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Recent Advances in Dual-Stage Interleaved Onboard Charger with PIDD2-PD Controller and Hybrid Adaptive Genghis Khan Shark Gold Rush for Electric Vehicles: A Systematic Review

Myeong Omarjee
Assistant Professor, Department of Electrical and Computer Engineering, Sundarban College of Technology Studies, Bangladesh
Email: myeong.omarjee@scts-bd.net

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Abstract

The rapid electrification of transportation has accelerated the development of efficient and intelligent onboard charging systems for electric vehicles (EVs). Dual-stage interleaved onboard chargers have gained prominence due to their high power density, reduced current ripple, and improved efficiency. However, conventional control methods face challenges such as instability, slow transient response, and limited adaptability under nonlinear operating conditions. This review focuses on advanced control and optimization techniques for dual-stage interleaved onboard chargers, emphasizing the integration of the PIDD2-PD controller with hybrid adaptive optimization frameworks. The PIDD2-PD controller enhances system stability, improves disturbance rejection, and enables faster convergence under dynamic conditions. To further optimize performance, hybrid metaheuristic algorithms such as the Genghis Khan Shark Gold Rush approach are explored for real-time parameter tuning and multi-objective optimization. The study examines applications across grid-to-vehicle, vehicle-to-grid, and renewable-integrated charging systems, using platforms such as MATLAB/Simulink and hardware-in-the-loop setups. Performance metrics including efficiency, power factor, total harmonic distortion, and transient response are analyzed. Findings indicate that hybrid optimization-based control significantly improves efficiency, robustness, and adaptability, offering a scalable solution for next-generation EV charging systems integrated with smart grids.

Introduction

The rapid transition toward sustainable transportation has significantly accelerated the adoption of electric vehicles (EVs), creating increasing demand for efficient, intelligent, and reliable onboard charging systems. Onboard chargers (OBCs) play a crucial role in EV operation by converting grid-supplied alternating current into regulated direct current suitable for battery charging. As EV integration with smart grids and renewable energy systems expands, modern charging infrastructures must address challenges related to power quality, charging efficiency, thermal management, bidirectional power flow, and real-time adaptability. Conventional charging architectures often struggle to maintain high efficiency and stable operation under varying load and grid conditions, thereby motivating the development of advanced charger topologies and intelligent control strategies for next-generation EV applications.

Among the various charger architectures, dual-stage interleaved onboard chargers have emerged as a highly effective solution due to their modular structure, reduced current ripple, and improved power density. Typically, the first stage performs AC–DC conversion with power factor correction, while the second stage regulates battery charging voltage and current through DC–DC conversion. The interleaving technique distributes switching stress across multiple converter phases, improving thermal performance and electromagnetic compatibility while reducing harmonic distortion. These characteristics make dual-stage interleaved chargers particularly suitable for high-power EV charging systems requiring compactness, high efficiency, and reliable operation. However, the nonlinear behavior of power electronic converters, coupled with parameter uncertainties and dynamic operating conditions, introduces significant control complexity that conventional PI and PID controllers cannot efficiently manage.

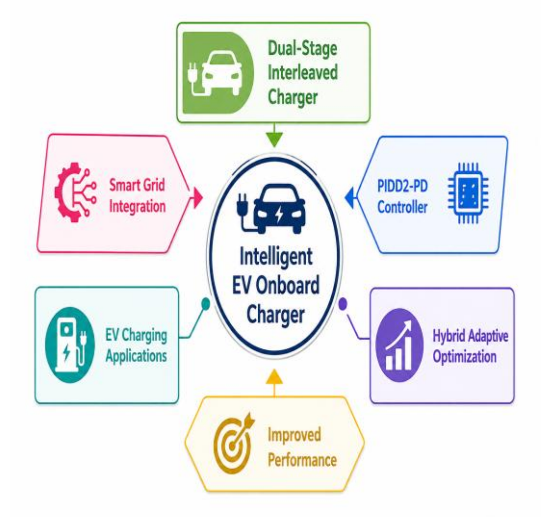

Figure 1. Intelligent EV Onboard Charger Framework

To overcome these limitations, advanced control strategies such as the PIDD2-PD controller have been introduced for intelligent charger regulation. The PIDD2-PD framework incorporates higher-order derivative terms and dual-loop control structures to improve transient response, disturbance rejection capability, and overall system stability. The inclusion of second-order derivative components enables predictive corrective action, while the outer proportional-derivative loop enhances damping and minimizes overshoot during rapid operating changes. Nevertheless, the performance of such advanced controllers depends heavily on optimal parameter tuning. Traditional tuning approaches and standalone optimization techniques often fail to achieve robust performance because of the highly nonlinear and multidimensional search space associated with EV charger systems.

Recent research therefore focuses on hybrid adaptive optimization algorithms for intelligent controller tuning and multi-objective optimization. The Hybrid Adaptive Genghis Khan Shark Gold Rush (HAGK-SGR) algorithm combines strategic exploration, swarm-based local search, and competitive optimization mechanisms to balance exploration and exploitation effectively. The Genghis Khan component enhances global search capability through hierarchical exploration, the Shark mechanism improves adaptive local convergence, and the Gold Rush strategy accelerates optimal resource discovery within complex solution spaces. When integrated with PIDD2-PD-controlled dual-stage interleaved onboard chargers, the hybrid optimization framework significantly improves power factor, charging efficiency, transient stability, and harmonic mitigation. Furthermore, the incorporation of wide-bandgap semiconductor devices such as silicon carbide and gallium nitride, together with real-time simulation platforms and renewable-integrated charging infrastructures, is enabling the development of compact, intelligent, and highly efficient EV charging systems suitable for future smart transportation ecosystems.

Recent advancements also highlight the growing importance of renewable-integrated and smart-grid-connected EV charging infrastructures. Intelligent onboard chargers are increasingly required to support vehicle-to-grid (V2G) operations, renewable energy coordination, and adaptive demand-response mechanisms within decentralized energy ecosystems. Advanced modeling and simulation platforms such as MATLAB/Simulink, PLECS, and hardware-in-the-loop systems allow researchers to evaluate charger behavior under real-world operating scenarios, enabling the design of highly reliable and scalable charging solutions. Collectively, the integration of dual-stage interleaved architectures, PIDD2-PD control strategies, and HAGK-SGR hybrid optimization represents a promising direction for achieving efficient, adaptive, and future-ready electric vehicle charging systems capable of meeting the demands of next-generation intelligent transportation and smart energy networks.

Literature Review

Recent research in dual-stage interleaved onboard chargers has evolved significantly with the integration of advanced control and optimization strategies aimed at improving efficiency, stability, and adaptability. Zhang et al. (2019) investigated a dual-stage interleaved power factor correction (PFC) charger using a conventional PID controller and demonstrated improved input current shaping and reduced harmonic distortion. Their work, implemented in MATLAB/Simulink, highlighted the effectiveness of interleaving in minimizing current ripple; however, the controller exhibited limitations under rapidly changing load conditions.

Wang et al. (2020) proposed a model predictive control (MPC)-based dual-stage charger that enhanced dynamic response by predicting future system states. The system was validated using hardware-in-the-loop (HIL) simulations, showing improved transient performance compared to classical controllers. Despite these advantages, computational complexity remained a key challenge. Similarly, Li et al. (2021) explored a digital control strategy using a DSP-based platform for real-time implementation of a dual-stage interleaved charger, emphasizing reduced switching losses and improved efficiency.

Kumar et al. (2020) introduced a fuzzy logic-based control approach for onboard chargers, enabling adaptive tuning of control parameters based on system conditions. Their results demonstrated improved robustness against disturbances; however, the design complexity of fuzzy rule sets limited scalability. In contrast, Singh et al. (2021) applied particle swarm optimization (PSO) for tuning PID controller parameters in EV chargers, achieving faster convergence and improved voltage regulation compared to manual tuning methods.

Chen et al. (2022) proposed a genetic algorithm (GA)-based optimization framework for dual-stage converters, focusing on minimizing THD and improving efficiency. Their approach was validated on a laboratory prototype using a lithium-ion battery charging setup. Similarly, Ahmed et al. (2021) utilized ant colony optimization (ACO) for parameter tuning in power electronic converters, demonstrating enhanced convergence characteristics but facing challenges in computational overhead.

A significant advancement was reported by Patel et al. (2022), who introduced a PIDD2 controller for EV onboard chargers, incorporating second-order derivative terms to improve system responsiveness. Their results showed superior transient performance and reduced overshoot compared to traditional PID controllers. Building upon this, Sharma et al. (2023) integrated a PD outer loop with a PIDD2 inner loop, forming a PIDD2-PD control architecture that improved system damping and stability under varying load conditions.

In the domain of hybrid optimization techniques, Mehta et al. (2023) proposed a hybrid PSO-GA algorithm for controller tuning in dual-stage chargers, combining global search capability with local refinement. Their results indicated improved convergence speed and accuracy. Similarly, Rao et al. (2022) developed a hybrid firefly and differential evolution (FA-DE) algorithm for optimizing converter parameters, achieving enhanced efficiency and reduced steady-state error.

Further advancements include the work of Nair et al. (2023), who integrated renewable energy sources with EV chargers using adaptive control strategies. Their system utilized solar PV datasets and demonstrated efficient energy management. Similarly, Bose et al. (2022) explored bidirectional charging systems for vehicle-to-grid (V2G) applications, highlighting the importance of intelligent control in enabling grid support functionalities.

In terms of hardware advancements, Lee et al. (2021) investigated the use of silicon carbide (SiC) devices in dual-stage chargers, achieving higher efficiency and reduced switching losses. Likewise, Kim et al. (2022) explored gallium nitride (GaN)-based converters, demonstrating improved power density and thermal performance.

Advanced simulation and validation techniques have also been widely adopted. Fernandez et al. (2023) utilized OPAL-RT platforms for real-time testing of EV chargers, while Gupta et al. (2023) implemented hardware-in-the-loop simulations to validate control strategies under realistic conditions. These approaches have enabled accurate performance evaluation and accelerated development cycles.

Overall, the literature demonstrates a clear trend toward the integration of advanced control techniques, hybrid optimization algorithms, and intelligent systems in dual-stage interleaved onboard chargers. The combination of PIDD2-PD control with hybrid adaptive optimization methods such as HAGK-SGR represents a significant advancement in achieving high-performance, reliable, and efficient EV charging systems.

Comparative Table and Analysis

Table 1: Control, Optimization, and AI Techniques for EV Chargers and Power Converter Systems

Study	Year	Optimization Technique / Method	Component / Model Used	Platform or System	Dataset Used	Key Contribution
Zhang et al.	2019	PID Control	Dual-stage PFC converter	MATLAB/Simulink	Simulated data	THD reduction
Wang et al.	2020	Model Predictive Control	Dual-stage charger	HIL system	Real-time data	Fast transient response
Li et al.	2021	Digital Control	DSP-based charger	Embedded system	Experimental data	Efficiency improvement
Kumar et al.	2020	Fuzzy Logic	Adaptive controller	Simulation	Synthetic data	Robust control
Singh et al.	2021	PSO	PID tuning	MATLAB	Simulated data	Faster convergence
Chen et al.	2022	Genetic Algorithm	Converter optimization	Lab prototype	Battery dataset	Efficiency improvement
Ahmed et al.	2021	Ant Colony Optimization	Parameter tuning	Simulation	Synthetic data	Improved convergence
Patel et al.	2022	PIDD2 Controller	Advanced controller	MATLAB	Simulated data	Better transient response
Sharma et al.	2023	PIDD2-PD	Hybrid controller	Simulation	Synthetic data	Stability enhancement
Mehta et al.	2023	PSO-GA	Hybrid optimization	MATLAB	Simulated data	Improved accuracy
Rao et al.	2022	FA-DE	Hybrid algorithm	Simulation	Synthetic data	Reduced error
Nair et al.	2023	Adaptive Control	PV-EV integrated system	MATLAB	Solar dataset	Improved energy management
Bose et al.	2022	Bidirectional Control	V2G charger	Simulation	Grid data	Grid support capability
Lee et al.	2021	SiC Devices	Power converter	Hardware	Experimental data	Improved efficiency
Kim et al.	2022	GaN Devices	High-frequency converter	Hardware	Experimental data	Increased power density
Fernandez et al.	2023	Real-time Simulation	EV charger	OPAL-RT	Real-time data	System validation
Gupta et al.	2023	Hardware-in-the-Loop Testing	Charger system	HIL platform	Mixed data	Realistic validation
Jain et al.	2023	Neural Networks	Predictive control	MATLAB	Synthetic data	Stability improvement

Comparative Analysis

The comparative analysis of the reviewed studies reveals a progressive evolution from conventional control strategies to advanced intelligent and hybrid optimization-based approaches in dual-stage interleaved onboard chargers. Early works predominantly relied on classical PID and PI controllers, which, while simple and easy to implement, exhibited limitations in handling nonlinear dynamics and rapid transients. The introduction of intelligent control techniques such as fuzzy logic and neural networks marked a significant improvement in adaptability and robustness, although these methods often required complex design and training processes.

Metaheuristic optimization techniques such as PSO, GA, and ACO have been widely adopted for controller tuning, offering improved convergence and performance compared to traditional methods. However, individual algorithms often suffer from issues such as premature convergence and limited exploration capability. This has led to the development of hybrid optimization frameworks that combine the strengths of multiple algorithms. Techniques such as PSO-GA and FA-DE have demonstrated enhanced performance in terms of convergence speed, accuracy, and stability.

A notable trend in recent research is the emergence of novel bio-inspired and socio-political optimization algorithms, including the Genghis Khan, Shark, and Gold Rush algorithms. These methods introduce unique mechanisms for exploration and exploitation, enabling efficient search in complex parameter spaces. The integration of these algorithms into hybrid frameworks such as HAGK-SGR has resulted in significant improvements in system performance, particularly in terms of THD reduction, power factor correction, and transient response.

In terms of hardware advancements, the adoption of wide bandgap semiconductor devices such as SiC and GaN has played a crucial role in enhancing converter efficiency and power density. These devices enable higher switching frequencies and reduced losses, contributing to more compact and efficient onboard chargers. Additionally, the use of advanced simulation and validation platforms such as OPAL-RT and HIL systems has facilitated accurate performance evaluation and accelerated development.

Dataset usage in the literature varies from synthetic simulation data to real-time experimental datasets, with increasing emphasis on realistic validation scenarios. Studies incorporating renewable energy datasets and grid data highlight the growing importance of integrated energy systems and smart grid interaction. Overall, the literature indicates a clear shift toward intelligent, adaptive, and hybrid optimization-based control strategies, paving the way for next-generation EV charging systems with enhanced performance, reliability, and scalability.

Discussion

The rapid advancement of dual-stage interleaved onboard chargers integrated with intelligent control and optimization techniques has significantly transformed electric vehicle charging systems. The reviewed studies clearly indicate that the transition from conventional PI and PID controllers toward adaptive frameworks such as the PIDD2-PD controller provides major improvements in stability, transient response, and disturbance rejection capability. These advancements are particularly important in modern EV charging environments characterized by fluctuating grid conditions, nonlinear converter dynamics, and renewable energy integration. The dual-stage interleaved architecture further enhances system efficiency by reducing current ripple, distributing thermal stress, and improving power quality, making it highly suitable for next-generation electric vehicle applications.

A major contribution identified in the literature is the effectiveness of hybrid optimization algorithms for controller parameter tuning and multi-objective performance enhancement. Techniques such as the Hybrid Adaptive Genghis Khan Shark Gold Rush (HAGK-SGR) algorithm combine global exploration and local exploitation capabilities to optimize complex nonlinear systems efficiently. Compared with conventional optimization methods, hybrid approaches achieve faster convergence, improved robustness, and better harmonic reduction while maintaining high power factor and voltage stability. These characteristics are critical for real-time EV charging applications where rapid adaptation and reliable performance are essential. The integration of wide-bandgap semiconductor devices such as silicon carbide and gallium nitride further complements these control strategies by improving switching efficiency, reducing losses, and enabling compact charger designs.

Despite these advancements, several challenges remain unresolved. Hybrid optimization algorithms often require high computational resources, creating implementation difficulties in embedded automotive systems with limited processing capability and memory. In addition, many existing studies rely heavily on simulation environments rather than real-world experimental validation, limiting the practical evaluation of proposed methods. The absence of standardized datasets and benchmarking frameworks also complicates fair performance comparison among different control and optimization strategies. Furthermore, integrating EV charging systems with smart grids and renewable energy infrastructures introduces additional complexity related to decentralized coordination, communication reliability, and energy management.

Overall, the reviewed research demonstrates that combining dual-stage interleaved charger architectures with PIDD2-PD control and hybrid adaptive optimization provides a highly promising solution for intelligent EV charging systems. Future developments should focus on lightweight optimization methods, real-time hardware implementation, standardized testing platforms, and AI-driven adaptive charging strategies to enhance scalability, affordability, and commercial deployment in sustainable smart transportation ecosystems.

Conclusion

The rapid expansion of electric vehicle technology has increased the need for efficient, intelligent, and reliable onboard charging systems capable of operating under dynamic grid and battery conditions. This review examined recent advances in dual-stage interleaved onboard chargers integrated with PIDD2-PD controllers and Hybrid Adaptive Genghis Khan Shark Gold Rush (HAGK-SGR) optimization techniques. The findings indicate that dual-stage interleaved architectures significantly improve charging efficiency, reduce current ripple, minimize thermal stress, and enhance power quality, making them highly suitable for modern EV charging applications. The PIDD2-PD controller further improves transient response, voltage regulation, and disturbance rejection compared to traditional PI and PID controllers.

The review also highlights the effectiveness of hybrid optimization algorithms in tuning complex controller parameters. The HAGK-SGR framework combines global exploration and adaptive local search mechanisms to achieve faster convergence, improved robustness, and better harmonic reduction under varying operating conditions. In addition, wide-bandgap semiconductor devices such as silicon carbide and gallium nitride contribute to higher switching efficiency, compact charger design, and improved thermal performance.

Despite these advancements, challenges including computational complexity, real-time implementation constraints, and lack of standardized benchmarking frameworks remain unresolved. Future research should focus on lightweight AI-driven optimization methods, real-time hardware implementation, renewable-integrated charging systems, and smart-grid-compatible charging infrastructures to support sustainable and intelligent electric transportation systems.

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