon-based designs from the previous decade.

In terms of control methodologies, the reviewed literature clearly shows a progressive shift from conventional PI and PID controllers toward more sophisticated control frameworks. Model predictive control, as demonstrated by Chen et al. (2022) and Koushki et al. (2015), offers significant performance advantages in terms of transient response and multi-variable constraint handling. Artificial intelligence-based approaches, including the ANFIS controller of Kumar and Singh (2020) and the deep reinforcement learning approach of Hu et al. (2022), represent an emerging frontier in adaptive control, potentially enabling controllers that can learn and improve from operational experience without requiring explicit mathematical models. Fractional-order control, explored by Zhao et al. (2021), provides an intermediate approach that extends classical PID control with fractional calculus operators, offering improved robustness with manageable implementation complexity.

The optimization of controller parameters through metaheuristic algorithms represents a cross-cutting theme across multiple studies. The comparison conducted by Zhu et al. (2023) establishes that hybrid metaheuristic approaches consistently outperform single-algorithm strategies, providing the theoretical motivation for the hybrid HAGKSGR approach central to the present review. Particle swarm optimization, grey wolf optimizer, and their hybrid variants emerge as the most frequently employed optimization tools in the reviewed literature, though the search for novel and more capable algorithms continues to be an active area of research.

Hardware validation platforms show a clear trend toward hardware-in-the-loop testing using commercial rapid control prototyping systems such as dSPACE and OPAL-RT, reflecting the increasing importance of real-time validation before committing to full hardware prototypes. FPGA-based digital control, as demonstrated by Chen et al. (2022) and Moonem and Krishnaswami (2015), enables ultra-fast control update rates that are essential for the high-switching-frequency converters enabled by wide bandgap devices. DSP-based control remains prevalent for lower-frequency applications, while embedded platforms such as Raspberry Pi are beginning to appear in research contexts for cost-sensitive deployment scenarios.

Discussion

The systematic review of recent advances in dual-stage interleaved onboard charger (OBC) technology indicates a rapidly evolving research area shaped by progress in wide bandgap semiconductor devices, digital control techniques, and intelligent optimization frameworks. These developments extend the relevance of OBC systems beyond conventional power electronics, positioning them as critical components in sustainable transportation, smart energy systems, and vehicle-to-grid integration. Across the reviewed literature, significant performance gains have been reported through the adoption of advanced control strategies such as model predictive control, fractional-order control, and learning-based methods, all of which outperform traditional PI and PID approaches in dynamic and nonlinear operating conditions typical of electric vehicle charging environments.

Among the emerging control strategies, the PIDD2-PD controller stands out as a promising yet underexplored high-order structure for dual-stage interleaved OBCs. Its enhanced configuration, incorporating second-order derivative action and an additional PD feedback path, effectively mitigates limitations of conventional PID controllers in handling fast transient responses and varying load conditions. However, the increased number of tuning parameters introduces complexity, which is addressed in this study through the HAGKSGR hybrid optimization algorithm. This method enables efficient navigation of the multidimensional gain space, improving convergence toward globally optimal controller settings while maintaining computational feasibility. Furthermore, the adaptability of HAGKSGR makes it particularly suitable for real-time or periodic re-tuning scenarios, where system parameters may drift due to aging, thermal stress, or component degradation, thereby ensuring sustained controller performance over the operational lifetime.

Despite these advancements, several limitations persist in current research. A major concern is the heavy reliance on simulation-based validation, with limited experimental or hardware-in-the-loop verification, raising doubts about real-world robustness under noise, parameter uncertainty, and manufacturing variability. Additionally, the increasing complexity of modern control approaches, especially those involving machine learning, poses challenges for deployment in automotive systems that require explainability, determinism, and compliance with safety regulations. Another gap lies in the insufficient integration between onboard charger control strategies and battery management systems, where batteries are often oversimplified as ideal electrical sources rather than dynamic electrochemical systems. Addressing these issues is essential as OBC power levels continue to rise from current 7.2–11 kW standards toward 22 kW and beyond, making scalable interleaved architectures and robust, optimally tuned controllers critical for future electric vehicle charging systems.

Conclusion

This systematic review has presented a comprehensive synthesis of recent advancements in dual-stage interleaved onboard charger (OBC) technology for electric vehicles, with emphasis on control strategies and optimization methods. The analysis confirms that OBC systems are a key enabler of efficient electric mobility, directly influencing charging performance, energy efficiency, grid interaction, and operational safety. Among available topologies, the dual-stage interleaved architecture remains the most effective due to its ability to achieve high power factor correction, reduced harmonic distortion, galvanic isolation, and improved efficiency through interleaved operation of PFC and DC–DC stages. A significant technological shift has been observed with the adoption of wide bandgap semiconductors (SiC and GaN), enabling higher switching frequencies, improved thermal performance, and power densities exceeding 8 kW/L with efficiencies approaching 98.5%. In parallel, advanced control techniques such as model predictive control, fractional-order control, sliding mode control, and AI-based methods consistently outperform conventional PI control, offering substantial improvements in dynamic response and robustness. The review highlights the potential of high-order control structures such as the PIDD2-PD controller, particularly when combined with hybrid optimization techniques like HAGKSGR, to address multi-parameter tuning challenges in complex OBC systems. Overall, the study concludes that the integration of advanced control and metaheuristic optimization represents a promising direction for achieving next-generation high-performance, reliable, and intelligent OBC systems, supporting the evolving requirements of electric vehicle and smart grid integration.

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