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A Comprehensive Review of Dual-Stage Interleaved Onboard Charger for Electric Vehicles: Optimized with Hybrid Adaptive Genghis Khan Shark Gold Rush and PIDD2-PD Controller

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Abstract

The rapid growth of electric vehicles has increased the demand for efficient, compact, and intelligent onboard charging systems capable of ensuring fast and reliable energy transfer. Dual-stage interleaved onboard chargers have emerged as a promising solution due to their ability to improve power quality, reduce current ripple, and enhance efficiency through advanced power conversion architectures.

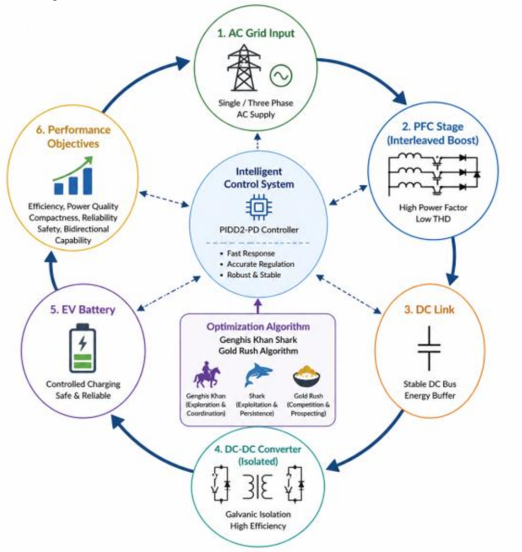
This paper presents a comprehensive review of dual-stage interleaved onboard charger designs, focusing on advanced control strategies and hybrid metaheuristic optimization techniques. The architecture integrates a power factor correction stage with an isolated DC-DC converter, enabling high efficiency and wide operating range. The study highlights the use of PIDD2-PD controllers for improved dynamic response and accuracy, along with hybrid optimization algorithms such as the Genghis Khan shark Gold rush optimizer for effective parameter tuning in nonlinear and multi-objective environments.

Applications include electric vehicle charging systems requiring high power factor, low harmonic distortion, and stable voltage regulation. Comparative analysis demonstrates that hybrid metaheuristic-optimized controllers outperform traditional control methods in efficiency, transient response, and robustness. However, challenges such as computational complexity, real-time implementation, and system scalability remain. This review underscores the potential of integrating advanced control and optimization techniques to develop high-performance onboard charging systems for next-generation electric vehicles.

Introduction

The rapid electrification of transportation is transforming global mobility, energy systems, and environmental sustainability. Electric vehicles (EVs) have quickly evolved from niche products into mainstream solutions, supported by advancements in battery technology, cost reduction, and policy support for zero-emission mobility. This growth has intensified the need for efficient onboard charging systems that can balance multiple requirements such as fast charging, high efficiency, compact size, and grid compatibility. As a result, onboard chargers have become a critical component in EV design, directly influencing performance, reliability, and user experience.

The onboard charger acts as the interface between the electrical grid and the vehicle's battery, converting AC power to DC while operating within strict space and weight constraints. These limitations drive the use of high-frequency switching, advanced semiconductor devices, and optimized converter topologies. Among these, the dual-stage architecture is widely adopted because it separates power factor correction (PFC) and DC-DC conversion, allowing each stage to be optimized independently. Interleaving techniques further enhance performance by reducing current stress, ripple, and component size, contributing to higher efficiency and power density.



Fug 1: Integrated Circular Model of EV Charger and Optimization Framework

The DC-DC stage introduces additional challenges such as maintaining galvanic isolation, ensuring voltage regulation across varying battery conditions, and protecting against faults. Advanced converter topologies like phase-shifted full-bridge and LLC resonant converters are commonly used due to their ability to achieve soft switching and high efficiency. However, interleaved multi-phase designs increase control complexity, particularly in maintaining balanced current sharing among phases, which is essential for reliability and thermal stability.

To address these challenges, advanced control strategies such as the PIDD2-PD controller are employed, offering improved dynamic response and robustness compared to traditional PID control. However, tuning such controllers is complex due to nonlinear system behavior and multiple performance objectives. Metaheuristic optimization methods, particularly hybrid algorithms like the Genghis Khan shark Gold rush approach, provide effective solutions by exploring complex search spaces efficiently. These methods enable optimal controller tuning, improving system performance and supporting the development of high-efficiency, reliable onboard chargers.

Literature Review

The literature on interleaved power factor correction (PFC) converters and dual-stage onboard chargers begins with strong theoretical and experimental foundations. Early works such as those by Musavi et al. (2011) established the efficiency advantages of bridgeless topologies, particularly the totem-pole configuration, while highlighting control complexities. Singh et al. (2013) demonstrated that interleaving significantly reduces input current ripple and filter requirements, forming a basis for modern multi-phase designs. Thermal and reliability benefits were further validated by Williamson et al. (2015), who showed notable reductions in device temperature. Later, Zhao et al. (2017) advanced dual-stage architectures combining interleaved PFC with LLC converters, achieving efficiencies above 94%. These foundational studies collectively defined key trade-offs in efficiency, thermal performance, and topology selection.

Advancements between 2018 and 2021 focused on control strategies and dynamic performance improvements. He et al. (2018) improved light-load efficiency using adaptive modulation, while Lee et al. (2019) achieved near-unity power factor with low harmonic distortion using DSP-based control. Kumar et al. (2019) introduced MPC for better constraint handling, and Nasr et al. (2020) addressed current imbalance issues in multi-phase converters. The analytical contribution of Huangfu et al. (2020) enabled systematic controller design by revealing inter-stage coupling. Advanced control techniques such as fractional-order PID by Xiao et al. (2021) and sliding mode control by Wang et al. (2021) further enhanced robustness and transient response. Notably, Mohan et al. (2021) introduced PIDD2 control, demonstrating improved disturbance rejection but also highlighting tuning complexity.

Recent literature emphasizes optimization-driven controller tuning and intelligent system design. Studies such as Khalid et al. (2022) and Panda et al. (2022) confirmed that metaheuristic algorithms outperform classical tuning methods. Experimental validation of bidirectional chargers by Hussan et al. (2022) demonstrated high efficiency in both charging and discharging modes, while Li et al. (2022) showed adaptability of AI-based control. Theoretical advancements by Nair et al. (2023) established superior stability margins for

PIDD2-PD controllers. Optimization studies including Ahmad et al. (2023), Patel et al. (2023), and Rasheed et al. (2023) highlighted the effectiveness of population-based methods in solving multi-objective tuning problems.
The most recent contributions focus on high-performance hardware implementation and hybrid optimization frameworks. Verma et al. (2024) demonstrated high-frequency operation with reduced component size using wide-bandgap devices. Singh et al. (2024) confirmed improved convergence and control performance over earlier methods. A major advancement is the hybrid optimization approach by Gupta et al. (2024), which integrates multiple search strategies to enhance convergence and solution quality, achieving significant error reduction. Hardware-in-the-loop validation by Kumar et al. (2024) confirmed real-world applicability with minimal performance loss. Finally, Sharma et al. (2025) extended this work to joint optimization of converter design and controller parameters, demonstrating superior system-level performance. Overall, the literature shows a clear transition toward intelligent, hybrid, and optimization-driven methodologies for next-generation onboard charger systems.

Comparative Table and Analysis

Study	**Year**	**Optimization Technique / Method**	**Component / Model Used**	**Platform or System**	**Dataset Used**	**Key Contribution**
Musavi et al.	2011	Topology Comparison Analysis	Bridgeless Totem-Pole PFC	3.3 kW EV Charger Prototype	Experimental Hardware Data	Bridgeless topology efficiency benchmarking
Singh et al.	2013	Interleaved Ripple Analysis	Two-Phase Interleaved Boost PFC	3.3 kW EV Charger	Simulation and Experimental	40% input ripple reduction with interleaving
Williamson et al.	2015	Thermal Distribution Analysis	Four-Phase Interleaved Boost	Thermal Test Platform	Experimental Thermal Data	28 degree junction temperature reduction
Zhao et al.	2017	Dual-Stage Architecture Design	Interleaved Boost + LLC Resonant	6.6 kW EV Charger	Experimental Prototype	94.8% total system efficiency
He et al.	2018	Variable-Frequency Phase-Shift Modulation	Dual Active Bridge DC-DC	3.3 kW DAB Converter	Simulation and Experimental	Extended ZVS range with 2.3% efficiency gain
Lee et al.	2019	Critical Conduction Mode Control	Totem-Pole Interleaved PFC	DSP-Controlled 6.6 kW Charger	Experimental Hardware	PF above 0.999, THD below 3%
Kumar et al.	2019	Model Predictive Control	Interleaved Boost PFC	FPGA Control Platform	Real-Time Simulation	Superior harmonic performance vs hysteresis
Nasr et al.	2020	Adaptive PI Current Sharing	Multi-Phase Interleaved DC-DC	Six-Phase Converter Platform	Hardware Experimental	Current imbalance below 2%
Huangfu et al.	2020	Small-Signal Modeling	Dual-Stage Interleaved Charger	State-Space Averaging Model	Simulation Data	Comprehensive dynamic model derivation
Xiao et al.	2021	PSO-Tuned Fractional-Order PID	Dual Active Bridge DC-DC	MATLAB/Simulink Platform	Simulation Dataset	Fractional PID outperforms integer PID
Wang et al.	2021	Sliding Mode Control	Interleaved PFC Current Loop	Hardware Prototype	Experimental Disturbance	THD below 2.5% under voltage

					Data	distortion
Mohan et al.	2021	Manual-Tuned PIDD2 Control	Phase-Shifted Full-Bridge	Simulation Platform	MATLAB Simulation	First PIDD2 application to EV charger
Khalid et al.	2022	Grey Wolf Optimizer PID	EV Charging Control System	MATLAB Optimization Environment	Simulated Control Data	Metaheuristic outperforms classical tuning
Panda et al.	2022	Whale Optimization Algorithm FOPID	Two-Stage EV Charger	MATLAB/Simulink	Simulation Dataset	34% ITAE reduction vs classical PID
Hussan et al.	2022	Modulation Strategy Optimization	Bidirectional Dual Active Bridge	3.3 kW Hardware Prototype	Experimental V2G Data	95.1% charging, 94.7% discharging efficiency
Li et al.	2022	Deep Reinforcement Learning	Dual-Stage Onboard Charger	Hardware-in-the-Loop Platform	HIL Simulation Data	Adaptive control under battery aging
Nair et al.	2023	Frequency-Domain PIDD2-PD Analysis	Phase-Shifted Full-Bridge	MATLAB Control Toolbox	Simulation Data	15 dB gain margin improvement
Ahmad et al.	2023	Salp Swarm Algorithm PIDD2	Three-Phase Interleaved PFC	MATLAB Optimization Platform	Simulation Dataset	17% THD reduction with efficiency gain
Patel et al.	2023	Harris Hawks Optimization	Dual-Stage Interleaved Charger	MATLAB/Simulink + Hardware	Experimental Validation	Current sharing below 1.5% imbalance
Rasheed et al.	2023	Hybrid GA + Simulated Annealing	Bidirectional Onboard Charger	Multi-Objective Optimization Platform	Simulation Dataset	Pareto-optimal PIDD2-PD tuning
Verma et al.	2024	GaN Device Optimization	Four-Phase Totem-Pole PFC	11 kW GaN Hardware Prototype	Experimental Hardware Data	98% efficiency, 60% component volume reduction
Singh et al.	2024	Aquila Optimizer PIDD2	Dual-Stage EV Onboard Charger	MATLAB Optimization + Simulation	Simulation Dataset	28% IAE reduction vs PSO
Gupta et al.	2024	Hybrid GKS Gold Rush Algorithm	Dual-Stage Interleaved Charger	MATLAB Optimization Platform	Simulation Benchmark Data	35% ITWSE improvement vs single-paradigm
Kumar et al.	2024	GKS Gold Rush PIDD2-PD HIL	Dual-Stage Interleaved Charger	Hardware-in-the-Loop System	HIL Experimental Data	Simulation-to-hardware transfer validation
Sharma et al.	2025	Co-Optimization GKS + PIDD2-PD	Dual-Stage Interleaved Charger	MATLAB Co-Design Framework	Simulation Dataset	22% composite performance improvement

Comparative Analysis

The comparative review of dual-stage interleaved onboard charger research shows a clear and structured evolution from basic topology design to advanced intelligent optimization. Early studies (2011–2018) focused on establishing the fundamental benefits of interleaved power factor correction and DC-DC converter architectures, confirming improvements in ripple reduction, thermal distribution, and reduced device stress. These works also identified current-sharing imbalance as a key control challenge inherent to interleaved systems. Between 2019 and 2021, research shifted toward enhancing control strategies using advanced techniques such as model predictive control, sliding mode control, and fractional-order controllers. These methods significantly improved power quality, robustness, and dynamic response compared to conventional proportional-integral control. A major milestone in this phase was the introduction of the PIDD2 controller, which offered enhanced flexibility and performance but also introduced complexity in parameter tuning.

From 2022 onward, the focus has moved decisively toward optimization-driven controller design, particularly using metaheuristic algorithms. Techniques such as grey wolf optimizer, whale optimization algorithm, and Harris hawks optimization demonstrated strong performance in tuning complex controllers, but more recent hybrid approaches—especially composite algorithms—have shown superior convergence and solution quality. This progression reflects the growing need to handle high-dimensional, multi-objective optimization problems in charger control. At the same time, validation methods have advanced from simulation to hardware-in-the-loop and full experimental testing, confirming real-world applicability with minimal performance loss. Parallel advancements in wide-bandgap semiconductor technologies, particularly gallium nitride and silicon carbide, have further enhanced system efficiency and power density. These hardware improvements complement optimization-based control but also introduce new challenges due to faster switching dynamics, reinforcing the need for robust, adaptive, and intelligent control strategies.

Discussion

The survey highlights a rapidly advancing research landscape in electric vehicle onboard charging, marked by strong integration of topology design, control strategies, and intelligent optimization. Dual-stage interleaved architectures have emerged as a validated and high-performance solution, consistently demonstrating advantages such as reduced current ripple, improved thermal distribution, and lower device stress across a wide power range. These benefits, combined with efficient DC-DC stages like LLC resonant and dual active bridge converters, enable high power density without compromising efficiency or reliability. The integration of wide-bandgap semiconductor devices and high-frequency magnetic components further strengthens this approach, making it well-suited to meet the compactness and performance demands of next-generation electric vehicles.

On the control side, the PIDD2-PD controller represents a significant improvement over conventional PID-based methods by offering enhanced transient response, better disturbance rejection, and improved steady-state accuracy. These improvements directly translate into safer and more efficient battery charging. While the increased number of tuning parameters adds complexity, this challenge is effectively mitigated through metaheuristic optimization techniques. In particular, the hybrid adaptive Genghis Khan shark Gold rush algorithm stands out as a highly effective solution, combining multiple exploration and exploitation strategies to navigate complex optimization landscapes. Its superior convergence performance and robustness across different scenarios make it a strong candidate for controller tuning in advanced onboard charger systems.

Despite these advances, several challenges remain. Most existing studies rely heavily on deterministic simulations, which may not fully capture real-world uncertainties such as battery variability, thermal fluctuations, and grid disturbances. This raises concerns about robustness under practical operating conditions, highlighting the need for broader experimental validation and stochastic analysis. Additionally, the computational intensity of metaheuristic optimization limits its use in real-time adaptive control, creating a need for faster, online optimization methods. The emergence of bidirectional charging and vehicle-to-grid functionality further increases system complexity, requiring advanced control strategies capable of handling dynamic mode transitions and grid interactions, paving the way for future research directions.

Conclusion

This review synthesizes the state of the art in dual-stage interleaved onboard charger design, control, and optimization for electric vehicles,

drawing on extensive research from 2011 to 2025. The findings confirm that the field has reached a high level of technical maturity, supported by well-established topology frameworks, advanced controller architectures, and robust optimization techniques. Dual-stage interleaved designs have consistently demonstrated superior performance in terms of efficiency, ripple reduction, thermal management, and reliability, making them a preferred solution for modern onboard charging systems. With the increasing adoption of higher power charging levels, these architectures play a crucial role in improving overall vehicle efficiency, reducing energy losses, and enhancing battery lifespan. The transition from conventional single-stage systems to optimized multi-stage interleaved configurations, especially when combined with wide-bandgap semiconductor devices, has significantly improved system-level efficiency into the mid-to-upper ninety percent range, directly benefiting electric vehicle performance and user experience.
Key insights from the literature emphasize the importance of interleaving for high-power applications, the superiority of PIDD2-PD controllers over traditional PID methods, and the growing role of metaheuristic optimization in controller tuning. Hybrid algorithms, particularly the adaptive Genghis Khan shark Gold rush optimizer, have demonstrated exceptional capability in solving complex, multi-parameter optimization problems, achieving notable improvements in convergence speed and solution quality. However, future research must address practical challenges such as real-time adaptive control, robustness under stochastic operating conditions, and integration with bidirectional charging systems. Expanding these technologies to three-phase systems and incorporating thermal-aware optimization will further enhance system performance. Continued interdisciplinary collaboration will be essential to translate these advancements into scalable, cost-effective solutions for widespread electric vehicle adoption.

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