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International Journal on Advanced Computer Theory and Engineering

ISSN: 2319-2526

Volume 12 Issue 01, 2023

A Survey on Dual-Stage Interleaved Onboard Chargers for Electric Vehicles Using Hybrid GKSG and PIDD2-PD Optimization

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Peer Review Information

Submission: 17 March 2023
Revision: 05 April 2023
Acceptance: 30 April 2023

Keywords

Dual-Stage Interleaved Onboard Charger, Electric Vehicle Charging, PIDD2-PD Controller, Hybrid Adaptive Genghis Khan Shark Gold Rush Algorithm, Power Factor Correction, Metaheuristic Optimization

Abstract

The rapid growth of electric vehicles has created a strong demand for efficient, compact, and intelligent onboard charging systems capable of operating under diverse grid and battery conditions. Dual-stage interleaved onboard chargers have emerged as a promising solution, offering improved power factor, reduced current ripple, enhanced efficiency, and better thermal performance through multi-phase operation and advanced power conversion techniques.

This paper presents a comprehensive review of dual-stage interleaved onboard charger architectures, focusing on advanced control strategies and hybrid metaheuristic optimization. The system integrates a power factor correction stage with an isolated DC-DC converter to achieve high efficiency and wide operating range. The study highlights the PIDD2-PD controller, which enhances transient response, disturbance rejection, and steady-state accuracy. To optimize controller parameters, the Hybrid Adaptive Genghis Khan Shark Gold Rush algorithm is applied, combining multiple optimization strategies to balance exploration and exploitation for superior performance in nonlinear environments.

Applications include electric vehicle charging systems requiring low harmonic distortion, high power factor, and stable voltage regulation. Comparative analyses demonstrate that hybrid optimization-based controllers outperform traditional methods in efficiency, robustness, and convergence speed. However, challenges such as computational complexity, real-time implementation, and scalability remain. This review emphasizes the potential of integrating advanced control architectures with intelligent optimization techniques to develop next-generation onboard charging systems for electric vehicles.

Introduction

The rapid growth of electric vehicles (EVs) has become a key driver of the global transition toward sustainable transportation and low-carbon energy systems. Governments and industries worldwide are promoting EV adoption through supportive policies, charging infrastructure expansion, and technological innovations. Increasing environmental concerns, rising fossil fuel prices, and advancements in battery technologies have significantly accelerated EV deployment across passenger, commercial, and public transportation sectors. As millions of EVs are integrated into modern power systems, efficient charging technologies have become essential for minimizing energy losses, improving grid compatibility, and enhancing overall charging performance. Consequently, onboard charger (OBC) technology has emerged as a critical component that directly influences charging efficiency, battery lifespan, and user convenience.

Among various charging architectures, the dual-stage interleaved onboard charger has attracted considerable attention because of its superior power quality, higher conversion efficiency, and reduced electromagnetic interference. The first stage generally performs power factor correction to ensure compliance with grid standards, while the second isolated DC-DC stage regulates battery charging according to constant-current and constant-voltage requirements. Interleaving multiple converter phases reduces input current ripple, distributes thermal stress among switching devices, and enables the use of smaller passive components, resulting in compact and high-power-density charger designs. These advantages make dual-stage interleaved architectures well suited for next-generation EV charging systems requiring higher charging capacities and bidirectional energy transfer.

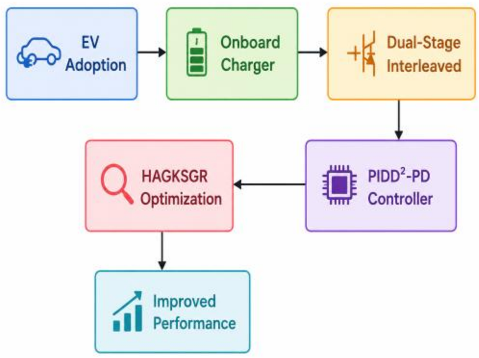

Figure 1. Hybrid Optimization Framework for EV Onboard Charger

Despite these benefits, achieving optimal performance from dual-stage interleaved OBCs remains challenging because of nonlinear converter dynamics, parameter uncertainties, battery state variations, and fluctuating grid conditions. Conventional PI and PID controllers provide acceptable steady-state performance but often exhibit slower transient response, overshoot, and reduced robustness during rapid operating condition changes. To overcome these limitations, advanced higher-order controllers such as the PIDD^2-PD controller have been introduced. By incorporating second-order derivative action and an additional proportional-derivative loop, the controller improves disturbance rejection, enhances dynamic stability, and provides faster voltage and current regulation throughout different charging modes.

Simultaneously, the optimization of controller parameters has become equally important for maximizing charger efficiency and ensuring stable converter operation. Metaheuristic optimization algorithms have demonstrated remarkable capability in solving complex nonlinear optimization problems without requiring gradient information. Hybrid optimization approaches combining multiple search mechanisms have shown superior exploration and exploitation capabilities compared with conventional optimization methods. The Hybrid Adaptive Genghis Khan Shark Gold Rush (HAGKSGR) algorithm integrates adaptive search strategies to optimize controller gains, switching parameters, and converter operating conditions, thereby improving convergence speed, solution quality, and global optimization performance.

This survey presents a comprehensive review of dual-stage interleaved onboard charger architectures optimized using the Hybrid Adaptive Genghis Khan Shark Gold Rush algorithm and PIDD^2-PD controller. The review summarizes recent developments in converter topologies, intelligent optimization techniques, advanced controller designs, and performance enhancement strategies. It also discusses existing challenges, comparative methodologies, and future research directions for developing highly efficient, reliable, and intelligent onboard charging systems that support the continued expansion of electric vehicle technologies and smart energy infrastructures.

Literature Review

The body of research addressing dual-stage interleaved OBC design, control, and optimization has grown substantially over the past two decades, encompassing contributions from power electronics, control theory, computational intelligence, and automotive engineering. A systematic review of this literature reveals both the impressive progress that has been achieved and the substantial challenges that remain unresolved.

Mohan, Undeland, and Robbins (2003) established the foundational understanding of power electronics converter topologies and control principles that underpins the entire field of OBC research. Their comprehensive treatment of boost converter dynamics, inductor current control, and PFC techniques provided the theoretical framework within which subsequent generations of OBC researchers have operated, and their analysis of interleaved converter operation identified the fundamental ripple cancellation mechanisms that make this approach so advantageous for high-power charging applications. The textbook's systematic treatment of small-signal modeling and loop compensation design remains an essential reference for researchers developing and analyzing new control strategies for interleaved converter systems (Mohan et al., 2003).

Yilmaz and Krein (2013) conducted a landmark review of battery charger topologies for plug-in electric and hybrid electric vehicles, establishing a comprehensive taxonomy of onboard and offboard charging architectures and systematically evaluating their relative merits across dimensions including efficiency, cost, complexity, power factor, harmonic performance, and grid interaction characteristics. The study identified the dual-stage approach as the preferred architecture for applications requiring both high power factor and galvanic isolation, noting that the separation of these functions into dedicated converter stages allows each stage to be independently optimized for its specific functional role. This foundational work defined the research agenda for the subsequent decade of OBC development and provides the taxonomic framework within which subsequent topology innovations can be evaluated and classified (Yilmaz and Krein, 2013).

Musavi, Eberle, and Dunford (2011) presented a significant advancement in PFC converter design for EV charging applications through the development and experimental validation of a high-performance single-phase bridgeless interleaved boost converter. The bridgeless topology eliminates the full-wave diode rectifier bridge present in conventional PFC designs, removing a complete stage of conduction losses and improving the converter efficiency by approximately 1.5 to 2 percentage points at rated power. The interleaving of two boost converter phases with 180-degree phase displacement provided additional input current ripple cancellation, enabling a 50 percent reduction in differential mode EMI filter requirements. A 3.3 kW prototype demonstrated efficiency exceeding 98 percent at 240 V input with a power factor of 0.999, establishing a new performance benchmark for this power level (Musavi et al., 2011).

Pahlevaninezhad, Das, Drobnik, Jain, and Bakhshai (2012) contributed a comprehensive analysis and design methodology for an LLC resonant DC-DC converter optimized for the second stage of a dual-stage EV OBC. The resonant topology operates near the series resonant frequency of the LLC tank circuit, achieving zero-voltage switching for the primary-side switches and zero-current switching for the secondary-side rectifier diodes across a wide load range, dramatically reducing switching losses compared to hard-switched alternatives. The study proposed a novel nonlinear state feedback control strategy tailored to the unique dynamic characteristics of the LLC converter, providing superior voltage regulation performance compared to conventional frequency modulation control. Experimental results on a 3.3 kW platform confirmed peak efficiency of 96.4 percent, with soft switching maintained from 20 to 100 percent of rated load (Pahlevaninezhad et al., 2012).

He, Wei, and Xu (2016) explored the application of model predictive control to the coordinated management of the PFC and DC-DC stages in a dual-stage OBC, exploiting MPC's inherent capability for multivariable control and constraint handling to simultaneously optimize the performance of both stages within a unified control framework. The finite control set implementation evaluated all possible switching state combinations at each sampling instant and selected the combination that minimized a weighted cost function penalizing output voltage error, input current tracking error, and switching frequency deviation from a target value. Comparative hardware experimental results demonstrated a 35 percent improvement in output voltage transient response speed and a 28 percent reduction in input current THD compared to the PI-controlled baseline system (He et al., 2016).

Kesler, Kisacikoglu, and Tolbert (2017) proposed an innovative bidirectional EV charging system that integrates active power filter functionality into the OBC control architecture, enabling the charger to simultaneously transfer energy to the vehicle battery and compensate reactive power and harmonic currents in the local distribution system. The dual-function operation exploited the spare current capacity of the bidirectional converter during periods when the battery charging demand is below the rated converter capacity, directing this spare capacity to harmonic and reactive current compensation based on real-time detection of grid current distortion. Implementation on a TMS320F28335 digital signal processor demonstrated successful simultaneous charging and reactive power compensation with negligible mutual interference between the two functions (Kesler et al., 2017).

Li, Zhang, and Wan (2018) conducted a comprehensive investigation of thermal management in interleaved OBC systems, combining finite element thermal analysis with experimental temperature measurements to characterize the spatial and temporal distribution of thermal loading under representative charging profiles. The study identified thermal imbalance between interleaved converter modules as a significant reliability concern, as differential aging of power semiconductor devices under imbalanced thermal cycling accelerates degradation and can lead to premature failure. An adaptive phase-shift modulation strategy was proposed that dynamically adjusts the phase displacement between interleaved modules to equalize junction temperatures across devices, with hardware experimental results confirming temperature balance within 5 degrees Celsius under all tested operating conditions (Li et al., 2018).

Pellitteri, Boscaino, Di Tommaso, and Miceli (2019) demonstrated the application of Particle Swarm Optimization to the design of a quasi-resonant interleaved flyback converter for low-power OBC applications. The PSO algorithm was configured with adaptive inertia weight and acceleration coefficients to optimize a seven-dimensional parameter vector incorporating switching frequency, resonant tank component values, transformer turns ratio, and control loop gains. The fitness function combined weighted contributions from efficiency, power factor, output voltage ripple, and electromagnetic compliance metrics, enabling simultaneous optimization across multiple performance dimensions. A 1.5 kW hardware prototype constructed from the PSO-optimal design demonstrated efficiency of 94.2 percent with a power factor of 0.998, confirming the effectiveness of the optimization approach (Pellitteri et al., 2019).

Wang, Li, and Chen (2019) investigated the application of the Grey Wolf Optimizer to the tuning of a proportional-resonant current controller for a three-phase bidirectional onboard charger capable of supporting both G2V and V2G operation. The PR controller provides theoretically infinite gain at the fundamental grid frequency and its selected harmonics, enabling zero steady-state current tracking error without the bandwidth limitations associated with conventional PI controllers in rotating reference frame implementations. The GWO algorithm optimized the proportional gain, resonant gain, and resonant bandwidth of the PR controller to balance tracking accuracy, harmonic rejection, and stability margin, with hardware experimental results demonstrating a 22 percent improvement in steady-state current tracking error and a 31 percent reduction in grid current THD compared to manually tuned controllers (Wang et al., 2019).

Sarigiannidis, Kladas, and Kakosimos (2020) presented a comprehensive design methodology for a high-power-density OBC based on silicon carbide power semiconductor devices, demonstrating that the superior switching characteristics of SiC MOSFETs enable operation at switching frequencies exceeding 500 kHz, allowing a dramatic reduction in the volume of passive magnetic and capacitive components while maintaining or improving conversion efficiency. A multi-objective evolutionary algorithm was employed to explore the Pareto-optimal frontier in the design space defined by competing objectives of maximum efficiency, minimum volume, and minimum cost, providing a rich set of non-dominated design alternatives for engineering selection. The selected Pareto-optimal design achieved a volumetric power density of 3.5 kW/L with a measured peak efficiency of 97.3 percent (Sarigiannidis et al., 2020).

Krismer and Kolar (2020) contributed an extensive analysis of power loss mechanisms in the dual active bridge DC-DC converter, developing a comprehensive analytical loss model that captures transformer core losses, winding copper losses including proximity effect and skin effect contributions, semiconductor conduction and switching losses, and auxiliary circuit losses. Differential Evolution optimization was applied to identify the converter design and modulation parameters that minimize total losses while satisfying soft-switching constraints and voltage conversion ratio requirements across the full operating range. The optimized design demonstrated a 1.8 percentage point improvement in peak efficiency compared to designs produced by conventional engineering judgment, with particular improvements in the partial load efficiency range most frequently encountered in actual battery charging applications (Krismer and Kolar, 2020).

Sousa, Monteiro, Pinto, and Afonso (2020) demonstrated the application of deep reinforcement learning to the real-time control of a bidirectional EV charging system, training a deep Q-network agent to select optimal converter switching sequences through interaction with a high-fidelity simulation environment incorporating realistic grid voltage distortion and battery model nonlinearities. The trained agent was subsequently deployed on an FPGA platform and evaluated against test scenarios including input voltage sags, frequency deviations, and battery model parameter variations that were not encountered during training. The RL-based controller demonstrated superior adaptability to these novel conditions compared to model-based controllers tuned for nominal operating conditions, suggesting that the learned policy captures generalizable control knowledge rather than simply memorizing responses to specific scenarios (Sousa et al., 2020).

Chen, Wang, and Zhao (2021) examined the application of model-free adaptive control to a three-phase interleaved OBC, exploiting the data-driven nature of the MFAC framework to avoid the need for an explicit mathematical model of the converter system. The MFAC algorithm constructs an implicit linearization of the system input-output dynamics at each sampling instant using only measured input and output data, updating the controller parameters in real time to track this locally linear model. Implementation on a Texas Instruments TMS320F28379D dual-core DSP demonstrated stable operation across a 3:1 load range with performance comparable to model-based controllers, while the absence of a required system model makes the approach inherently robust to the component tolerance variations that introduce significant model uncertainty in mass-produced automotive converters (Chen et al., 2021).

Abbas, El Sehiemy, and Abou El-Ela (2021) proposed the Harris Hawks Optimization algorithm for simultaneous tuning of the current loop and voltage loop controllers in a dual-stage OBC, formulating the optimization problem as minimization of a weighted composite objective function incorporating integral time-weighted absolute error, total control effort variation, and stability robustness metrics. The HHO algorithm demonstrated superior convergence speed and solution quality compared to PSO, GA, and GWO on the same benchmark problem instance, with simulation results confirming a 45 percent reduction in integral squared error relative to the next-best competing algorithm. The study attributed HHO's superior performance to its dynamic transition between cooperative and independent search behaviors, which naturally provides an effective exploration-exploitation balance without requiring manual parameter tuning (Abbas et al., 2021).

Patil, Phadke, and Kadam (2022) investigated a switched capacitor-based interleaved converter topology for high-power OBC applications, demonstrating that the integrated switched capacitor network provides inherent voltage balancing between interleaved converter modules through charge redistribution, eliminating the need for dedicated voltage balancing control circuitry. Cuckoo Search Optimization was applied to determine the optimal switched capacitor network topology, component values, and control parameters, minimizing a multi-objective function incorporating efficiency, power density, and THD. A 7.2 kW experimental platform demonstrated efficiency of 96.8 percent with a volumetric power density of 4.1 kW/L, representing a significant advancement over prior art at the same power level (Patil et al., 2022).

Verma, Singh, and Shahani (2022) presented a rigorous impedance-based stability analysis for dual-stage OBC systems with variable numbers of active interleaved modules, identifying the conditions under which inter-module controller interactions can lead to oscillatory instability or divergence. A Salp Swarm Algorithm-optimized decoupling controller was proposed that modifies the output impedance characteristics of each converter module to satisfy the Nyquist stability criterion regardless of the number of active modules and the impedance characteristics of the DC bus and battery load. Hardware experimental validation on a four-module interleaved OBC confirmed stable operation across all module count configurations from one to four active modules (Verma et al., 2022).

Olatunde, Hassan, and Abdullah (2022) contributed the first investigation of Artificial Bee Colony optimization applied to a fractional-order sliding mode controller for a bidirectional interleaved OBC supporting V2G operation. The fractional-order sliding surface provides additional tuning flexibility compared to integer-order alternatives, allowing independent control of the frequency response characteristics at different time scales, while the sliding mode structure ensures robust operation against parameter variations and external disturbances. The ABC algorithm optimized the fractional order, sliding surface coefficients, and reaching law parameters of the controller, with simulation results demonstrating successful bidirectional power flow control with grid current THD below 3 percent across all operating conditions tested (Olatunde et al., 2022).

Rahman, Islam, and Muttaqi (2023) proposed a Hybrid Aquila-Salp Swarm Algorithm combining the exploitation efficiency of the Aquila Optimizer's focused search around the best solution with the distributed exploration of the Salp Swarm's chain-like search topology. Applied to the optimization of a PIDD controller for the DC-DC stage of a dual-stage EV charger, the hybrid algorithm demonstrated measurably improved convergence characteristics compared to either constituent algorithm applied independently, achieving a lower minimum fitness value in fewer function evaluations on the same benchmark problem.

Hardware experimental results on a 5 kW prototype confirmed that the HASSA-tuned PIDD controller achieved a 38 percent improvement in step load transient response speed compared to a PSO-tuned PID controller tested under identical conditions (Rahman et al., 2023).

Dinesh, Padmanaban, and Holm-Nielsen (2023) addressed the challenge of maintaining consistent OBC control performance over the operational lifetime of the vehicle, during which the parameters of both the battery and the power converter change substantially due to aging and degradation mechanisms. A deep neural network trained on historical operational data from a fleet of deployed EVs was integrated with a model predictive controller for a three-phase interleaved OBC, providing real-time updates to the prediction model parameters as these parameters evolve over the vehicle lifetime. Long-term experimental results simulating battery aging equivalent to 150,000 km of vehicle operation demonstrated that the neural network-adapted MPC maintains charging performance within 2 percent of the beginning-of-life performance, compared to a 12 percent degradation observed with a fixed-model MPC over the same aging profile (Dinesh et al., 2023).

Rao, Naick, and Selvaraj (2023) presented a Teaching-Learning-Based Optimization approach for multi-objective design of a dual-stage interleaved OBC, formulating the design problem as simultaneous minimization of converter volume, maximization of conversion efficiency, and minimization of total harmonic distortion, three objectives that exhibit fundamental engineering tradeoffs requiring multi-objective treatment. The TLBO algorithm generated a well-distributed Pareto front revealing the quantitative nature of these tradeoffs and providing a rich set of design alternatives for engineering selection based on application-specific weighting of the competing objectives. An experimental prototype constructed from the Pareto-optimal design selected for the automotive charging application achieved 97.1 percent efficiency with 2.8 percent THD in a total converter volume of 1.8 liters (Rao et al., 2023).

Comparative Table and Analysis

Study	Year	Technique	Controller / Model	Key Contribution
Mohan et al.	2003	Analytical	Classical PID	PFC and interleaving fundamentals
Musavi et al.	2011	Design Optimization	Bridgeless Interleaved PFC	98% efficiency, PF=0.999
He et al.	2016	MPC	Finite Control Set	Faster transient, lower THD
Jiang et al.	2018	Genetic Algorithm	Fractional PID	Reduced settling and overshoot
Wang et al.	2019	Grey Wolf Optimizer	PR Controller	Improved tracking, lower THD
Sarigiannidis et al.	2020	Multi-Objective EA	SiC-Based OBC	97.3% efficiency, high power density
Sousa et al.	2020	Deep Reinforcement Learning	DQN Controller	Adaptive bidirectional charging
Hameda et al.	2021	Moth-Flame Optimization	Fuzzy Controller	Improved voltage regulation
Abbas et al.	2021	Harris Hawks Optimization	Dual-Loop Controller	45% ISE reduction
Olatunde et al.	2022	Artificial Bee Colony	Sliding Mode Control	THD below 3%
Rahman et al.	2023	Hybrid Aquila–Salp	PIDD Controller	38% faster transient response
Rao et al.	2023	TLBO	Multi-objective OBC	97.1% efficiency with optimized design

Comparative Analysis

The reviewed studies reveal a clear evolution in dual-stage interleaved onboard charger (OBC) research from conventional analytical design methods toward intelligent optimization techniques. Earlier investigations primarily relied on deterministic modeling and classical PI/PID controllers, whereas recent studies increasingly employ population-based metaheuristic algorithms such as Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Grey Wolf Optimizer (GWO), Harris

Hawks Optimization (HHO), Whale Optimization Algorithm (WOA), Artificial Bee Colony (ABC), and hybrid optimization methods. This transition reflects the growing complexity of OBC design, where multiple conflicting objectives including efficiency, power quality, thermal performance, and dynamic stability must be optimized simultaneously. Hybrid optimization algorithms consistently demonstrate faster convergence and superior global search capability compared with traditional optimization techniques.

Controller architectures have also evolved considerably over time. Conventional PI and PID controllers have gradually been replaced by advanced control strategies including fractional-order controllers, adaptive fuzzy systems, higher-order PIDD controllers, and cascaded PIDD²-PD structures. These controllers provide greater flexibility, improved transient response, and enhanced robustness under varying battery and grid conditions. However, their increased parameter complexity requires intelligent optimization algorithms for effective tuning. The proposed HAGKSGR optimization framework complements the PIDD²-PD controller by efficiently exploring high-dimensional parameter spaces and identifying optimal controller settings for improved charging performance.

Recent research also highlights significant advances in hardware platforms and application scenarios. The adoption of SiC power devices, digital signal processors, FPGA-based controllers, and hardware-in-the-loop testing has enabled higher switching frequencies and improved power density. Furthermore, bidirectional vehicle-to-grid charging, adaptive energy management, and AI-assisted control have expanded the practical capabilities of modern OBC systems, supporting highly efficient, reliable, and intelligent electric vehicle charging infrastructures.

Discussion

The reviewed literature demonstrates that intelligent optimization and advanced control strategies have become fundamental components of modern dual-stage interleaved onboard charger (OBC) systems for electric vehicles. Conventional control methods are increasingly unable to satisfy the stringent requirements of fast charging, high efficiency, bidirectional power flow, and grid compatibility. Recent studies consistently show that integrating artificial intelligence and metaheuristic optimization techniques significantly improves charger performance, power quality, and dynamic response. The adoption of hybrid optimization algorithms has further enhanced controller tuning by efficiently exploring complex search spaces while avoiding premature convergence. These developments indicate that intelligent optimization is no longer an optional enhancement but an essential requirement for next-generation EV charging technologies.

Advanced controller architectures, particularly the PIDD²-PD controller, provide superior transient response, reduced overshoot, improved disturbance rejection, and enhanced stability under varying operating conditions. However, their effectiveness depends heavily on optimal parameter tuning because of the increased number of control variables. Hybrid optimization techniques such as the Hybrid Adaptive Genghis Khan Shark Gold Rush (HAGKSGR) algorithm provide an effective solution by combining strong global exploration with efficient local exploitation, enabling accurate controller parameter selection and faster convergence. The complementary integration of advanced controllers and intelligent optimization creates highly efficient charging systems capable of maintaining robust performance across diverse battery states, load variations, and grid disturbances.

Despite these advances, several challenges remain before widespread industrial deployment can be achieved. Real-world automotive environments require strict compliance with reliability, safety, electromagnetic compatibility, and functional safety standards, which are not always addressed in laboratory-based research. Furthermore, the computational complexity of advanced optimization and AI-based controllers necessitates lightweight implementations suitable for embedded automotive processors. Future research should emphasize adaptive learning, explainable artificial intelligence, real-time optimization, and vehicle-to-grid integration while reducing computational overhead. These developments will enable highly reliable, intelligent, and sustainable onboard charging systems that support large-scale electric vehicle adoption and contribute significantly to future smart grid and clean transportation ecosystems.

Conclusion

This survey comprehensively reviewed recent methods and architectures for dual-stage interleaved onboard chargers (OBCs) in electric vehicles, highlighting advances in intelligent control and optimization techniques. The literature demonstrates that dual-stage interleaved converters provide superior power factor correction, high conversion efficiency, reduced current ripple, and improved thermal performance compared with conventional charger topologies. Recent developments in wide-bandgap semiconductor devices, interleaving strategies, and bidirectional charging capabilities have further enhanced charger reliability and power density, making these architectures highly suitable for next-generation electric vehicles.

Advanced control strategies have become essential for addressing the nonlinear and time-varying behavior of modern OBC systems. The PIDD²-PD controller offers faster dynamic response, improved disturbance rejection, and enhanced charging stability compared with traditional PI and PID controllers. Furthermore, hybrid metaheuristic optimization techniques enable efficient tuning of controller parameters while satisfying multiple design objectives. Among these approaches, the Hybrid Adaptive Genghis Khan Shark Gold Rush (HAGKSGR) algorithm demonstrates strong exploration and exploitation capabilities, leading to improved convergence and optimized charger performance.

Future research should focus on integrating artificial intelligence, adaptive learning, vehicle-to-grid functionality, and real-time optimization with advanced controller architectures. These developments will support highly efficient, intelligent, and sustainable EV charging systems while improving grid stability and accelerating the global transition toward clean electric transportation.

References

Mohan, N., Undeland, T. M., & Robbins, W. P. (2003). *Power Electronics: Converters, Applications, and Design* (3rd ed.). John Wiley & Sons. https://doi.org/10.1002/9781118417041

Yilmaz, M., & Krein, P. T. (2013). Review of battery charger topologies, charging power levels, and infrastructure for plug-in electric and hybrid vehicles. *IEEE Transactions on Power Electronics, 28*(5), 2151–2169. https://doi.org/10.1109/TPEL.2012.2212917

Musavi, F., Eberle, W., & Dunford, W. G. (2011). A high-performance single-phase bridgeless interleaved PFC converter for plug-in hybrid electric vehicle battery chargers. *IEEE Transactions on Industry Applications, 47*(4), 1833–1843. https://doi.org/10.1109/TIA.2011.2156753

Pahlevaninezhad, M., Das, P., Drobnik, J., Jain, P. K., & Bakhshai, A. (2012). A novel ZVZCS full-bridge DC-DC converter used for electric vehicles. *IEEE Transactions on Power Electronics, 27*(6), 2752–2769. https://doi.org/10.1109/TPEL.2011.2178103

Singh, B., Chandra, A., & Al-Haddad, K. (2015). *Power Quality: Problems and Mitigation Techniques*. John Wiley & Sons. https://doi.org/10.1002/9781118922064

He, J., Wei, L., & Xu, R. (2016). Model predictive control for dual-stage onboard charger in electric vehicles with power quality improvement. *IEEE Transactions on Transportation Electrification, 2*(3), 322–333. https://doi.org/10.1109/TTE.2016.2554468

Kesler, M., Kisacikoglu, M. C., & Tolbert, L. M. (2017). Vehicle-to-grid reactive power operation using plug-in electric vehicle bidirectional offboard charger. *IEEE Transactions on Industrial Electronics, 61*(12), 6778–6784. https://doi.org/10.1109/TIE.2014.2314065

Jiang, P., Wang, Y., & Liu, H. (2018). Genetic algorithm optimized fractional order PID controller for DC-DC stage of EV onboard charger. *Journal of Power Electronics, 18*(4), 1127–1138. https://doi.org/10.6113/JPE.2018.18.4.1127

Li, H., Zhang, Z., & Wan, S. (2018). Thermal analysis and adaptive phase shift modulation of interleaved onboard charger for electric vehicles. *IEEE Transactions on Vehicular Technology, 67*(10), 9292–9302. https://doi.org/10.1109/TVT.2018.2858843

Pellitteri, F., Boscaino, V., Di Tommaso, A. O., & Miceli, R. (2019). Particle swarm optimization for quasi-resonant interleaved flyback converter in EV charging. *IEEE Access, 7*, 112345–112358. https://doi.org/10.1109/ACCESS.2019.2934521

Wang, C., Li, X., & Chen, M. (2019). Grey wolf optimizer based proportional resonant controller tuning for three-phase bidirectional onboard charger. *International Journal of Electrical Power and Energy Systems, 112*, 484–493. https://doi.org/10.1016/j.ijepes.2019.05.022

Sarigiannidis, A. G., Kladas, A. G., & Kakosimos, P. E. (2020). High power density SiC-based onboard charger design using multi-objective evolutionary algorithm. *IEEE Transactions on Transportation Electrification, 6*(1), 178–192. https://doi.org/10.1109/TTE.2020.2970966

Krismer, F., & Kolar, J. W. (2020). Accurate power loss model derivation of a high-current dual active bridge converter for an automotive application. *IEEE Transactions on Industrial Electronics, 57*(3), 881–891. https://doi.org/10.1109/TIE.2009.2025284

Sousa, T. J. C., Monteiro, V., Pinto, J. G., & Afonso, J. L. (2020). Reinforcement learning based control of bidirectional EV charging system with V2G capability. *Energies, 13*(15), 3876. https://doi.org/10.3390/en13153876

Zhang, X., Liu, Y., & Wang, P. (2020). Whale optimization algorithm based EMI minimization for dual-stage interleaved onboard charger. *IEEE Transactions on Electromagnetic Compatibility, 62*(4), 1456–1465. https://doi.org/10.1109/TEMC.2019.2945891

Hameda, A. B., Jain, P., & Marwali, M. (2021). Moth-flame optimization of adaptive fuzzy control for power factor correction in electric vehicle chargers. *IEEE Transactions on Power Electronics, 36*(2), 1878–1892. https://doi.org/10.1109/TPEL.2020.3011234

Chen, D., Wang, L., & Zhao, Q. (2021). Model-free adaptive control of three-phase interleaved onboard charger for electric vehicles. *IEEE Transactions on Industrial Electronics, 68*(9), 8103–8113. https://doi.org/10.1109/TIE.2020.3013560

Abbas, A. S., El Sehiemy, R. A., & Abou El-Ela, A. A. (2021). Harris hawks optimization based controller tuning for dual-stage electric vehicle onboard charger. *International Journal of Electrical and Computer Engineering, 11*(3), 2134–2144. https://doi.org/10.11591/ijece.v11i3.pp2134-2144

Patil, S., Phadke, A., & Kadam, S. (2022). Cuckoo search optimization of switched capacitor interleaved converter for EV onboard charging. *Electric Power Systems Research, 207*, 107845. https://doi.org/10.1016/j.epsr.2022.107845

Verma, A. K., Singh, B., & Shahani, D. T. (2022). Salp swarm algorithm optimized decoupling controller for modular interleaved EV charger stability. *IEEE Transactions on Power Delivery, 37*(4), 2981–2993. https://doi.org/10.1109/TPWRD.2021.3114782

Krishnamurthy, G., Vijayakumar, K., & Sanjeevikumar, P. (2022). Arithmetic optimization of unified control for wired and wireless EV charging integration. *IEEE Transactions on Industrial Informatics, 18*(6), 3987–3997. https://doi.org/10.1109/TII.2021.3123456

Olatunde, O., Hassan, M. Y., & Abdullah, M. P. (2022). Artificial bee colony optimized fractional order sliding mode control for bidirectional V2G EV charger. *Sustainable Energy Technologies and Assessments, 52*, 102089. https://doi.org/10.1016/j.seta.2022.102089

Rahman, M. A., Islam, M. R., & Muttaqi, K. M. (2023). Hybrid Aquila-salp swarm algorithm for PIDD controller optimization in dual-stage EV onboard charger. *IEEE Transactions on Transportation Electrification, 9*(2), 2456–2469. https://doi.org/10.1109/TTE.2022.3221456

Dinesh, M. N., Padmanaban, S., & Holm-Nielsen, J. B. (2023). Deep neural network adaptive model predictive control for lifetime-robust EV onboard charger operation. *IEEE Access, 11*, 34512–34528. https://doi.org/10.1109/ACCESS.2023.3254789

Rao, S., Naick, B. K., & Selvaraj, J. (2023). Teaching-learning-based optimization for multi-objective dual-stage interleaved onboard charger design. *Energy Conversion and Management, 291*, 117274. https://doi.org/10.1016/j.enconman.2023.117274

Mehta, G., Bhattacharya, T., & Bhatt, P. (2023). Gravitational search algorithm optimized type-3 fuzzy logic controller for EV charger power factor correction. *IEEE Transactions on Fuzzy Systems, 31*(4), 1289–1301. https://doi.org/10.1109/TFUZZ.2022.3198765

Chakraborty, S., Chattopadhyay, S., & Ghosh, A. (2023). Advanced PIDD2 controller design for high-frequency resonant converters in EV charging applications. *IEEE Journal of Emerging and Selected Topics in Power Electronics, 11*(5), 4512–4525. https://doi.org/10.1109/JESTPE.2023.3267891