

Research on PID-Based Constant Current-Constant Voltage Transition Control Techniques for Lithium Battery Chargers

Yongkang Min

*International College, Chongqing University of Posts and Telecommunications, Chongqing, China
1579442174@qq.com*

Abstract. To address the challenge of smooth constant-current constant-voltage (CC-CV) transitions in lithium battery charging, this paper investigates recent studies on PID control applications. Thus, it highlights PID-based CC-CV transition techniques for lithium battery chargers and details their improvements, constraints, and future directions. Though recent literature on lithium battery charging characteristics, core control requirements, PID control theory, Buck converter modeling, and transition architecture evolution has been reviewed and analyzed, this study further provides a comprehensive summary and comparison of the design, implementation, and optimization of PID control in CC-CV charging systems. The results reveal that PID control, valued for its simplicity and ease of implementation, remains central but struggles with parameter tuning and robustness under complex conditions. Key improvements include enhancing hysteresis transition methods with anti-windup techniques, adopting smooth transition schemes through fuzzy PID adaptive control and state observers, and advancing multi-objective strategies to optimize efficiency and thermal management. Future progress depends on interdisciplinary efforts like machine learning-based parameter tuning, high-frequency control using wide-bandgap semiconductors, and broader adoption in wireless charging applications.

Keywords: Constant-Current Constant-Voltage Transition Control, PID Controller, Lithium Battery Charging Management, Buck Converter, Multi-Objective Optimization

1. Introduction

Lithium batteries, valued for their high energy density, require charging management that balances efficiency, speed, and safety due to voltage limits and overcharge risks impacting lifespan. Thus, the Constant-Current Constant-Voltage (CC-CV) strategy, which balances charging rate and safety, has been widely adopted in engineering practice, yet a key challenge lies in achieving smooth and rapid transitions between these two phases [1]. In addition, PID control, valued for its simplicity and fast response, is widely used to regulate charging current and mitigate temperature rise risks. However, its poor adaptability in complex operating conditions and limited capability in handling nonlinear systems restrict performance in high-demand scenarios such as fast charging [2]. Hence, the examination of the core role, progress, and bottlenecks of PID control in CC-CV transitions is essential for advancing efficient, safe, and adaptive charging technologies. This paper explores PID control-based CC-CV transition techniques for lithium battery chargers, covering core mechanisms,

implementation methods, performance improvements, and main technical challenges. Specifically, it evaluates the role of PID control in ensuring safe and efficient execution of the CC-CV strategy while assessing its adaptability and limitations under battery parameter variations, load disturbances, and fast-charging conditions. By reviewing recent progress such as improved hysteresis switching, fuzzy adaptive integration, and state-observer-based control, it investigates their ability to improve regulation accuracy, boost system robustness, and enable coordinated control of charging efficiency, thermal management, and battery life. Besides, it outlines key challenges and proposes solutions like machine learning tuning, high-frequency control, and wireless charging to guide future work.

2. Lithium battery charging strategy and control requirements

2.1. Intercalation/deintercalation mechanisms and multi-stage charging characteristics

Lithium batteries store energy through lithium ion movement in electrodes, with electrode stability and process reversibility directly impacting energy density, lifespan, and safety. During charging, lithium ions move from the cathode through the electrolyte and separator into the graphite anode's layers; during discharging, they reverse direction, returning to the cathode for reduction [3]. Limited by material chemical stability and electrolyte voltage tolerance, lithium battery charging voltage is usually capped at 4.2 V, while current control must balance ion diffusion and polarization. As such, the industry widely uses a combined CC-CV charging strategy to improve efficiency and reduce side-reaction risks. In the CC phase, a constant current raises the battery voltage to a set limit by quickly injecting charge. In the CV phase, the voltage is held constant while the current slowly decreases to a safe cutoff, ensuring full charging of the electrode materials, as shown in Figure 1 [4]. This multi-stage charging method blocks lithium plating, lowers electrolyte decomposition risks, and maintains electrode structural integrity, ensuring high safety and extended lifespan.

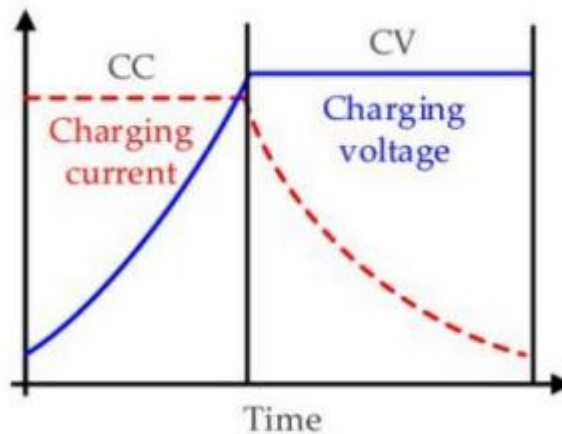


Figure 1. CC-CV transition process

2.2. Charging safety constraints and performance optimization requirements

Throughout charging, lithium batteries face risks such as overcharging, overcurrent, and localized overheating, which can lead to capacity loss, internal shorts, or thermal runaway if left unchecked. Consequently, charging systems must possess high-precision voltage/current monitoring and rapid response capabilities to immediately interrupt charging or switch control strategies upon detecting voltage overshoots or abnormal currents [5]. During product design, multi-level safety protection

loops combine overvoltage protection ICs, fuses, temperature sensors, and backup alarms to boost stability and reliability in complex conditions. During product design, multi-level safety protection loops, comprising overvoltage protection ICs, fuse circuits, temperature sensors, and redundant alarm mechanisms, are used to improve system stability and reliability in complex conditions. Beyond safety, system design aims for fast, efficient charging while minimizing performance loss. Factors like charging current, C-rate, ambient temperature, and internal heat affect electrode life and side reactions. Therefore, precise setting of CC current, CV cutoff, and the CC-CV transition point is essential to balance efficiency and battery lifespan. In recent years, PID-based charging strategies have shifted from single-parameter control of voltage or current to multi-parameter schemes that include temperature feedback and adaptive state estimation, improving safety, efficiency, and cycle life in fast charging [6].

3. Implementation and optimization of PID control in lithium battery CC-CV charging

3.1. Fundamental principles and parameter design

In lithium battery charging control, the PID controller adjusts voltage and current through feedback, serving as an important tool for balancing system stability and response speed. Its basic structure, shown in Figure 2, consists of three components: proportional (P), integral (I), and derivative (D), which address the present value, accumulated value, and rate of change of the error, respectively, enabling dynamic tracking and correction toward the set target.

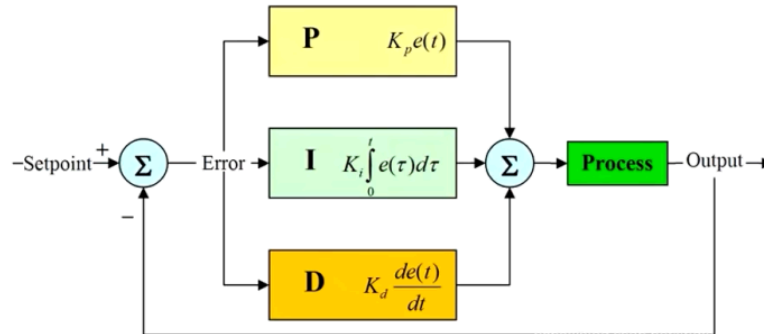


Figure 2. Principle of PID control

In the continuous domain, the output $u(t)$ of a PID controller is expressed as:

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau + K_d \frac{de(t)}{dt} \quad (1)$$

where K_p , K_i , and K_d denote proportional, integral, and derivative gains respectively, and $e(t)$ represents the deviation between setpoint and actual values.

In digital control systems, the controller operates in discrete form, requiring transformation into a difference equation at sampling intervals. With the sampling period set as T_s , the discrete form of the controller is expressed as follows.

$$u(k) = K_p e(k) + K_i T_s \sum_{i=0}^{k-1} e(i) + K_d \frac{e(k) - e(k-1)}{T_s} \quad (2)$$

The PID controller can operate in digital control systems through discretization, though this also introduces issues such as sampling delay that must be addressed through careful design to optimize performance. Classical heuristic methods, including Ziegler-Nichols and Cohen-Coon, work well for most linear processes but are less effective for nonlinear or strongly coupled systems [7,8]. In recent years, optimization-based auto-tuning methods have been widely adopted to improve adaptability and accuracy. Algorithms like Particle Swarm Optimization (PSO), Genetic Algorithm (GA), and Ant Colony Algorithm (ACA) define objective functions such as Integral Absolute Error (IAE) or Integral Squared Error (ISE) and automatically search for optimal gain parameters, thus enhancing responsiveness across varying battery states and charging phases [9,10]. Furthermore, model-based control designs, including Internal Model Control, H_∞ control, and Model Predictive Control, offer multi-goal, constraint-based dynamic adjustment for CC-CV charging [11,12].

3.2. Analog circuit and digital implementation of PID control

The implementation of PID controllers, whether via analog circuits or digital algorithms, reflects the evolution of charging control strategies in terms of system architecture, tuning flexibility, and real-time responsiveness. Early systems used analog PID controllers with operational amplifier circuits to handle proportional, integral, and derivative actions for error correction and response prediction in real time. To improve stability and suppress high-frequency noise, designs often added lead-lag compensation networks to boost phase margin and speed up response [13]. Despite their fast response and simple structure, analog implementations relied on physical component tuning, limiting adaptability to complex or rapidly changing charging conditions. As embedded systems advanced, PID control moved toward digital implementation, where continuous laws are discretized into difference equations for execution on MCU or DSP platforms. Methods such as forward Euler, backward Euler, and Tustin transformations are used, with positional or incremental structures balancing computational load and response performance [14,15]. The digital approach enables high tunability and system integration, allowing real-time parameter adjustments while simultaneously acquiring key variables, such as voltage, current, temperature, and State of Charge, to optimize PID gains across charging phases and conditions. Compared with analog control, digital PID offers better compatibility with the nonlinear, variable-state nature of lithium battery systems, thus making it the dominant strategy in modern battery management.

3.3. Transition and evolution from single PID to dual PID strategies

During lithium battery charging, phase-specific electrochemical behaviors demand different control needs, making it difficult for a single PID controller to maintain high performance in both the CC and CV stages. In the CC phase, the system must quickly and stably deliver current, while in the CV phase it must accurately regulate terminal voltage to avoid overcharging. However, a single PID controller with fixed parameters cannot simultaneously accommodate these distinct operational characteristics. Parameter mismatches during CC–CV transitions or under heavy load disturbances can cause oscillations or overshoot, reducing efficiency and increasing thermal and safety risks. To address this limitation, dual PID strategies use separate closed loops, one for current control in the CC phase to speed charging, and another for voltage control in the CV phase to avoid overcharging. Figure 3 illustrates this architecture, where a state monitoring module continuously analyzes key indicators like State of Charge, voltage, and temperature to determine transition logic. Compared to single PID structures, the dual PID strategy improves transition smoothness and adapts parameters for dynamic compensation against nonlinear disturbances and load fluctuations [16,17].

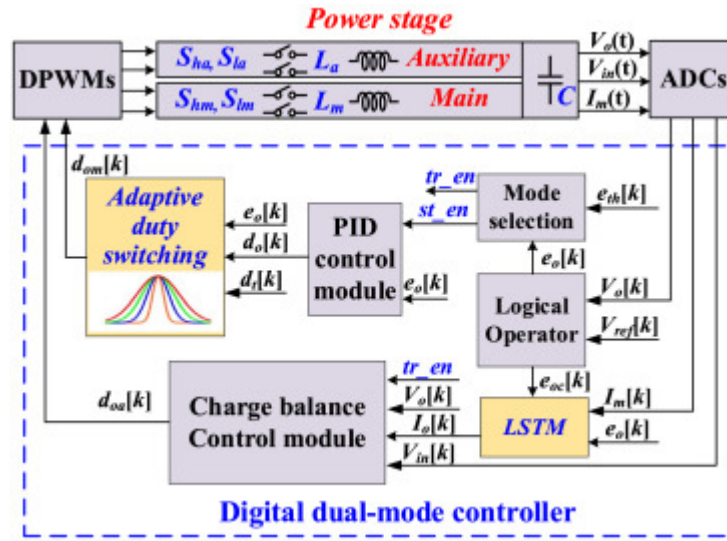


Figure 3. Dual-PID control architecture

4. Evolution and optimization strategies for CC-CV transition control

4.1. Buck converter modeling and control fundamentals

The Buck converter, widely used as a step-down power module in lithium battery chargers, ensures steady conversion of high input voltage to the battery's required voltage and current via MOSFET switching control, thereby meeting the control demands of both CC and CV charging stages [18]. Using PWM control, the output voltage is adjusted through duty cycle modulation ($V_{out} \approx D \times V_{in}$), enabling closed-loop regulation for CC/CV operation. To support controller design, the Buck circuit is typically modeled with the state-space averaging method for small signals, approximating the nonlinear switching behavior as a linear time-invariant system. This approach enables analysis of the dynamic response near the steady state. The modeling uses inductor current and output capacitor voltage as state variables to derive the input-output transfer function, which serves as a fundamental basis for PID controller tuning, stability analysis, and frequency compensation design [19,20].

However, in practical systems, the Buck control process faces various non-ideal factors such as switching losses during MOSFET conduction and cutoff, non-ideal conduction characteristics of the MOSFET, parasitic parameters of inductors and capacitors, and sudden load changes. These can cause output voltage deviations, reduced system bandwidth, and delayed response [21]. Especially at the CC-CV stage transition, inadequate filter design or poor control response can cause overshoot, fluctuations, or even instability. Hence, to enhance control robustness and ensure stable filter output, control strategies must further improve disturbance rejection based on the modeling foundation. For example, current mode control (CMC) with feedback compensation can improve dynamic response, while adaptive and nonlinear controllers can enhance stability and tracking performance under load disturbances and voltage fluctuations in non-ideal conditions [22].

4.2. Hysteresis control strategy and transition challenges

The stage transition in the CC-CV charging strategy relies on threshold settings, and the hysteresis control mechanism, which is known for its simplicity and fast response, is commonly adopted as the default switching method in practical applications. It works by setting an upper and lower hysteresis

band around the target voltage. To avoid frequent switching from noise or small disturbances and boost system stability, a state transition is triggered whenever the battery voltage or current reaches the hysteresis thresholds, as shown in the typical hysteresis switching diagram in Figure 4 [23,24].

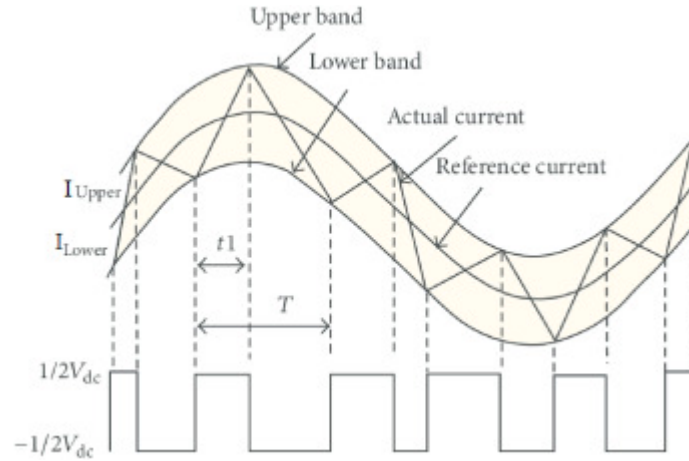


Figure 4. Hysteresis switching diagram

The effectiveness of the hysteresis strategy depends on the selected threshold bandwidth. If the bandwidth is too narrow, increased sensitivity to noise and minor disturbances will cause oscillatory switching between CC and CV phases, thereby increasing control loop load and lowering charging efficiency. Conversely, an excessively wide bandwidth may result in delayed switching, keeping the system in a suboptimal state that slows charging and adds heat stress to the battery. Besides, battery characteristics dynamically vary with temperature, charge rate, and aging, making fixed thresholds inadequate for all operating conditions. To enhance hysteresis switching stability and adaptability, some studies use fuzzy logic to dynamically adjust the upper and lower limits based on voltage rise or charge rate, allowing automatic sensitivity tuning during different charging phases. Furthermore, the optimization of hysteresis width and adjustment of controller bandwidth and filter parameters improve disturbance robustness and reduce switching oscillations caused by control delays [24]. In addition, smooth transition strategies have been proposed, employing slope-tracking control at the CC-CV boundary to enable gradual current or voltage changes, hence avoiding shocks from abrupt switching [25]. For embedded implementations, integrating real-time detection capabilities from the Battery Management System (BMS) is necessary to dynamically update threshold parameters based on actual State of Charge (SOC) and temperature feedback, enhancing the overall adaptability and safety margin of the control strategy [26].

4.3. Fuzzy control and state observation techniques

To overcome the limitations of traditional PID control in lithium battery CC-CV transitions, such as inadequate adaptive parameter tuning and poor response to nonlinear, time-varying systems, more intelligent control strategies have been integrated. Key advancements include adaptive parameter adjustment and state-observer enhancement. Fuzzy PID adaptive switching techniques combine the nonlinear processing of fuzzy logic with the structural advantages of PID control [27]. Using fuzzy rules, PID parameters are dynamically adjusted online to adapt to the nonlinear, time-varying characteristics and external disturbances of the battery charging process. This approach greatly improves system robustness, effectively reduces oscillations during transitions, and facilitates smooth switching between the CC and CV stages. Besides, optimization algorithms like PSO and its

improved version (IPSO) can tune fuzzy PID parameters offline or online, improving dynamic response and accuracy, and enabling fast charging with optimized performance, as shown in Figure 5 [27]. Using measurable inputs and outputs, state observer-based smooth transition techniques estimate internal states like State of Charge and resistance, improving state estimation accuracy [28]. During the CC-CV transition, the PID controller relies on these precise state estimates for more reliable feedback. Using observed states to adjust PID parameters or setpoints results in smoother, more precise switching and avoids sudden voltage or current shifts. As a result, charging efficiency is improved while better protecting battery health and extending lifespan [26].

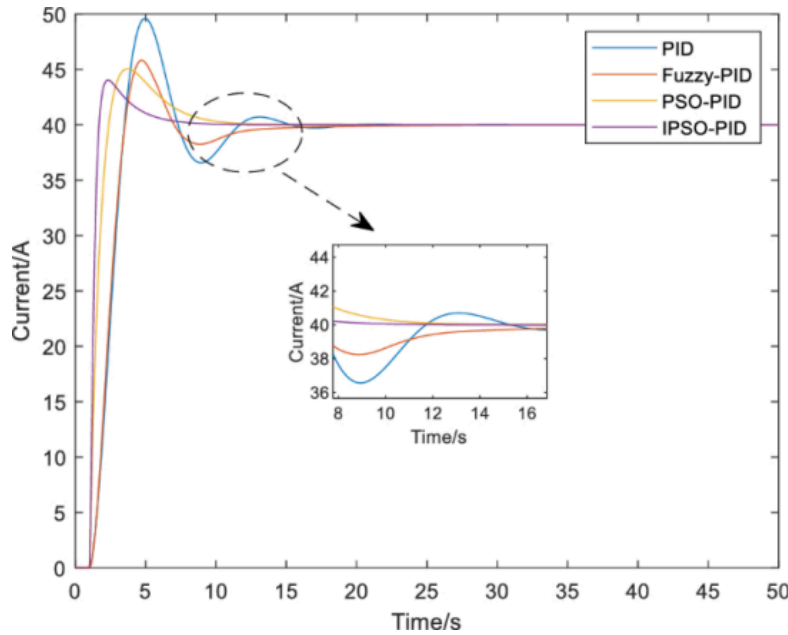


Figure 5. Current variation over time for four control algorithms

4.4. Thermal management optimization and multi-objective coordination

As lithium battery charging demands rise, CC-CV transition control evolves toward multi-objective optimization, balancing charging speed, efficiency, thermal management, battery life, and safety. In particular, efficiency-thermal coupling control is a key focus since charging heat affects battery life and safety, while higher efficiency reduces thermal stress, showing strong interdependence [29]. In response, precise temperature sensors, active cooling, and dynamic control algorithms are proposed for integration. These systems dynamically adjust charging current, voltage setpoints, and CC-CV transition thresholds based on real-time temperature and State of Charge, optimizing overall thermal conditions while maintaining high-efficiency operation [30]. Fast-charging conditions push control systems to be more responsive and adaptable. As such, real-time state monitoring systems are used to track critical internal variables, such as internal resistance, temperature rise, enabling dynamic adjustment of controller parameters or transition thresholds. Intelligent optimization methods like fuzzy control, Model Predictive Control, and neural networks are employed to improve transition stability and accuracy while reducing stress from voltage and current transients [1]. Through these dynamic adjustment strategies, high-performance charging management can be achieved, fulfilling fast-charging requirements while minimizing negative impacts on battery health [1].

5. Future development trends

To overcome the current limitations of PID-based CC-CV charging technology for lithium batteries and enable sustainability, a deep integration of algorithmic innovation, hardware advancement, and expanded application scenarios is essential. At the algorithm level, machine learning can reshape PID parameter tuning. Unlike trial-and-error methods, it uses large datasets to adaptively optimize PID parameters in complex, variable battery conditions, enhancing control system speed, stability, and robustness while enabling predictive charging and boosting PID adaptability in next-generation battery management systems [31]. At the hardware level, the widespread adoption of wide-bandgap semiconductor devices (SiC/GaN) is set to greatly enhance PID control performance. These devices inherently offer high switching frequencies, low conduction losses, and excellent heat tolerance. They boost charging efficiency and expand PID design space, while higher switching frequencies allow finer control and faster response. Meanwhile, their high reliability eases thermal management, supporting PID control in fast-charging systems targeting maximum efficiency and power density. At the application scenario level, extending PID control to wireless charging offers a promising path for regulating power transfer in inductive coupling, supporting safe, efficient modes such as constant-power operation. When paired with ML-based adaptive tuning, it can address efficiency fluctuations and alignment deviations, boosting robustness and flexibility in complex environments [31]. This integration extends the application boundaries of PID control from wired to wireless systems, opening up new avenues to meet the growing demand for convenient and safe charging.

6. Conclusion

This paper reviews the research progress of PID-based CC-CV transition control for lithium battery chargers, revealing that PID remains the core strategy in such systems for its structural simplicity and ease of implementation, while effectively ensuring charging safety and efficiency. Nevertheless, limited parameter adaptability and robustness under complex conditions hinder its performance in fast-charging scenarios, while recent studies improve it by integrating fuzzy adaptive control and state observers for smoother transitions, using dual PID architectures for phase-specific adaptability, and co-optimizing efficiency with thermal management. Future research should target machine learning-driven dynamic tuning, wide-bandgap-based high-frequency control, and wireless charging, integrating electrochemistry, control theory, materials science, and data algorithms to advance PID for safer, faster, more versatile charging.

References

- [1] Su, J., & Zhang, Y. (2024). Research on lithium battery charging technology and intelligent lithium battery charging system applications. *Digital User*, (50), 257-258.
- [2] Chang, X. (2024). Design of battery temperature control system based on PID technology. *Electronics Technology*, 53(11), 88-89.
- [3] Li, J. (2024). Research on health state estimation and remaining useful life prediction method of lithium batteries. *Shenyang University of Technology*.
- [4] Zheng, Y., et al. (2024). A family of hybrid topologies for efficient constant-current and constant-voltage output of magnetically coupled wireless power transfer systems. *World Electric Vehicle Journal*, 15(12), 578.
- [5] Caraballo-Gomez, M., Restrepo, M., & Orozco-Henao, C. (2024). An optimal overcurrent protection strategy for mitigating the impacts of opportunity charging stations in distribution systems. *International Journal of Electrical Power & Energy Systems*, 159, 110007.
- [6] Wu, T., et al. (2020). Application of PID optimization control strategy based on particle swarm optimization (PSO) for battery charging system. *International Journal of Low-Carbon Technologies*, 15(4), 528-535.

- [7] Zhai, X., Guo, Q., & Gao, F. (2020). Application of Ziegler-Nichols method in engine idle speed controller tuning. *Internal Combustion Engine*, (04), 33-35.
- [8] Ladjouzi, S., & Grouni, S. (2024). A single-neuron-based temperature control of a continuous stirred tank reactor. *MAPAN*, 39(3), 707-719.
- [9] Kong, M., Zhang, L., & Zhang, L. (2025). Research on PID parameter optimization method based on improved particle swarm algorithm. *Computing Technology and Automation*, 44(02), 38-43.
- [10] Ahmed, A., Roy, N.K., & Mahmud, K. (2024). Achieving robust and optimal speed control of DC motor through sliding mode control tuned by genetic and particle swarm optimization algorithms. *Smart Grids and Sustainable Energy*, 9(2).
- [11] Ranjan, A., Mehta, U., & Saxena, S. (2023). A comprehensive review of modified internal model control (IMC) structures and their filters for unstable processes. *Annual Reviews in Control*, 56, 100895.
- [12] Mate, S., et al. (2023). Simultaneous tuning of multiple PID controllers for multivariable systems using deep reinforcement learning. *Digital Chemical Engineering*, 9, 100131.
- [13] Rezaei, I., et al. (2023). Circuit design of a three-stage CMOS amplifier by circuit theory and analysis miller compensation network. *Memories - Materials, Devices, Circuits and Systems*, 6, 100084.
- [14] Sun, S., & Li, S. (2024). Design of temperature control system for water-heated mattress based on positional PID. *Electronic Design Engineering*, 32(15), 66-69+75.
- [15] Song, A., & Liu, J. (2024). Design of switching converter based on incremental PID correction technology. *Automotive Practical Technology*, 49(22), 37-43.
- [16] Li, Q., et al. (2024). Control strategy of bidirectional DC/DC converter under variable load state. *Journal of Physics: Conference Series*, 2703(1), 012087.
- [17] Liu, J., Wei, T., Chen, N., et al. (2024). A dual-mode digital controller with a high accuracy load current estimator and Gaussian adaptive duty cycle switching for fast transient recovery in DC-DC buck converters. *Computers and Electrical Engineering*, 118, 109463.
- [18] Fuchs, M., Spielberger, L., Odreitz, K., et al. (2020). Fast and simple model generation for superjunction power MOSFETs. *E & i Elektrotechnik und Informationstechnik*, 138(1), 48-52.
- [19] Ma, C., Wang, J., Wang, K., et al. (2024). Small-signal modeling and digital control of ZVT-PWM buck converter. *Power Electronics Technology*, 58(05), 129-132.
- [20] Ma, Y., Ma, L., & Zhou, X. (2014). CCM mode modeling and simulation of non-ideal buck converter based on state-space averaging method. *Journal of Tianjin University of Technology*, 30(05), 13-16.
- [21] Alberdi, B., Mazuela, M., San-Sebastian, J., et al. (2023). Switching losses estimation for a push-pull converter based on analytical models considering parasitic elements. In *2023 25th European Conference on Power Electronics and Applications*, 1-8.
- [22] Kim, D., & Shin, J.-W. (2021). Dynamic response of buck converter with auxiliary current control: Analysis and design of practical implementation. *IEEE Transactions on Power Electronics*, 36(12), 13917-13929.
- [23] Lopez-Santos, O., Dantonio, D. S., Flores-Bahamonde, F., et al. (2021). Hysteresis control methods. In *Multilevel Inverters*, 35-60.
- [24] Kudiyanasan, S., Sthalasayanam, N., & Karunakaran, V. (2023). Minimization of torque pulsations by using a novel fuzzy controller in SRM drives for EV applications. *Heliyon*, 9(3), e14437.
- [25] Shi, Y., Ai, X., Rong, J., et al. (2022). A novel constant current control strategy with seamless switching between CC and CV. In *2022 IEEE International Symposium on Circuits and Systems*, 2905-2908.
- [26] He, S., Ruan, W., Deng, R., et al. (2022). Research on IPT constant current and constant voltage charging system based on primary reconstruction. *Power Electronics Technology*, 56(07), 99-101+105.
- [27] Wang, X., Tang, Y., Li, Z., et al. (2024). Research on charging strategy based on improved particle swarm optimization PID algorithm. *Complex & Intelligent Systems*, 10(5), 6421-6433.
- [28] Chen, L., Fu, S., Zhao, Y., et al. (2020). State and fault observer design for switched systems via an adaptive fuzzy approach. *IEEE Transactions on Fuzzy Systems*, 28(9), 2107-2118.
- [29] Tai, L.D., Garud, K.S., Hwang, S.G., et al. (2024). A review on advanced battery thermal management systems for fast charging in electric vehicles. *Batteries*, 10(10), 372.
- [30] Wang, X., & Li, Y. (2024). Optimal efficiency point membership incorporating fuzzy logic and automatic control of various charging stages for electric vehicles. *Frontiers in Mechanical Engineering*, 10.
- [31] Soomro, H.A., Khir, M.H.B.M., Zulkifli, S.A.B.M., et al. (2025). Applications of wide bandgap semiconductors in electric traction drives: Current trends and future perspectives. *Results in Engineering*, 26, 104679.