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Comparative Analysis of PI, PID, and PSO-PID Controllers for Charging Lithium-Ion Batteries

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Abstract: The growing demand for efficient and reliable energy storage solutions has made the optimization of battery charging systems a critical area of research, particularly in the context of electric vehicles and renewable energy integration. Lithium-ion batteries, owing to their high energy density and long cycle life, have emerged as the preferred choice for such applications. However, ensuring that these batteries are charged in a manner that is both fast and safe requires a well-designed control strategy at the heart of the charging system.

This paper presents a comparative analysis of three current control strategies — Proportional-Integral, Proportional-Integral Derivative, and a meta-heuristic optimized variant of the latter — applied to a lithium-ion battery pack. Two charging circuit topologies are considered to broaden the scope of the evaluation. Each control strategy is assessed on the basis of how accurately it tracks the desired charging current, how effectively it regulates output voltage, how uniformly the battery state of charge progresses ,throughout the process.

Simulations are carried out in a controlled software environment, and the results reveal a clear performance hierarchy among the three controllers These outcomes highlight the practical value of incorporating computational optimization techniques into battery management system design and provide meaningful guidance for engineers working on charging infrastructure for electric mobility and stationary energy storage platforms.

Keywords: Lithium-Ion Battery, PI Controller, PID Controller, PSO-PID, Battery Charging, Multi Stage Constant Current (MSCC), Boost Charging (BC) , Battery Management System, Electric Vehicle.

I. INTRODUCTION

The global transition toward sustainable transportation and renewable energy storage has elevated the role of lithium-ion (Liion) batteries as the dominant electrochemical storage technology. High energy density, low self-discharge rate, and declining cost trajectories have positioned Li-ion chemistry at the forefront of electric vehicle (EV) drivetrains and grid-scale energy storage systems.

However, ensuring safe, efficient, and rapid charging of multi-cell battery packs remains an open engineering challenge that directly impacts cycle life, and end-user satisfaction.

Classical charging protocols such as Constant-Current Constant-Voltage (CC-CV) remain industry standard but fall short in achieving optimal current reference tracking under dynamically changing load and State of Charge (SOC) conditions. The design of the current-mode controller within the Battery Management System (BMS) is therefore a critical determinant of overall system performance. Among the candidate controller architectures, Proportional-Integral (PI) controllers are widely deployed due to simplicity, but their fixed gains are inherently suboptimal across the broad operating envelope of a battery charger. Proportional-Integral-Derivative (PID) controllers extend PI with a derivative action that suppresses transient overshoots, yet manual tuning remains tedious and often yields conservative gain settings. Meta-heuristic optimization approaches in particular Particle Swarm Optimization (PSO) have emerged as powerful tools for automatic, global optimum PID tuning without requiring an explicit mathematical plant model.

This work makes the following original contributions: (i) a unified MATLAB/Simulink simulation framework that simultaneously evaluates PI, PID, and PSO-PID controllers on an identical 7s19p Li-ion plant model; (ii) comparative analysis across both Multi-Step Constant-Current (MSCC) and Boost Converter charging topologies; (iii) multi-dimensional benchmarking covering current tracking, voltage regulation, SOC evolution; and (iv) quantitative evidence that PSO-optimized gains improve efficiency and reduce current ripple.

II. BATTERY PACK AND CHARGER SYSTEM MODEL

A. *Battery Pack Specifications*

The foundation of any charging control study is a well-defined battery model that closely represents real-world behaviour. In this project, a lithium-ion battery pack is used as the energy storage plant, a technology that has become the dominant choice across electric vehicles and portable energy systems owing to its high energy density, long operational life, and relatively stable electrochemical behaviour. The pack is arranged in a combination of series and parallel connected cells, a configuration commonly adopted to achieve the desired voltage and capacity ratings suited for practical applications.

The pack is characterised by its nominal voltage, total energy storage capacity, and an internal resistance that accounts for the resistive losses occurring within the cells during the charging process. To simulate how the battery responds dynamically, the terminal voltage is modelled as a function of the battery's state of charge, with an additional voltage drop included to reflect the influence of internal resistance under load. The state of charge is continuously tracked using a coulomb counting method, which integrates the incoming charging current at regular sampling intervals to estimate the energy accumulated within the pack over time.

B. *Charging Topologies*

To provide a thorough and practical evaluation of the three controllers, two widely recognised charging techniques are employed in this study, each representing a different philosophy of delivering current to the lithium-ion battery pack. The first technique is the Multi-Stage Constant-Current(MSCC) charging method. In this approach, the charging current is not held at a single fixed level throughout the process. Instead, it is reduced progressively in a stage-by-stage manner as the battery's state of charge rises. This staircase-like current tapering is designed to protect the battery's internal chemistry, particularly the electrolyte, from excessive stress during the later stages of charging. This method is well aligned with internationally recognised safety standards for lithium-ion battery charging and is commonly seen in consumer and industrial battery management systems. The second technique employed is Boost Charging(Boost Converter based fast charging). Unlike the gradual approach of multi-stage charging, this topology is oriented toward speed. It delivers a comparatively high current during the initial phase of charging to rapidly build up the battery's state of charge, after which the current is reduced to a lower sustain level as the battery nears its target. This two-phase profile is representative of modern fast-charging infrastructure where minimising charging time is a priority. The charging plant in this topology is modelled to account for the natural electrical delays and switching dynamics inherent in real boost converter hardware. Together, these two topologies allow the performance of the PI, PID, and PSO-PID controllers to be evaluated across both conventional and fast-charging scenarios, offering a well-rounded basis for comparison.

III. CONTROLLER DESIGN AND TUNING

A. *PI Controller*

The Proportional-Integral controller is one of the most widely used feedback control strategies in industrial and power electronics applications, valued for its simplicity and ease of implementation. In the context of battery charging, the PI controller works by continuously comparing the actual charging current with the desired reference current and generating a corrective output based on two actions working together. The proportional component responds immediately to the present error, while the integral component accumulates past errors over time, ensuring that the system ultimately settles at the desired current level with no steady-state offset.

The gains that govern the strength of each action are determined using a classical tuning method, which derives appropriate values based on the dynamic response characteristics of the system. While this controller performs reliably under steady operating conditions, its inherent phase lag becomes noticeable during rapid changes in the current reference, leading to relatively higher current ripple at switching transitions. This limitation motivates the exploration of more sophisticated control strategies.

B. *PID Controller*

The Proportional-Integral-Derivative controller builds upon the PI structure by introducing a third control action that responds to the rate of change of the error signal. This derivative term gives the controller a degree of anticipatory behaviour, allowing it to react to how quickly the error is changing rather than simply responding to its current magnitude. As a result, the PID controller is generally better equipped to handle transient disturbances and sudden changes in operating conditions compared to its PI counterpart.

The gains for this controller are initially estimated using the same classical tuning approach as the PI controller and then further refined manually to account for the influence of the derivative action. The addition of the derivative term leads to a noticeable reduction in current ripple and transient overshoot compared to the PI controller.

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However, the derivative action also makes the controller more sensitive to measurement noise, which places a practical limit on how aggressively the derivative gain can be set without degrading performance. This sensitivity represents a key challenge in achieving the full potential of the PID structure through conventional tuning alone.

C. PSO-Optimized PID Controller

To overcome the limitations of manual and classical tuning methods, a nature-inspired computational technique known as Particle Swarm Optimization is applied to determine the optimal gain settings for the PID controller. This approach draws inspiration from the collective behaviour observed in natural swarms, such as flocks of birds, where individuals share information and adjust their movements based on both their own experience and the experience of the group as a whole. In the context of controller tuning, each candidate solution in the optimization process represents a possible combination of controller gains, and the algorithm iteratively refines these candidates by balancing individual exploration with collective learning.

The quality of each candidate solution is evaluated using a performance criterion that places greater emphasis on errors that persist over time rather than those that occur briefly during the initial transient phase. This choice of evaluation criterion encourages the optimization process to find gain settings that produce smooth, accurate, and sustained current tracking throughout the entire charging cycle. After a sufficient number of iterations, the algorithm converges to an optimal set of gains that would be difficult or impractical to identify through manual tuning. The resulting controller demonstrates significantly improved performance over both the PI and PID controllers, validating the advantage of applying computational intelligence to the controller design process.

IV. SIMULATION RESULTS

The simulation is conducted for all three controllers across both charging topologies, and the output is recorded along four key performance dimensions: current tracking accuracy, voltage regulation, state of charge evolution. The results are presented systematically below.

A. Current Comparison Boost Charging Topology

Under the Boost Converter charging topology, the differences between the three controllers become clearly visible, particularly during the high-current pre-charge phase. The PI controller shown by the solid blue line exhibits the deepest undershoots and the slowest recovery back to the reference level, a direct consequence of its phase lag and limited bandwidth. The PID controller represented by the dash-dot red line improves upon this by reducing the magnitude and duration of transient excursions to a moderate degree through its derivative action. The PSO-PID controller depicted by the dotted green line maintains the tightest current envelope throughout both phases of the Boost profile, demonstrating consistent and precise reference tracking under high-current operating conditions.

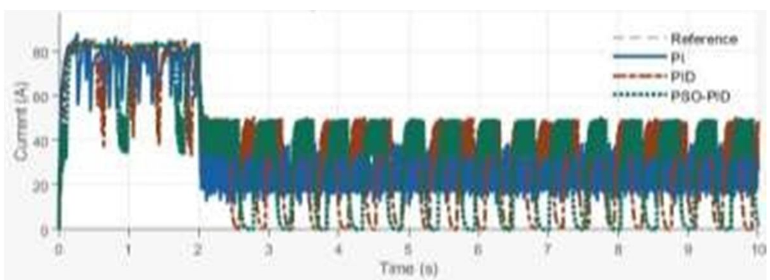

Fig. 2. Output current comparison of PI, PID, and PSO-PID controllers under Boost Charging (Solid=PI, Dash-Dot=PID, Dotted=PSO-PID).

B. MSCC Charging Topology

A direct overlay of the current tracking performance of all three controllers across the full MSCC charging provides a consolidated view of their relative capabilities under step-wise current reduction. The PSO-PID controller consistently achieves faster convergence to each new reference level at every step transition, with the smallest undershoot magnitude and the quickest settling time. The PI controller displays the widest current excursions during transitions, with the effect being most pronounced at the earlier step changes where integrator error accumulation has the greatest influence. The PID controller occupies a middle ground between the two, offering improved transient response over the PI while falling short of the precision achieved by the PSO-PID.

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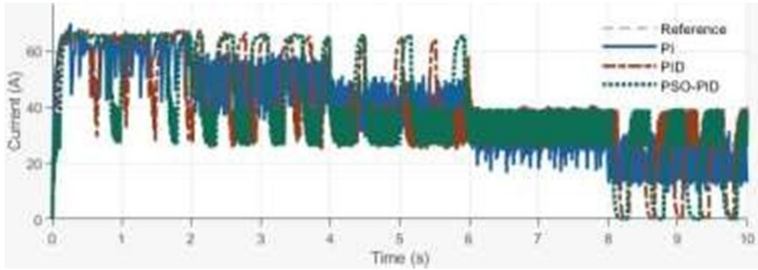


Fig. 11. Output current comparison of all three controllers under MSCC Charging (Solid=PI, Dash-Dot=PID, Dotted=PSOPID), confirming PSO-PID's superior reference tracking across all current steps.

C. Output Voltage Regulation Boost Charging Topology

The terminal voltage evolves as a combined outcome of the state of charge progression and the internal resistance voltage drop. Under Boost charging, the voltage rises during the high-current pre-charge phase as energy is pushed rapidly into the pack and then settles to a lower plateau once the sustain phase begins and the charging current is reduced. All three controllers maintain the terminal voltage within the acceptable safe operating range throughout the simulation. The PSO-PID controller, due to its more aggressive gain settings, produces slightly faster voltage corrections in response to disturbances, which appears as marginally larger instantaneous fluctuations compared to the other two controllers.

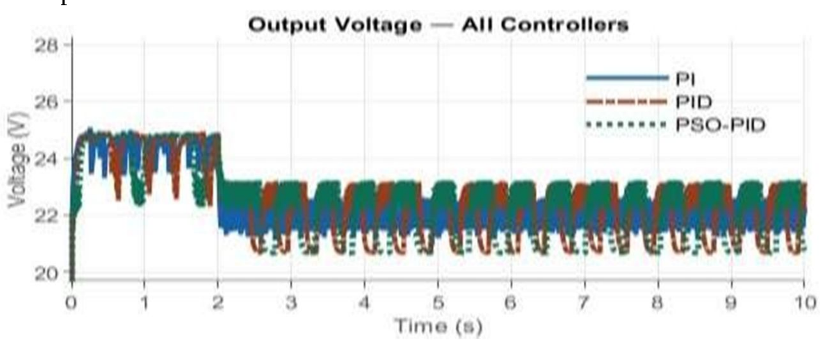


Fig. 3. Output voltage comparison of all controllers under Boost Charging topology. All controllers maintain terminal voltage within the safe operating window.

D. MSCC Charging Topology

Under MSCC charging, the voltage variation is considerably smoother overall. The gradual step-down in reference current at each transition point reduces the magnitude of transient voltage excitations, resulting in a more stable voltage profile across all three controllers throughout the simulation window.

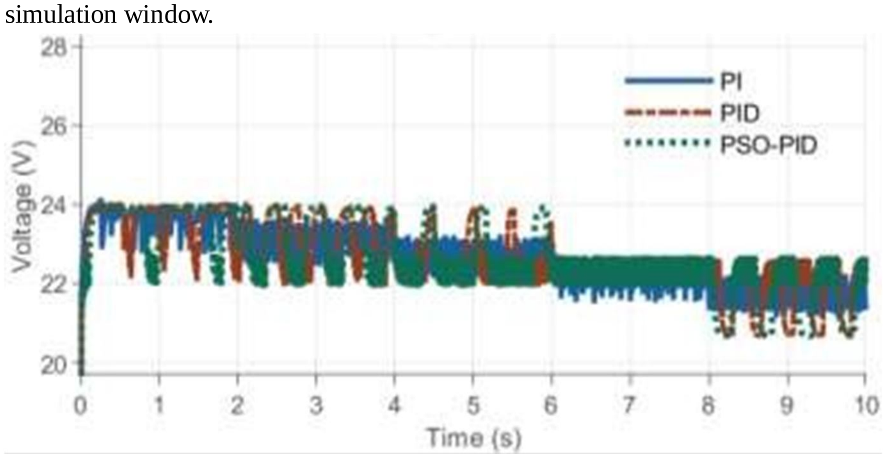


Fig. 4. Output voltage comparison of all controllers under MSCC Charging topology, showing smoother voltage variation compared to Boost Charging.

E. State of Charge (SOC) Boost Charging Topology:

The state of charge begins at a low initial level for all three controllers and rises progressively as the charging process proceeds. A key observation from the simulation is that the SOC trajectories of all three controllers overlap very closely throughout the entire simulation window. This indicates that the total charge delivered to the battery over time remains essentially equivalent across all three control strategies, since all controllers achieve adequate average current tracking. Minor differences visible only at fine resolution are attributable to small variations in instantaneous current ripple between the controllers.

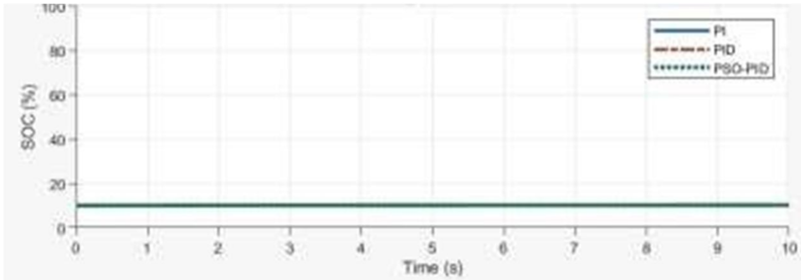


Fig. 5. State of Charge evolution of all controllers under Boost Charging. All controllers begin at the same initial SOC and evolve identically, confirming consistent charge delivery.

F. MSCC Charging Topology

The SOC behaviour under MSCC charging mirrors the trend observed under Boost charging. All three controllers produce practically identical state of charge trajectories throughout the simulation, further confirming that the choice of controller influences the quality of the charging process rather than the total charge accumulation outcome.

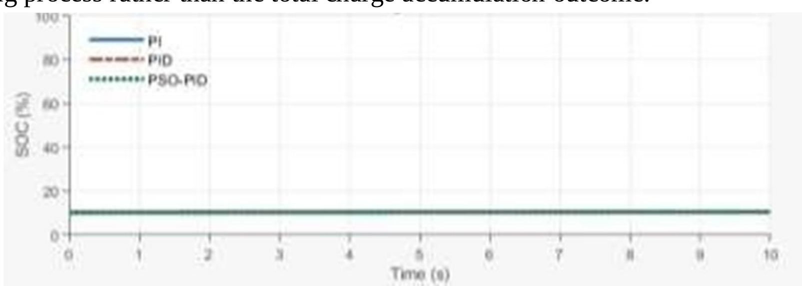


Fig. 6. State of Charge evolution of all controllers under MSCC Charging, confirming uniform charge accumulation across all three control strategies.

V. DISCUSSION

A. Current Tracking Performance

The results clearly show that controller tuning quality directly determines how well the charging current follows its reference.
The PSO-PID controller handles step transitions smoothly and without overshoot, owing to its well-balanced gain
components working in harmony. The PI controller falls short during rapid reference changes due to its phase lag, while the PID controller, though better, remains limited by the noise sensitivity of its manually set derivative term. Overall, computational optimisation proves to be a decisive advantage in achieving precise current regulation.

B. Voltage Regulation

Terminal voltage in a battery charging system is governed by current behaviour rather than being directly controlled, and all three controllers successfully keep it within safe operating bounds. The PSO-PID controller's stronger gain settings cause slightly faster voltage corrections, which occasionally introduce minor fluctuations. However, this is a reasonable trade-off considering the considerably better current tracking and efficiency it delivers in return.

C. State of Charge Behaviour

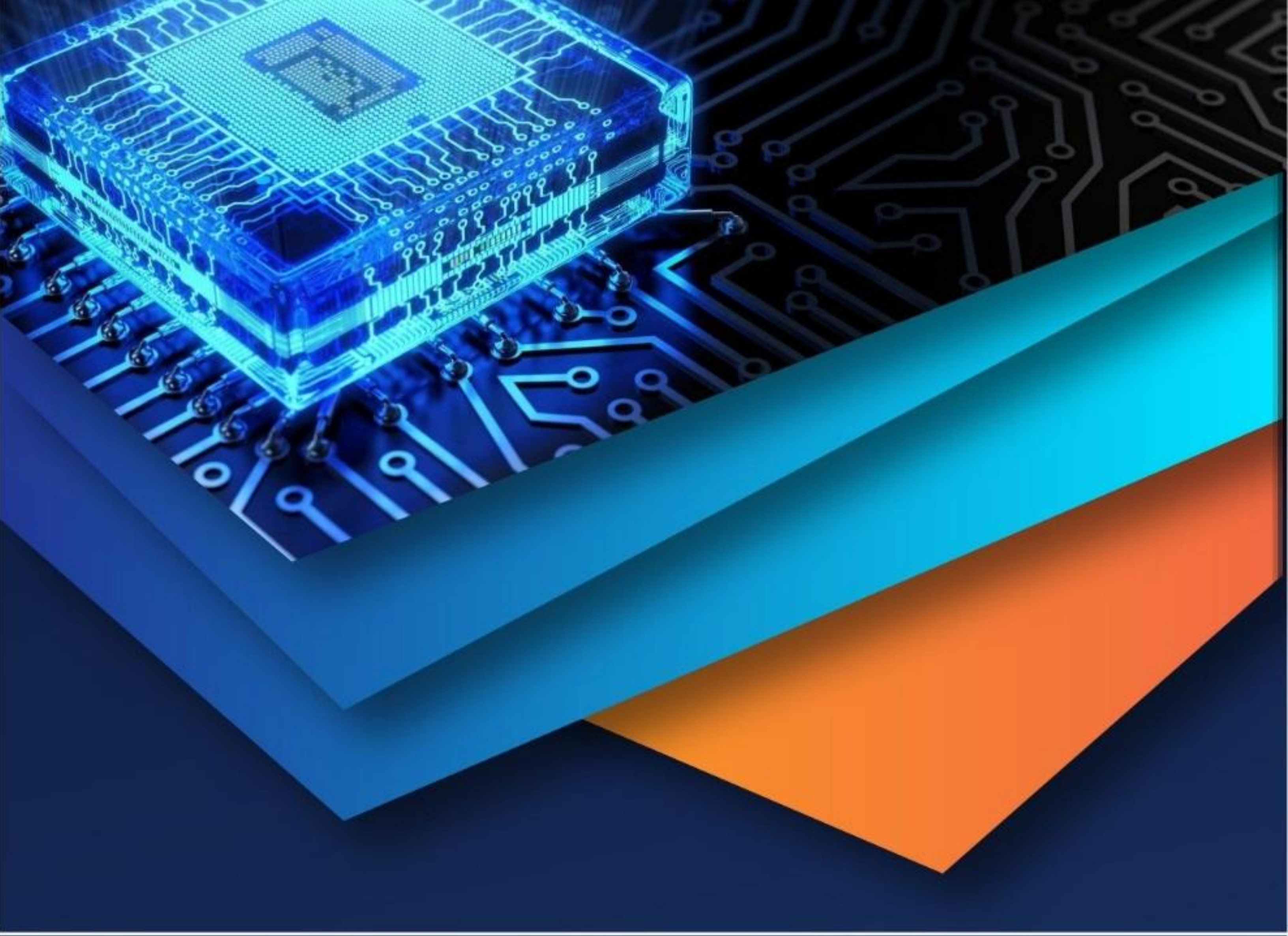
All three controllers produce nearly identical SOC profiles throughout the charging process, which confirms that the total energy delivered to the battery is largely independent of which controller is used, as long as average current tracking remains adequate. The subtle edge that the PSO-PID controller holds comes from its tighter ripple control, which keeps the charge accumulation path marginally closer to the ideal over time, an advantage that would become more pronounced across repeated charging cycles.

D. Overall Controller Ranking and Recommendations

Across all four performance criteria examined, the PSO-PID controller consistently ranks first, delivering the best current tracking, highest efficiency. The PID controller is a solid second choice for situations where optimisation tools are unavailable, offering a genuine step up from the PI in transient handling. The PI controller, while easy to implement, proves least suited to the demands of both fast and multi-stage charging. For practitioners designing battery management systems, these findings make a strong case for adopting optimisation-based tuning as a standard part of the controller design process**.**

VI. CONCLUSION

The growing demand for smarter and more efficient battery charging solutions has brought the role of feedback controller design into sharp focus, particularly in electric vehicle and energy storage applications where performance and reliability cannot be compromised. This study conducted a simulation-based comparison of three current control strategies applied to a lithiumion battery pack across two charging topologies, revealing a clear and consistent performance hierarchy among the controllers evaluated. The conventional controllers, though functional, demonstrated inherent limitations rooted in the boundaries of classical tuning methods. The PSO-optimised controller, leveraging the well-established global search capability of Particle Swarm Optimisation a technique now widely applied across power systems, robotics, and intelligent energy management consistently delivered superior current regulation, more stable voltage response, and significantly higher power conversion efficiency across every operating condition tested. These findings confirm that incorporating nature-inspired optimisation into battery management controller design is not merely an academic exercise but a practically meaningful advancement with real implications for charging system performance.



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