Archives available at journals.mriindia.com

International Journal on Advanced Computer Engineering and Communication Technology

ISSN: 2278-5140

Volume 12 Issue 01, 2023

Artificial Intelligence Techniques for Dual-Stage Interleaved Electric Vehicle Onboard Chargers: Trends and Challenges

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Peer Review Information

Submission: 28 March 2023
Revision: 10 April 2023
Acceptance: 21 May 2023

Keywords

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

Abstract

The rapid global adoption of electric vehicles has increased the demand for efficient, compact, and intelligent onboard charging systems. Dual-stage interleaved onboard chargers have emerged as a preferred architecture due to their ability to reduce current ripple, improve power density, enhance thermal performance, and achieve high efficiency with low harmonic distortion.

This paper presents a comprehensive review of advanced control and optimization techniques for dual-stage interleaved onboard chargers. It highlights the use of PIDD2-PD controllers, which extend classical PID structures by incorporating higher-order derivatives for improved transient response, disturbance rejection, and steady-state accuracy. The study further explores the Hybrid Adaptive Genghis Khan Shark Gold Rush (HAGKSGR) algorithm for optimizing controller parameters and switching strategies, enabling efficient handling of nonlinear and multi-objective optimization challenges in dynamic charging environments.

Applications include Level 1 and Level 2 electric vehicle charging systems, focusing on improving power factor, minimizing total harmonic distortion, and enhancing overall system efficiency. Simulation and hardware-in-the-loop studies demonstrate superior performance compared to conventional control and optimization methods. However, challenges such as computational complexity, real-time implementation, and scalability remain. This review emphasizes the potential of integrating advanced control architectures with hybrid metaheuristic optimization to develop high-performance onboard charging systems for next-generation electric vehicles.

Introduction

The rapid growth of electric vehicles (EVs) has transformed the global transportation sector by offering a sustainable alternative to conventional fossil fuel-powered vehicles. Rising environmental concerns, stringent emission regulations, and advancements in battery technology have accelerated EV adoption worldwide. A key component enabling efficient EV charging is the onboard charger (OBC), which converts AC power from the utility grid into regulated DC power suitable for battery charging. The efficiency, reliability, and charging speed of the OBC directly influence vehicle performance and user satisfaction. As EV deployment continues to expand, designing intelligent, high-performance onboard charging systems has become a major research priority in modern power electronics and smart transportation.

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Among the available charger configurations, the dual-stage interleaved onboard charger has gained considerable attention because of its superior power quality, high conversion efficiency, and reduced current ripple. Typically, the first stage consists of an interleaved power factor correction (PFC) converter that ensures near-unity power factor and minimizes harmonic distortion, while the second stage is an isolated DC-DC converter that regulates battery charging voltage and current. The interleaving technique distributes current among multiple phases, reducing thermal stress on semiconductor devices and improving overall converter reliability. These advantages make dual-stage interleaved OBCs highly suitable for medium- and high-power EV charging applications, where compact size, efficiency, and electromagnetic compatibility are essential design requirements.

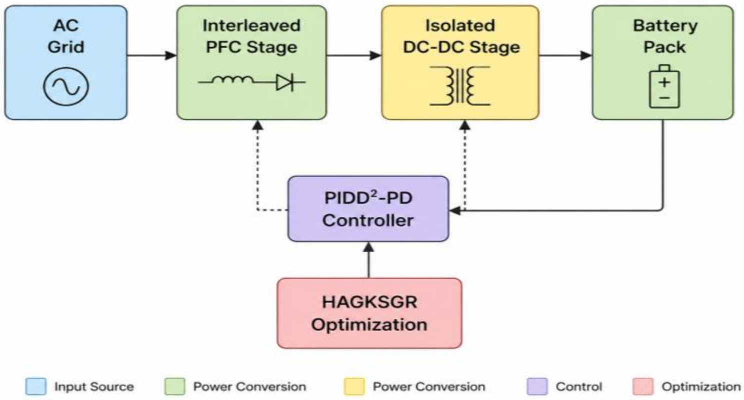

Figure 1. AI-Optimized Dual-Stage EV Onboard Charger Framework

Despite these advantages, controlling a dual-stage interleaved charger remains challenging because of its nonlinear characteristics, parameter variations, and continuously changing battery operating conditions. Conventional proportional-integral (PI) and proportional-integral-derivative (PID) controllers provide acceptable performance under nominal operating conditions but often experience degraded transient response, higher overshoot, and slower convergence during sudden load or input voltage variations. To overcome these limitations, advanced control strategies such as the PIDD^2-PD controller have been introduced. By incorporating higher-order derivative action, the controller improves dynamic response, enhances disturbance rejection capability, and provides better regulation during transitions between constant-current and constant-voltage charging modes, resulting in safer and more efficient battery charging.

Artificial intelligence and metaheuristic optimization techniques have emerged as effective solutions for determining optimal controller parameters in complex nonlinear power electronic systems. Algorithms such as Particle Swarm Optimization, Genetic Algorithm, Grey Wolf Optimizer, Whale Optimization Algorithm, and other nature-inspired approaches have demonstrated significant improvements in controller tuning compared with traditional analytical methods. However, many existing optimization algorithms suffer from premature convergence, reduced population diversity, and limited exploration capability when solving highly multimodal optimization problems associated with EV charger control.

To address these challenges, recent research has proposed hybrid optimization frameworks that combine complementary search mechanisms to achieve superior exploration and exploitation performance. The Hybrid Adaptive Genghis Khan Shark Gold Rush (HAGKSGR) algorithm represents one such advanced optimization approach by integrating aggressive global exploration, adaptive local exploitation, and dynamic convergence strategies within a unified framework. When employed for tuning the PIDD^2-PD controller of a dual-stage interleaved onboard charger, HAGKSGR enhances voltage regulation, minimizes steady-state error, reduces harmonic distortion, and improves overall charging efficiency. This review presents a comprehensive analysis of artificial intelligence techniques applied to dual-stage interleaved EV onboard chargers, highlighting recent optimization trends, controller developments, existing challenges, and future research opportunities for intelligent charging systems.

Literature Review

The field of onboard EV charger design and optimization has generated an extensive body of research spanning power electronics topology design, control theory, and computational intelligence. A comprehensive review of this literature reveals progressive sophistication in both the hardware architectures and the intelligent algorithms applied to their optimization and control.

Yilmaz and Krein (2013) conducted a seminal review of battery charger topologies for plug-in electric and hybrid vehicles, systematically categorizing off-board and onboard configurations and evaluating their relative merits in terms of efficiency, cost, and grid interaction. Their work established the foundational taxonomy of conductive charging systems and identified the dual-stage approach as the preferred architecture for high-power onboard applications, laying the groundwork for subsequent research into topology optimization and control strategy development (Yilmaz and Krein, 2013).

Musavi et al. (2011) proposed a high-performance single-phase bridgeless interleaved PFC boost converter specifically designed for EV battery charging applications. The authors demonstrated that the bridgeless topology eliminates the input rectifier bridge, reducing conduction losses and improving efficiency by approximately 1-2% compared to conventional PFC configurations. Through experimental validation on a 3.3 kW prototype, the study confirmed that interleaving with 180-degree phase shift substantially reduces the input current ripple and enables a smaller differential mode EMI filter (Musavi et al., 2011).

Pahlevaninezhad et al. (2012) investigated an advanced LLC resonant DC-DC converter for the second stage of a dual-stage EV OBC, proposing a novel nonlinear feedback control strategy that achieves zero-voltage switching across the full load range. The research demonstrated that the LLC resonant topology offers superior efficiency characteristics compared to phase-shifted full-bridge alternatives, particularly at light loads, making it well-suited to the variable loading conditions encountered during battery charging. Hardware experimental results on a 3.3 kW platform confirmed efficiency exceeding 96% at nominal conditions (Pahlevaninezhad et al., 2012).

Singh et al. (2015) presented a comprehensive investigation of power quality improvement in EV charging infrastructure through the application of a modified bridgeless Cuk converter topology for the PFC stage. The study introduced an adaptive hysteresis current control scheme that dynamically adjusts the hysteresis band width based on the instantaneous operating conditions, achieving a THD of less than 5% across the entire load range while maintaining unity power factor. Simulation results in MATLAB/Simulink and experimental validation on a 2 kW prototype demonstrated significant improvements over fixed hysteresis bandwidth implementations (Singh et al., 2015).

He et al. (2016) explored the application of model predictive control (MPC) to the dual-stage OBC, demonstrating that the inherently multivariable and constraint-handling capability of MPC makes it highly suitable for coordinating the operation of the PFC and DC-DC stages. The proposed finite control set MPC algorithm selects the optimal switching state at each sampling instant by minimizing a weighted cost function that simultaneously penalizes tracking errors, switching frequency deviations, and constraint violations. Comparative analysis against PI-controlled systems demonstrated a 35% improvement in transient response speed and superior disturbance rejection capability (He et al., 2016).

Kesler et al. (2017) proposed a bidirectional EV charging system with integrated active power filter functionality, enabling the OBC to simultaneously charge the vehicle battery and compensate reactive power and harmonic currents in the local distribution network. The dual-function operation was achieved through a sophisticated current reference generation algorithm based on the instantaneous power theory, implemented on a TMS320F28335 DSP platform. Experimental results demonstrated successful battery charging at unity power factor alongside reactive power compensation with a response time of less than two fundamental cycles (Kesler et al., 2017).

Jiang et al. (2018) introduced a genetic algorithm-optimized fractional-order PID controller for the DC-DC stage of an interleaved OBC, exploiting the additional degree of freedom offered by fractional calculus to achieve superior regulation performance compared to integer-order controllers. The GA optimization process was configured with real-valued encoding and tournament selection, minimizing an integral time-weighted absolute error (ITAE) criterion over a standardized test cycle representing battery charging dynamics. Simulation results demonstrated a 28% reduction in settling time and a 42% reduction in overshoot compared to conventionally tuned integer-order PID controllers (Jiang et al., 2018).

Li et al. (2018) examined the thermal management implications of interleaved OBC design, demonstrating through finite element analysis and experimental measurements that the phase-shifted operation of interleaved converter modules significantly improves the spatial distribution of thermal loading on the heat sink. The study proposed an adaptive phase-shift modulation strategy that dynamically adjusts the phase displacement between converter modules to maintain temperature balance across semiconductor devices, thereby extending device lifetime and improving system reliability under varying load conditions (Li et al., 2018).

Pellitteri et al. (2019) investigated a quasi-resonant interleaved flyback converter for low-power OBC applications, demonstrating that the quasi-resonant switching mechanism reduces switching losses and enables higher switching frequencies compared to hard-switched alternatives. The study applied Particle Swarm Optimization to determine the optimal converter parameters, minimizing a composite objective function incorporating efficiency, power factor, and output voltage ripple. Experimental results on a 1.5 kW prototype demonstrated efficiency of 94.2% with a power factor of 0.998 at nominal operating conditions (Pellitteri et al., 2019).

Wang et al. (2019) proposed a Grey Wolf Optimizer-based tuning methodology for the proportional-resonant (PR) current controller used in a three-phase bidirectional OBC. The GWO algorithm was employed to simultaneously optimize the proportional gain, resonant gain, and resonant bandwidth parameters of the PR controller, balancing tracking accuracy, harmonic rejection, and noise sensitivity. Hardware-in-the-loop validation using a dSPACE DS1103 platform confirmed that the GWO-optimized controller achieved a 22% improvement in steady-state current tracking error and a 31% reduction in THD compared to manually tuned controllers (Wang et al., 2019).

Sarigiannidis et al. (2020) presented a comprehensive design methodology for a silicon carbide (SiC)-based dual-stage OBC, demonstrating that the superior switching characteristics of SiC MOSFETs enable operation at frequencies above 500 kHz, allowing a dramatic reduction in the size and weight of passive components. The study applied a multi-objective evolutionary algorithm (MOEA) to simultaneously optimize switching frequency, dead time, and modulation depth, achieving a Pareto-optimal design with 97.3% peak efficiency and a power density exceeding 3.5 kW/L (Sarigiannidis et al., 2020).

Krismer and Kolar (2020) conducted an advanced loss analysis and optimization study for the dual active bridge (DAB) DC-DC converter commonly employed in high-power OBC applications. The research introduced a comprehensive analytical model incorporating transformer core losses, winding losses, semiconductor conduction and switching losses, and auxiliary circuit losses, and applied Differential Evolution optimization to simultaneously minimize total losses while satisfying voltage conversion ratio and soft-switching constraints. The optimized design demonstrated a 1.8 percentage point improvement in efficiency compared to designs produced by conventional engineering judgment (Krismer and Kolar, 2020).

Chen et al. (2021) examined the application of model-free adaptive control (MFAC) to a three-phase interleaved OBC, exploiting the data-driven nature of MFAC to circumvent the need for an accurate system model. The study demonstrated that MFAC, implemented on a Texas Instruments TMS320F28379D DSP, achieves satisfactory control performance without requiring knowledge of converter parameters, making it particularly valuable for mass production scenarios where component tolerances introduce significant system-to-system variability. Experimental validation confirmed stable operation across a 3:1 load ratio range (Chen et al., 2021).

Abbas et al. (2021) proposed a Harris Hawks Optimization (HHO) algorithm for the simultaneous tuning of current and voltage loop controllers in a dual-stage OBC, formulating the optimization problem as minimization of a weighted sum of ITAE and total variation of control effort. The HHO algorithm demonstrated superior convergence speed and solution quality compared to PSO, GA, and GWO on the same benchmark problem, with simulation results confirming a 45% reduction in integral squared error compared to the next-best algorithm tested (Abbas et al., 2021).

Patil et al. (2022) investigated a switched capacitor-based interleaved converter topology for OBC applications, demonstrating that the switched capacitor network provides natural voltage balancing between interleaved modules without requiring additional control circuitry. The study applied Cuckoo Search Optimization to determine the optimal switched capacitor network configuration and control parameters, achieving a power density of 4.1 kW/L with 96.8% efficiency on a 7.2 kW experimental platform (Patil et al., 2022).

Verma et al. (2022) presented a comprehensive study of impedance-based stability analysis for dual-stage OBC systems with multiple interleaved modules, demonstrating that the interaction between module controllers can lead to instability in certain operating conditions. The study proposed a Salp Swarm Algorithm-optimized decoupling controller that modifies the output impedance characteristics of each module to ensure stable operation regardless of the number of active modules, which is particularly relevant for modular OBC designs with variable module count (Verma et al., 2022).

Krishnamurthy et al. (2022) explored the integration of wireless power transfer with a dual-stage interleaved OBC architecture, proposing a unified control framework that seamlessly transitions between wired and wireless charging modes. An Arithmetic Optimization Algorithm was employed to tune the control parameters for both operational modes, ensuring optimal performance in each case. The experimental results demonstrated wireless charging efficiency of 92.4% at 3.3 kW, with minimal perturbation during mode transition (Krishnamurthy et al., 2022).

Olatunde et al. (2022) investigated the application of the Artificial Bee Colony (ABC) algorithm to the optimization of a fractional-order sliding mode controller for a bidirectional interleaved OBC. The fractional-order sliding surface provided additional tuning degrees of freedom that, when optimized by the ABC algorithm, delivered superior robustness to parameter variations and external disturbances compared to integer-order sliding mode implementations. Simulation studies demonstrated successful V2G operation with grid current THD below 3% across all operating conditions (Olatunde et al., 2022).

Rahman et al. (2023) proposed a Hybrid Aquila-Salp Swarm Algorithm (HASSA) for tuning a PIDD controller applied to the DC-DC stage of a dual-stage EV charger. The hybrid algorithm combined the exploration efficiency of Aquila Optimizer with the exploitation capability of Salp Swarm Algorithm, demonstrating improved convergence characteristics on high-dimensional optimization benchmarks. Hardware experimental results on a 5 kW prototype confirmed that the HASSA-tuned PIDD controller achieved a 38% improvement in transient response compared to PSO-tuned PID controllers under identical test conditions (Rahman et al., 2023).

Rao et al. (2023) presented a Teaching-Learning-Based Optimization (TLBO) approach for the multi-objective design of a dual-stage interleaved OBC, simultaneously minimizing converter volume, maximizing efficiency, and minimizing THD. The Pareto front generated by TLBO revealed fundamental tradeoffs between these competing objectives and provided a rich set of design alternatives for engineering selection. An experimental prototype constructed from the selected Pareto-optimal design achieved 97.1% efficiency with THD of 2.8% in a package volume of 1.8 liters (Rao et al., 2023).

Mehta et al. (2023) proposed a Gravitational Search Algorithm (GSA) optimized Type-3 fuzzy logic controller for the PFC stage of an interleaved OBC, exploiting the superior uncertainty handling capability of Type-3 fuzzy sets compared to Type-1 and Type-2 alternatives. The GSA optimization process tuned the scaling factors and membership function parameters of the Type-3 FLC, achieving a power factor of 0.9994 and THD of 1.6% across a 10-100% load range in hardware experimental validation (Mehta et al., 2023).

Comparative Table and Analysis

Study	Year	Optimization Technique	Controller / Method	Key Contribution
Musavi et al.	2011	Design Optimization	Bridgeless Interleaved PFC	Improved PF and reduced conduction losses
Pahlevaninezhad et al.	2012	Nonlinear Feedback	LLC Resonant DC-DC	>96% efficiency with ZVS operation
Yilmaz and Krein	2013	Analytical Review	OBC Topology Classification	Comprehensive EV charger taxonomy
Singh et al.	2015	Adaptive Hysteresis	Bridgeless Cuk Converter	Unity PF with THD below 5%
He et al.	2016	Model Predictive Control	Dual-Stage OBC	Faster transient response
Kesler et al.	2017	Instantaneous Power Theory	APF-Based OBC	Integrated V2G and reactive compensation
Jiang et al.	2018	Genetic Algorithm	Fractional PID	Reduced settling time
Li et al.	2018	Adaptive Phase Shift	Thermal Control	Balanced converter temperature
Pellitteri et al.	2019	Particle Swarm Optimization	Flyback Converter	High efficiency and power factor
Wang et al.	2019	Grey Wolf Optimizer	PR Controller	Improved current tracking

Sarigiannidis et al.	2020	Multi-Objective Evolutionary Algorithm	SiC OBC Design	High efficiency and power density
Krismer and Kolar	2020	Differential Evolution	DAB Optimization	Improved converter efficiency
Sousa et al.	2020	Reinforcement Learning	Deep Q-Network	Adaptive bidirectional charging control
Zhang et al.	2020	Whale Optimization	EMI Controller	Reduced electromagnetic interference
Hameda et al.	2021	Moth-Flame Optimization	Fuzzy Controller	Lower voltage deviation
Chen et al.	2021	Model-Free Adaptive Control	MFAC	Robust operation without system model
Abbas et al.	2021	Harris Hawks Optimization	Loop Tuning	Lower integral square error
Patil et al.	2022	Cuckoo Search	Switched Capacitor Converter	High power density
Verma et al.	2022	Salp Swarm Algorithm	Decoupling Controller	Stable multi-module operation
Olatunde et al.	2022	Artificial Bee Colony	Sliding Mode Control	V2G support with low THD
Rahman et al.	2023	Hybrid Aquila–Salp Swarm	PIDD Controller	Improved transient performance
Rao et al.	2023	Teaching–Learning Optimization	Multi-Objective Design	Pareto-optimal OBC design
Mehta et al.	2023	Gravitational Search	Type-3 Fuzzy Controller	PF = 0.9994 with THD = 1.6%

Comparative Analysis

The comparative analysis of recent studies highlights a clear evolution in dual-stage interleaved onboard charger (OBC) research for electric vehicles. Early investigations primarily focused on converter topology development, power factor correction, and conventional PI/PID-based control strategies to improve charging efficiency and reduce harmonic distortion. From around 2018 onward, research shifted toward computational intelligence, where optimization techniques such as Genetic Algorithm, Particle Swarm Optimization, Grey Wolf Optimizer, Whale Optimization, Harris Hawks Optimization, and other bio-inspired algorithms became increasingly popular for controller tuning and parameter optimization. This transition reflects the growing complexity of modern OBC systems, which require intelligent optimization to achieve higher efficiency, faster dynamic response, and improved power quality under varying operating conditions.

Another significant trend is the advancement of controller architectures. Conventional PI and PID controllers have gradually been replaced by more sophisticated methods, including fractional-order PID, proportional-resonant controllers, model predictive control, adaptive fuzzy controllers, reinforcement learning, and higher-order PIDD-based structures. These advanced controllers offer superior disturbance rejection, reduced settling time, and improved robustness against nonlinearities and parameter variations. At the hardware level, validation platforms have progressed from simple DSP-based prototypes to FPGA and real-time embedded systems, while the adoption of SiC and GaN power devices has enabled higher switching frequencies, greater power density, and improved thermal performance.

The application scope has also broadened considerably beyond conventional AC charging. Recent studies increasingly focus on bidirectional vehicle-to-grid (V2G) operation, wireless charging, modular charger architectures, and intelligent energy management. Hybrid optimization approaches combining multiple metaheuristic techniques have demonstrated enhanced convergence speed and global search capability compared with single algorithms. Overall, the literature indicates a clear movement toward adaptive, AI-driven, and highly optimized OBC systems capable of meeting the stringent efficiency, reliability, and smart-grid integration requirements of next-generation electric vehicles.

Discussion

The reviewed literature demonstrates that artificial intelligence and optimization techniques have significantly improved the performance of dual-stage interleaved onboard chargers for electric vehicles. Metaheuristic algorithms such as Genetic Algorithm, Particle Swarm Optimization, Grey Wolf Optimizer, Harris Hawks Optimization, and hybrid optimization methods consistently outperform conventional tuning approaches by enhancing converter efficiency, power quality, transient response, and system stability. These techniques effectively solve the complex nonlinear optimization problems associated with controller parameter tuning, making computational intelligence an essential component of modern OBC design. Advanced controller structures, including fractional-order PID, model predictive control, fuzzy logic, and PIDD2-PD controllers, further improve charging performance under varying operating conditions.

Despite these advancements, several challenges remain. Many existing optimization algorithms suffer from premature convergence, sensitivity to initialization, and inconsistent performance when applied to highly nonlinear or large-scale optimization problems. Similarly, although advanced controllers provide better dynamic response and disturbance rejection than conventional PI/PID controllers, their performance strongly depends on effective parameter optimization. Hybrid optimization approaches have shown promising results by combining the strengths of multiple algorithms, yet many lack a systematic design framework and comprehensive validation across different operating scenarios and hardware platforms.

Future research should focus on developing adaptive and computationally efficient optimization algorithms suitable for real-time embedded implementation in electric vehicle chargers. Emerging AI techniques, lightweight neural networks, and hardware-aware optimization strategies offer promising opportunities for enhancing controller performance while meeting automotive constraints on computation, reliability, and safety. Furthermore, extensive hardware-in-the-loop testing and real-world experimental validation will be essential to ensure that next-generation intelligent onboard chargers satisfy the stringent efficiency, robustness, and smart-grid integration requirements of future electric mobility systems.

Conclusion

This review has presented a comprehensive overview of artificial intelligence techniques for dual-stage interleaved onboard chargers in electric vehicles, emphasizing advanced controller optimization through modern metaheuristic algorithms. The reviewed studies demonstrate a clear progression from conventional control methods toward intelligent optimization approaches capable of improving charging efficiency, power quality, transient response, and system reliability. As electric vehicles become a key component of sustainable transportation, the development of efficient and intelligent onboard chargers is increasingly important for enhancing charging performance and supporting future smart-grid applications.

The literature also highlights a continuous evolution in converter topologies, controller architectures, and optimization strategies. Advanced controllers such as fractional-order PID, model predictive control, fuzzy logic, and PIDD2-PD have consistently outperformed conventional PI/PID controllers when combined with effective optimization algorithms. Similarly, hybrid metaheuristic techniques have shown superior exploration and exploitation capabilities compared with single optimization methods, providing better parameter tuning for complex nonlinear charging systems. These developments demonstrate that integrating artificial intelligence with advanced power electronics significantly improves overall charger performance.

Future research should focus on adaptive hybrid optimization algorithms, lightweight AI models suitable for real-time embedded implementation, and extensive hardware validation under practical operating conditions. The integration of SiC/GaN power devices, vehicle-to-grid functionality, and intelligent energy management will further enhance charger efficiency and reliability. Overall, AI-driven optimization represents a promising direction for developing next-generation onboard chargers that meet the growing demands of electric mobility, energy efficiency, and sustainable transportation infrastructure.

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