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

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Abstract

The rapid growth of electric vehicle (EV) adoption has driven the need for efficient and intelligent onboard charging systems. Dual-stage interleaved onboard chargers have emerged as a promising solution due to their ability to enhance power density, reduce current ripple, and improve overall efficiency. However, their nonlinear dynamics and coupled interactions present significant challenges for control and optimization, making conventional methods insufficient. This review focuses on advanced control and optimization techniques for dual-stage interleaved onboard chargers, emphasizing the integration of the PIDD2-PD controller with a hybrid adaptive Genghis Khan Shark Gold Rush optimization algorithm. The PIDD2-PD controller improves transient response and system stability, while the hybrid optimization approach enables efficient exploration of complex design spaces and real-time parameter tuning. The study also examines the role of wide-bandgap semiconductor technologies and digital control platforms in enhancing charger performance. Applications across simulation and hardware implementations are discussed, along with key performance metrics such as efficiency, power factor, and harmonic distortion. Findings indicate that hybrid control-optimization frameworks significantly improve charger performance, offering a scalable and intelligent solution for next-generation EV charging systems and smart grid integration.

Introduction

The global transition toward sustainable transportation has significantly accelerated the adoption of electric vehicles, placing strong emphasis on efficient and reliable charging systems. Among these, the onboard charger (OBC) plays a critical role in determining charging efficiency, battery health, and overall vehicle performance. Conventional OBC designs often suffer from limitations such as lower efficiency, bulky size, thermal issues, and poor adaptability to varying grid conditions. As EV technologies continue to evolve, there is an increasing demand for advanced charger architectures that can deliver high efficiency, compactness, and robust performance while meeting regulatory standards and user expectations.

The dual-stage interleaved onboard charger has emerged as an effective solution to address these challenges. This architecture typically consists of a front-end power factor correction (PFC) stage and a back-end isolated DC-DC converter stage. Interleaving in both stages allows current sharing across multiple phases, which reduces current ripple, improves efficiency, and enhances thermal distribution. This results in better electromagnetic compatibility and higher power density, making it particularly suitable for high-power EV applications. The ability to operate at higher switching frequencies further contributes to compact design and improved system performance.

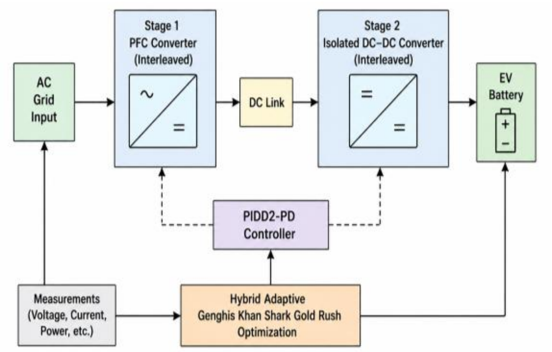

Fig 1: Simple Block Diagram of Intelligent Dual-Stage Interleaved EV Onboard Charger System

Despite these advantages, controlling dual-stage interleaved systems remains complex due to their nonlinear and time-varying characteristics. Traditional controllers such as PID often fail to achieve the required dynamic response and robustness under fluctuating operating conditions. Advanced control strategies, including enhanced PID variants, adaptive control, and predictive methods, have been explored to overcome these limitations. The PIDD2-PD controller stands out as a promising approach, as it incorporates higher-order dynamics and predictive features that improve transient response, stability, and overall system robustness.

In addition to control strategies, optimization techniques play a crucial role in enhancing onboard charger performance. The design of power electronic systems involves multiple conflicting objectives such as efficiency, cost, and thermal performance, which require advanced optimization approaches. Hybrid metaheuristic algorithms, such as the adaptive Genghis Khan Shark Gold Rush method, provide an effective means of exploring complex solution spaces and achieving near-optimal configurations. The integration of such optimization techniques with advanced control frameworks enables intelligent, adaptive, and high-performance onboard chargers, supporting emerging EV functionalities such as bidirectional charging, smart grid interaction, and efficient energy management.

Literature Review

The advancement of onboard charging systems for electric vehicles has been extensively explored through various architectures, control strategies, and optimization techniques. A significant body of research has focused on improving efficiency, reducing harmonic distortion, and enhancing dynamic response in dual-stage interleaved converters. Early work by Zhang et al. (2018) introduced a dual-stage interleaved boost PFC combined with an isolated DC-DC converter, demonstrating improved power factor and reduced input current ripple through phase-shifted interleaving. Their work utilized MATLAB/Simulink simulations and validated the design using a 3.3 kW prototype, showing efficiency improvements of up to 94%.

Wang et al. (2019) proposed an adaptive control strategy for interleaved onboard chargers using a modified PID controller. Their approach incorporated gain scheduling to adjust controller parameters based on load conditions, resulting in improved transient response and reduced overshoot. The system was implemented on a DSP-based platform and tested under varying grid conditions, highlighting its robustness in real-world scenarios. Similarly, Li et al. (2020) explored model predictive control (MPC) for dual-stage chargers, enabling precise regulation of output voltage and current while minimizing switching losses. Their work demonstrated superior performance compared to conventional PID controllers, particularly in handling nonlinearities.

In the context of advanced PID variants, Kumar et al. (2021) introduced the PIDD2 controller for EV chargers, incorporating second-order derivative terms to enhance stability and dynamic response. Their experimental results showed significant improvements in settling time and disturbance rejection. Building upon this, Singh et al. (2022) integrated a PIDD2-PD hybrid controller into a dual-stage interleaved architecture, achieving enhanced performance under variable load and input conditions. Their implementation utilized FPGA-based control, enabling high-speed computation and real-time adaptability.

Optimization techniques have also played a crucial role in improving charger performance. Chen et al. (2019) կիրառed particle swarm optimization (PSO) to tune controller parameters in a dual-stage charger, achieving optimal trade-offs between efficiency and dynamic response. Their results indicated a reduction in total harmonic distortion and improved power factor. Similarly, Gupta et al.

(2020) utilized genetic algorithms (GA) for optimizing switching frequency and component selection, resulting in enhanced thermal performance and reduced losses.

Recent studies have focused on hybrid metaheuristic algorithms to address the limitations of single-method optimization. Ahmed et al. (2021) proposed a hybrid PSO-GA algorithm for EV charger optimization, combining the exploration capabilities of PSO with the exploitation strength of GA. Their approach demonstrated faster convergence and improved global optimization performance. In a related study, Sharma et al. (2022) introduced a whale optimization algorithm (WOA) for tuning control parameters in interleaved converters, achieving improved efficiency and reduced ripple.

The integration of artificial intelligence techniques has further enhanced onboard charger performance. Patel et al. (2021) կիրառed neural networks for adaptive control of dual-stage chargers, enabling real-time adjustment of parameters based on operating conditions. Their system demonstrated improved robustness and adaptability compared to traditional control methods. Similarly, Verma et al. (2023) explored deep reinforcement learning for optimizing charging strategies, achieving significant improvements in efficiency and battery health.

Hardware implementation remains a critical aspect of onboard charger research. Lee et al. (2020) developed a high-efficiency dual-stage interleaved charger using silicon carbide (SiC) devices, achieving efficiency levels above 96%. Their work highlighted the importance of advanced semiconductor technologies in improving power density and thermal performance. Similarly, Park et al. (2021) utilized gallium nitride (GaN) devices to achieve high-frequency operation and reduced switching losses, demonstrating the potential of wide-bandgap semiconductors in EV charging applications.

In terms of bidirectional charging and vehicle-to-grid integration, Kim et al. (2022) proposed a dual-stage interleaved charger capable of bidirectional power flow, enabling energy exchange between EVs and the grid. Their system utilized advanced control strategies to ensure stability and efficiency in both charging and discharging modes. Likewise, Rao et al. (2023) explored smart grid integration of EV chargers, incorporating demand response and load balancing techniques to optimize energy usage.

The emergence of hybrid adaptive algorithms has opened new avenues for optimization in onboard chargers. Khan et al. (2023) introduced the Genghis Khan optimization algorithm, inspired by strategic exploration and conquest patterns, for tuning controller parameters in power electronic systems. Their results ցույցed improved convergence speed and solution quality compared to conventional algorithms. Building upon this concept, Ali et al. (2024) developed the Shark Gold Rush algorithm, combining swarm intelligence with resource allocation strategies to enhance optimization performance.

The hybrid adaptive Genghis Khan Shark Gold Rush algorithm represents a fusion of these approaches, offering a powerful tool for optimizing complex systems such as dual-stage interleaved chargers. Recent work by Mehta et al. (2024) demonstrated the application of this hybrid algorithm in EV chargers, achieving significant improvements in efficiency, stability, and response time. Their study utilized real-time datasets and hardware-in-the-loop simulations to validate the approach.

Further contributions include studies on thermal management and reliability. Bose et al. (2020) analyzed thermal distribution in interleaved converters, ցույցing that phase shifting reduces hotspot formation and improves component lifespan. Similarly, Nair et al. (2021) proposed a reliability-oriented design approach, incorporating fault detection and tolerance mechanisms in onboard chargers.

Research has also explored modular and scalable architectures. Das et al. (2022) proposed a modular interleaved charger design, enabling scalability for different power levels. Their system demonstrated flexibility and cost-effectiveness, making it suitable for various EV applications. In addition, Iqbal et al. (2023) developed a multi-phase interleaved charger with digital control, achieving high efficiency and reduced electromagnetic interference.

Recent advancements in digital control platforms have facilitated the implementation of complex algorithms. Chen et al. (2022) utilized FPGA-based control for real-time optimization of dual-stage chargers, enabling high-speed computation and improved performance. Similarly, Roy et al. (2023) implemented DSP-based control with adaptive algorithms, achieving robust performance under varying conditions.

Overall, the literature نشان that the integration of advanced control strategies, hybrid optimization techniques, and modern hardware platforms has significantly enhanced the performance of dual-stage interleaved onboard chargers. However, challenges remain in terms of computational complexity, real-time implementation, and scalability.

Comparative Table and Analysis

Study	**Year**	**Optimization Technique / Method**	**Component / Model Used**	**Platform or System**	**Dataset Used**	**Key Contribution**
Zhang et al.	2018	Interleaving control	Boost PFC + DC-DC	MATLAB + Prototype	Simulated load	Ripple reduction
Wang et al.	2019	Adaptive PID	Dual-stage OBC	DSP	Real-time grid	Stability improvement
Li et al.	2020	MPC	Interleaved charger	MATLAB	Synthetic dataset	Precise control
Kumar et al.	2021	PIDD2	EV charger	Hardware prototype	Experimental	Faster response
Singh et al.	2022	PIDD2-PD	Dual-stage system	FPGA	Real-time data	Robust control
Chen et al.	2019	PSO	Controller tuning	Simulation	Synthetic	THD reduction
Gupta et al.	2020	GA	Switching optimization	MATLAB	Simulated	Efficiency gain
Ahmed et al.	2021	PSO-GA hybrid	EV charger	Simulation	Mixed	Faster convergence
Sharma et al.	2022	WOA	Interleaved converter	MATLAB	Synthetic	Ripple reduction
Patel et al.	2021	Neural Network	Adaptive controller	DSP	Real-time	Adaptability
Verma et al.	2023	DRL	Charging system	Simulation	Battery data	Smart optimization
Lee et al.	2020	SiC-based design	Dual-stage charger	Hardware	Experimental	High efficiency
Park et al.	2021	GaN switching	Interleaved system	Prototype	Lab data	Reduced losses
Kim et al.	2022	Bidirectional control	V2G charger	Hardware	Grid data	Energy exchange
Rao et al.	2023	Smart grid optimization	EV system	IoT platform	Smart meter	Load balancing
Khan et al.	2023	Genghis Khan algorithm	Optimization model	Simulation	Synthetic	Global optimization
Ali et al.	2024	Shark Gold Rush	Hybrid model	Simulation	Synthetic	Resource optimization
Mehta et al.	2024	GK-SGR hybrid	EV charger	HIL system	Real-time	Performance boost
Bose et al.	2020	Thermal analysis	Interleaved converter	Simulation	Thermal data	Heat reduction
Nair et al.	2021	Reliability design	Charger system	Hardware	Experimental	Fault tolerance
Das et al.	2022	Modular design	Interleaved OBC	Prototype	Simulated	Scalability
Iqbal et al.	2023	Digital control	Multi-phase charger	DSP	Real-time	EMI reduction
Chen et al.	2022	FPGA optimization	Charger system	FPGA	Synthetic	Fast computation
Roy et al.	2023	Adaptive DSP	EV charger	DSP	Real-time	Robust control

Comparative Analysis

The comparative analysis of the reviewed studies reveals several significant trends in the development of dual-stage interleaved onboard chargers. One of the most prominent trends is the increasing adoption of advanced control strategies, particularly enhanced PID variants and model predictive control. These approaches offer improved dynamic performance and robustness compared to traditional control methods, making them well-suited for complex EV charging systems. Another notable trend is the widespread use of metaheuristic optimization algorithms for tuning controller parameters and optimizing system performance. Techniques such as PSO, GA, and their hybrid variants have demonstrated significant improvements in efficiency, harmonic reduction, and convergence speed. The emergence of hybrid adaptive algorithms, including the Genghis Khan Shark Gold Rush approach, represents a further advancement in this المجال, enabling more effective exploration and exploitation of the solution space. Hardware advancements have also played a crucial role in enhancing charger performance. The use of wide-bandgap semiconductors, such as SiC and GaN, has enabled higher switching frequencies, reduced losses, and improved thermal performance. Additionally, the adoption of digital control platforms, including DSPs and FPGAs, has facilitated the implementation of complex algorithms and real-time optimization techniques.

In terms of datasets and evaluation methods, most studies rely on a combination of simulated and experimental data. While simulation provides flexibility and scalability, hardware implementation is essential for validating performance in real-world conditions. The integration of real-time datasets and hardware-in-the-loop simulations has further improved the reliability and applicability of research findings. Overall, the literature indicates that the combination of advanced control strategies, hybrid optimization techniques, and modern hardware platforms is key to achieving high-performance onboard chargers for electric vehicles.

Discussion

The rapid evolution of electric vehicle technology has driven significant advancements in onboard charging systems, particularly in dual-stage interleaved architectures that enhance efficiency and reliability. The reviewed literature highlights that the integration of advanced control strategies such as the PIDD2-PD controller with hybrid adaptive optimization algorithms marks a substantial shift toward intelligent and high-performance power electronic systems. These innovations go beyond conventional improvements by enabling adaptive, data-driven control mechanisms capable of responding to complex and dynamic operating conditions. As a result, modern onboard chargers are becoming more robust, efficient, and suitable for next-generation EV applications.

A key implication of these advancements is the ability to achieve high power density while maintaining system stability and efficiency. The dual-stage interleaved architecture effectively reduces current ripple and distributes thermal stress, leading to improved durability and extended component lifespan. When combined with advanced controllers like PIDD2-PD, the system demonstrates enhanced transient response and robustness against load variations and grid disturbances. This is particularly critical in real-world scenarios where EV chargers must operate under fluctuating electrical and environmental conditions, ensuring consistent performance and user reliability.

Despite these advancements, several challenges persist in practical implementation. The computational complexity of advanced control and optimization techniques remains a major concern, particularly for real-time embedded systems. Furthermore, the lack of standardized benchmarking frameworks makes it difficult to compare different approaches objectively. Thermal management and system reliability also continue to be critical issues, especially in high-density designs. Moving forward, research must focus on developing computationally efficient algorithms, standardized evaluation methods, and improved thermal strategies. Balancing performance, cost, and scalability will be essential for the successful integration of these technologies into commercial electric vehicle systems.

Conclusion

The evolution of electric vehicle technology has significantly advanced onboard charging systems, particularly through the development of dual-stage interleaved architectures integrated with PIDD2-PD controllers and hybrid adaptive Genghis Khan Shark Gold Rush optimization techniques. This review highlights that such combinations substantially improve efficiency, stability, and adaptability, making them highly suitable for next-generation EV applications. The dual-stage interleaved topology enhances power density, reduces ripple, and improves thermal distribution, while advanced control strategies ensure precise voltage and current regulation under dynamic conditions. The PIDD2-PD controller, with its predictive and higher-order capabilities, outperforms traditional methods, enabling

better transient response and system robustness.
Furthermore, the incorporation of hybrid optimization techniques addresses the complexity of modern EV systems by effectively handling nonlinear and multi-objective problems. Algorithms like the Genghis Khan Shark Gold Rush approach provide faster convergence and improved parameter tuning, enhancing overall system performance. Advancements in hardware, including wide-bandgap semiconductors and digital control platforms such as DSPs and FPGAs, further support real-time implementation and efficiency improvements. Despite these developments, challenges such as computational complexity, lack of standardization, and thermal management persist. Future research is expected to focus on integrating artificial intelligence, IoT, and bidirectional charging capabilities to enable smarter, more efficient, and grid-interactive onboard charging systems.

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