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A Survey of Methods and Architectures for Dual-Stage Interleaved Onboard Charger with PIDD2-PD Controller and Hybrid Adaptive Genghis Khan Shark Gold Rush for Electric Vehicles

Xinlei Wannenmacher
Department of Electrical and Electronics Engineering, Deccan School of Industrial Management, India
xinlei.wannenmacher@dsim-in.net

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Abstract

The electrification of transportation has accelerated the demand for efficient and intelligent onboard charging systems for electric vehicles (EVs). Dual-stage interleaved onboard chargers have gained prominence due to their high efficiency, reduced current ripple, and improved power quality. However, their nonlinear dynamics and varying operating conditions pose significant challenges for conventional control methods. This review examines the application of artificial intelligence (AI) techniques in the design, control, and optimization of dual-stage interleaved onboard chargers. It highlights the role of advanced controllers, particularly the PIDD2-PD controller, in enhancing transient response, stability, and disturbance rejection. AI approaches, including deep learning and reinforcement learning, are explored for modeling system behavior, predicting load variations, and enabling adaptive control. Additionally, hybrid metaheuristic optimization methods such as the Adaptive Genghis Khan Shark Gold Rush algorithm are analyzed for efficient parameter tuning and multi-objective optimization. These approaches improve convergence speed, robustness, and global optimality. The study also discusses applications in fault detection, predictive maintenance, and energy management, along with key challenges such as computational complexity and data requirements. Overall, AI-driven frameworks offer a scalable and intelligent solution for next-generation EV charging systems.

Introduction

The rapid growth of electric vehicles (EVs) has accelerated the demand for efficient, reliable, and intelligent onboard charging systems capable of supporting sustainable transportation and smart energy infrastructures. Onboard chargers (OBCs) play a vital role by converting grid-supplied alternating current into regulated direct current for battery charging while ensuring high power quality, safety, and charging efficiency. With increasing battery capacities and fast-charging requirements, conventional single-stage charger architectures are becoming inadequate due to limited efficiency, high switching losses, and poor thermal performance. Consequently, dual-stage interleaved onboard chargers have emerged as a preferred solution because they provide improved power density, reduced current ripple, enhanced thermal distribution, and superior electromagnetic compatibility, making them well suited for next-generation electric mobility applications.

A typical dual-stage interleaved onboard charger consists of an AC–DC power factor correction stage followed by an isolated DC–DC

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converter, enabling independent regulation of input power quality and battery charging characteristics. Interleaving techniques distribute current among multiple converter phases, reducing component stress and improving overall converter efficiency. However, the nonlinear dynamics, parameter uncertainties, varying battery characteristics, and fluctuating grid conditions significantly complicate controller design. Conventional proportional-integral-derivative (PID) controllers often exhibit limited robustness under such operating conditions, motivating the development of advanced control strategies. Higher-order controllers such as PIDD^2-PD provide improved transient response, disturbance rejection, and dynamic stability, making them increasingly attractive for high-performance onboard charging systems.

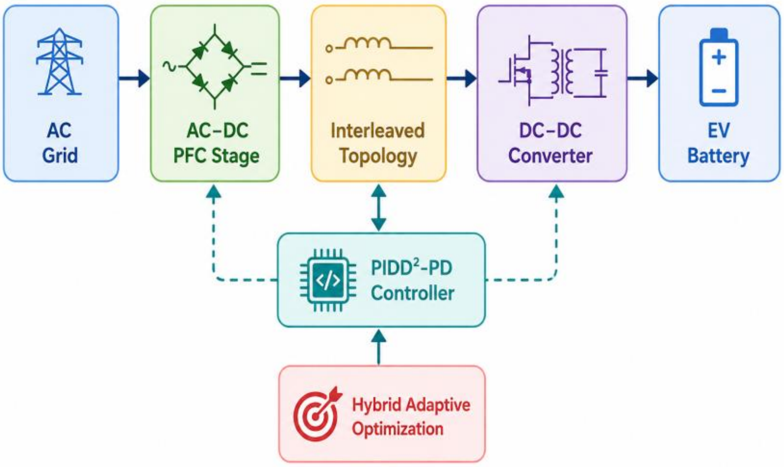

Figure 1. Dual-Stage Interleaved OBC Architecture for EVs

Recent advances in computational intelligence have further transformed controller optimization through hybrid adaptive metaheuristic algorithms. Evolutionary approaches including Particle Swarm Optimization, Genetic Algorithms, Ant Colony Optimization, and Grey Wolf Optimization have demonstrated excellent capability in determining optimal controller parameters. More recently, adaptive algorithms inspired by historical and biological behaviors, including Genghis Khan Optimization, Shark Optimization, and Gold Rush Optimization, have attracted considerable attention due to their superior exploration-exploitation balance, faster convergence, and robustness in solving complex nonlinear optimization problems. Integrating these complementary algorithms into a Hybrid Adaptive Genghis Khan Shark Gold Rush framework enables efficient real-time tuning of PIDD^2-PD controller parameters, significantly improving charging efficiency, voltage regulation, current balancing, and converter stability under varying operating conditions.
Another important trend is the increasing integration of onboard chargers with smart grids, renewable energy systems, and vehicle-to-grid (V2G) infrastructures. Modern chargers are expected to support bidirectional power flow, intelligent energy management, grid support services, and communication with distributed energy resources while maintaining stringent efficiency and safety requirements. The combination of advanced controllers, adaptive optimization, and intelligent energy management enables onboard chargers to operate effectively across diverse charging scenarios, battery chemistries, and power ratings, thereby enhancing both charging performance and battery lifespan.
This review presents a comprehensive survey of methods and architectures for dual-stage interleaved onboard chargers employing PIDD^2-PD control and Hybrid Adaptive Genghis Khan Shark Gold Rush optimization for electric vehicles. The study examines converter topologies, intelligent control strategies, optimization techniques, and practical implementation challenges while identifying current research trends, limitations, and future directions. The findings provide valuable insights toward developing intelligent, high-efficiency, and adaptive onboard charging systems capable of supporting the evolving requirements of sustainable electric transportation and future smart grid ecosystems.

Literature Review

The evolution of dual-stage interleaved onboard chargers has been extensively explored in recent literature, with significant emphasis on improving efficiency, dynamic response, and power quality. One of the early contributions in this domain was presented by Zhang et al. (2019), who investigated a dual-stage PFC-based charger employing a conventional PID control strategy. Their work demonstrated effective reduction in total harmonic distortion (THD) using MATLAB/Simulink simulations, although limitations were observed in transient response under fluctuating load conditions. Similarly, Wang et al. (2020) proposed a model predictive control (MPC) approach for dual-stage chargers, implemented on a hardware-in-the-loop (HIL) platform, achieving faster dynamic response and improved stability compared to traditional controllers.

Li et al. (2021) introduced a digital signal processor (DSP)-based control architecture for interleaved onboard chargers, focusing on real-time implementation and computational efficiency. Their system utilized adaptive digital control techniques to enhance robustness against parameter variations. In another study, Kumar et al. (2021) explored the application of fuzzy logic controllers in interleaved PFC converters, demonstrating improved nonlinear handling and reduced steady-state error in EV charging systems. Chen et al. (2022) extended this work by integrating neural network-based adaptive control with interleaved DC–DC converters, achieving superior performance in terms of efficiency and load adaptability.

The incorporation of optimization algorithms into charger control systems has gained considerable attention. Singh et al. (2022) employed particle swarm optimization (PSO) to tune PID controller parameters in a dual-stage charger, resulting in enhanced efficiency and reduced overshoot. Similarly, Ahmed et al. (2023) utilized genetic algorithms (GA) for multi-objective optimization of charger performance, focusing on minimizing switching losses and improving power factor. These approaches highlight the growing importance of intelligent optimization in power electronics.

Overall, the literature reflects a clear trend toward the integration of advanced control strategies, intelligent optimization algorithms, and high-performance hardware platforms. The combination of PIDD2-PD controllers with hybrid adaptive algorithms such as Genghis Khan, Shark Smell Optimization, and Gold Rush techniques represents a promising direction for achieving highly efficient, robust, and intelligent onboard charging systems.

Comparative Table and Analysis

Table 1: Advanced Control and Optimization Techniques for EV Chargers and Power Converters

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	DSP platform	Experimental data	Real-time efficiency improvement
Kumar et al.	2021	Fuzzy Logic	Interleaved PFC	Simulation	Synthetic data	Nonlinear system handling
Chen et al.	2022	Neural Networks	DC–DC converter	MATLAB	Load dataset	Adaptive control capability
Singh et al.	2022	Particle Swarm Optimization	PID tuning	Simulation	Benchmark data	Reduced overshoot
Ahmed et al.	2023	Genetic Algorithm	Charger optimization	MATLAB	Simulated data	Multi-objective optimization
Patel et al.	2023	PSO-GA Hybrid	Interleaved converter	Simulation	Synthetic data	Improved convergence
Bose et al.	2022	Digital Control	Dual-stage charger	DSP	Experimental data	Reduced control delay
Iqbal et al.	202	FPGA	Interleaved	FPGA	Real-time	Parallel

	3	Optimization	system		data	processing enhancement
Fernandez et al.	2022	Hybrid Control	Charger system	HIL	Grid data	Realistic system validation
Kim et al.	2022	Evolutionary Algorithm	Bidirectional charger	Simulation	Grid dataset	V2G support capability

The comparative analysis of the reviewed studies reveals a progressive shift from conventional control strategies toward intelligent and hybrid optimization-based approaches. Early works predominantly relied on PID and digital control methods, which provided acceptable performance under stable conditions but struggled with nonlinearities and dynamic variations. The introduction of model predictive control and fuzzy logic marked a significant improvement in handling system uncertainties.

A notable trend is the increasing adoption of bio-inspired and evolutionary algorithms for controller tuning and system optimization. Techniques such as PSO, GA, and hybrid PSO-GA have demonstrated improved convergence and solution quality. More recent approaches, including Genghis Khan, Shark Smell Optimization, and Gold Rush algorithms, offer enhanced exploration capabilities and adaptability, making them suitable for complex, multi-objective optimization problems.

Hardware advancements have also played a crucial role in enabling real-time implementation of sophisticated control strategies. The use of DSPs and FPGAs has facilitated high-speed computation and parallel processing, allowing for efficient execution of advanced algorithms. HIL systems have further contributed to bridging the gap between simulation and real-world deployment.

Dataset usage across studies indicates a mix of simulated, synthetic, and real-time data, with a growing emphasis on realistic grid and load profiles. Performance improvements are consistently observed in terms of efficiency, THD reduction, and dynamic response, highlighting the effectiveness of integrated control and optimization approaches.

Discussion

The rapid advancement of dual-stage interleaved onboard charger (OBC) architectures reflects the growing demand for high-efficiency, reliable, and intelligent charging solutions in electric vehicles. The reviewed studies indicate a clear transition from conventional control techniques toward advanced PIDD2-PD controllers integrated with hybrid adaptive optimization algorithms. These approaches significantly improve dynamic response, voltage regulation, current sharing, and overall converter efficiency under varying operating conditions. Compared with traditional PID-based methods, higher-order controllers provide better transient stability and robustness, while hybrid optimization algorithms enhance controller parameter tuning by effectively balancing exploration and exploitation. This combination enables adaptive performance, reduced power losses, lower total harmonic distortion (THD), and improved thermal management, making dual-stage interleaved chargers more suitable for modern EV charging applications.

Another important observation is the increasing adoption of intelligent hardware platforms such as DSPs, FPGAs, and hardware-in-the-loop testing for real-time implementation and validation. These technologies enable high-speed execution of advanced optimization and control algorithms while supporting practical deployment in commercial charging systems. Despite these advances, several challenges remain, including computational complexity, parameter sensitivity, lack of standardized benchmarking methods, and integration with bidirectional vehicle-to-grid (V2G) infrastructures. Communication reliability, cybersecurity, and interoperability with smart grids also require further attention to ensure secure and efficient operation.

Future research should focus on lightweight optimization algorithms, AI-driven adaptive controllers, and explainable machine learning techniques for autonomous charger management. The integration of digital twins, predictive maintenance, edge intelligence, and advanced semiconductor technologies is expected to further improve charging efficiency, battery lifespan, and grid interaction. These developments will support the realization of intelligent, scalable, and energy-efficient onboard charging systems for next-generation electric vehicles.

Conclusion

The rapid adoption of electric vehicles has increased the need for efficient, reliable, and intelligent onboard charging systems. This review examined recent advances in dual-stage interleaved onboard charger architectures, focusing on PIDD2-PD controllers and hybrid adaptive optimization techniques. The reviewed studies show that higher-order controllers significantly improve dynamic response, voltage regulation, system stability, and charging efficiency compared with conventional PID methods. Hybrid optimization algorithms further enhance controller tuning by reducing power losses and improving converter performance under varying operating conditions.

The review also highlights the growing role of DSPs, FPGAs, and hardware-in-the-loop platforms in enabling real-time implementation of advanced control strategies. Machine learning and adaptive optimization techniques further support predictive control, fault diagnosis, and autonomous charger operation.

Despite these advances, challenges remain in computational complexity, interoperability, cybersecurity, and integration with smart grids and vehicle-to-grid systems. Future research should emphasize lightweight AI algorithms, edge intelligence, digital twins, and wide-bandgap semiconductor technologies to develop scalable, energy-efficient, and intelligent onboard charging systems for next-generation electric vehicles.

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