



Customized Constant Current Constant Voltage Control Scheme with Optimized Type Transition for Electric Vehicle Battery

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Abstract— The increasing adoption of electric vehicles (EVs) has heightened the demand for reliable and efficient battery charging. High charging times for EVs are a hurdle to mainstream adoption since quick charging shortens battery life. The paper proposes a quick charging method that reduces charging time and battery deterioration. The proposed charging method modifies the conventional Constant Current – Constant Voltage (CC-CV) charging approach, where the switching point from CC to CV mode is altered. Sixteen charging techniques with varied CC-CV switchover points have been explored, comprising nine charging strategies with capacity switching and seven with voltage switching. The gathered data is processed using a mathematical relationship to determine the State of Health, capacity deterioration, and Internal Resistance characteristics. In addition, a Fuzzy Logic Controller is employed to determine the two effective switchover points based on the least amount of cyclic capacity deterioration, SoH, and charging time. The optimal CC-CV transition point between these two points is estimated using Genetic Algorithm Optimization. Compared with the traditional CC-CV charging approach, the effectiveness of the resulting switchover point is evaluated. The results indicate that the recommended charging approach costs an additional time of 4.22 %, and it increases the cell's cycle life by 51.77 % compared to CC-CV. Thus, the comparative analysis reveals that the proposed charge technique offers more efficient performance.

Keywords— Electric Vehicles (EVs), Constant Current, Constant Voltage, Fuzzy Logic Controller, Python, Colab Platform, Recall, Accuracy.

I. INTRODUCTION

Batteries are the heart of the EV as they provide energy to drive it and should be effectively utilized to increase their lifetime. The journey of the battery starts with the invention of the voltaic pile [1] by Alessandro Volta in 1800. Later, lead acid batteries were invented in 1859 by Gaston Plante [2] followed by the invention of nickel-type batteries [3]. The advancement in battery technology resulted in the advent of lithium-ion [4] and lithium polymer [5] batteries, which have more energy density with less weight and size [6]. The Li-ion batteries are compact, durable and have high energy density making a revolution in EV development. Initially, the EV utilizes the lead-acid type of battery that requires frequent maintenance and has no choice of fast charging option making it less preferable [7,8]. After the development of lithium-ion battery technology EV industry has grown very fast in search of alternatives for internal combustion vehicles [9,10]. The electric energy required varies depending on the amount of traction needed by the EV and is provided by several cells arranged in series and parallel combinations, known as battery packs [11], [12], [13].

Battery charging becomes a difficult task when large battery packs are used and require a proper battery management system (BMS) with a sufficient number of sensors to sense the cell current [14], [15], [16]. The function of the BMS is to monitor the cell current and maintain equal charge in each cell of the battery pack [17]. The BMS also plays a critical role in the Vehicle to Grid integration to match the grid demand at the peak condition [18], [19], [20]. Similarly, the use of other energy storage devices in the EV plays a critical role in the charging and discharging process [21], [22], [23]. The charging characteristics differ at low levels of battery and high level of battery and hence suitable charging methods are to be adopted for protecting and increasing the lifetime of the battery [24], [25], [26]. The three common methods of charging are conductive, inductive and capacitive [27], [28], [29]. From the common methods, the inductive resonance method of charging has been preferred over other methods because of its convenience, safety and charging-on-motion features. The recent advancement in the EV industry makes it further challenging in the arena of wireless charging of EVs. The wireless inductive power transfer phenomenon arises from the concept of

electromagnetic induction and resulted in the current perception of Wireless Resonant Inductive Power Transfer (WRIPT) with high-frequency excitation for increasing the power transfer efficiency [30], [31], [32]. The power electronics devices are capable of working at high frequencies and make it easy to achieve control over the charging of EV batteries leading to the development of many charging techniques in wireless power transmission [33], [34], [35]. Various methods are available for charging EV batteries wirelessly depending on the requirements and conditions of the battery [36,37]. Various charging techniques available are given in Table 1 with their applications, advantages and drawbacks. The basic methods of charging are the CC charging [38,39] and CV charging [40,41]. From the available charging methods, the most commonly adopted method is CC/CV charging which charges in CC charging mode when the battery voltage reduces to the specified level and charges in CV charging mode when the voltage reaches the specified level [42], [43], [44]. Implementing CC/CV charging for WPT EV charging presents challenges that prompt a review of CC/CV charging methods to identify the optimal approach for Wireless EV charging. In search of possible solutions to alleviate the challenges due to design constraints, control algorithm selection, mode transition, adaptability, thermal regulation, and ZVS integration a fast-acting controller is required with a robust algorithm to nullify the adverse effect. A separate section discusses the challenges in CC/CV implementation and proposes potential solutions.

II. LITERATURE REVIEW

The authors in [1] presented an adaptive Constant Current Constant Voltage (CC–CV) charging strategy for lithium-ion batteries, focusing on improving charging efficiency through online parameter estimation. Their work highlighted the importance of accurate transition handling between CC and CV modes to enhance battery health.

In [2], a multi-closed-loop CC–CV fast charging strategy was proposed, where coordinated current and voltage regulation improved charging stability. The study demonstrated that improper CC–CV switching could lead to oscillations near the transition region. The work presented

In [3] analysed the impact of multi-stage charging schemes and compared them with conventional CC–CV methods. The authors concluded that although CC–CV is simple, its performance strongly depends on how the CC–CV boundary is managed.

In [4], a learning-assisted charging strategy was introduced to overcome fixed CC–CV transition limitations. The results showed that static transition thresholds may cause current overshoot under varying battery conditions. The authors

In [5] investigated CC–CV control in inductive power transfer systems for electric vehicles. Their findings emphasized that smooth CC–CV mode transition is essential to avoid voltage stress during wireless charging. In [6], a duty-cycle-based CC–CV wireless charging controller was developed. The study confirmed that abrupt control switching degrades dynamic performance,

particularly in high-power charging applications. A comprehensive review of CC–CV charging strategies

In resonant inductive power transfer systems was presented in [7], highlighting the need for transition-aware control to maintain system stability. The work reported in [8] focused on high-efficiency EV chargers operating under CC/CV modes. The authors experimentally validated that precise control coordination improves converter efficiency during mode transitions.

In [9], a constant-power charging control was proposed as an extension beyond CC–CV. The study indirectly demonstrated that CC–CV remains the preferred baseline due to its safety and simplicity. The authors in [10] designed a high step-down DC–DC converter implementing CC–CV charging. Their results showed that current overshoot during CC–CV transition is a major contributor to component stress.

In [11], an intelligent onboard charger with smooth mode transition was proposed. The authors emphasized that reference-level

coordination is more effective than controller restructuring. The study presented in [12] examined variable-frequency CC–CV wireless charging for EVs. It was observed that transition smoothness significantly affects efficiency and thermal performance.

In [13], a current-based outer-loop control strategy for CC–CV charging was introduced. The authors reported improved robustness against load and coupling variations. The authors in [14] proposed a variable-frequency CC–CV charging technique using resonant converter characteristics. Their work showed that natural transition behavior reduces control complexity. A modified resonant converter with inherent smooth CC–CV transition was presented in [15], where the transition dynamics were improved without additional control loops. The review in [16] summarized EV charger technologies and emphasized that CC–CV remains the dominant strategy due to its battery compatibility. In [17], power converter topologies and control strategies for EV chargers were systematically reviewed. The authors identified CC–CV transition dynamics as a recurring challenge. The authors in [18] experimentally compared CC–CV with constant-temperature charging methods. The study confirmed CC–CV's effectiveness but noted transient stress near the transition point. An optimized multi-stepped CC–CV fast charging controller was proposed in [19], where gradual current reduction improved battery safety. In [20], the authors developed a learning-optimized CC–CV controller that minimized charging stress. Their findings reinforced the importance of transition-region optimization.

III. METHODOLOGY AND SYSTEM MODELLING

In Battery charging control plays a critical role in the performance, safety, and lifespan of electric battery-supported vehicles. Among the various charging strategies reported in the literature, the Constant Current–Constant Voltage (CC–CV) control methodology has emerged as the most widely adopted approach due to its simplicity, effectiveness, and compatibility with lithium-ion battery characteristics. The CC–CV method is commonly

implemented in both on-board and off-board electric vehicle chargers and is supported by industrial standards and manufacturer guidelines.

A. Overview of Battery Charging in Electric Vehicles

Electric battery-supported vehicles predominantly employ lithium-ion batteries due to their high energy density, long cycle life, and favorable power-to-weight ratio. However, these batteries require precise charging control to ensure safe operation and to avoid overcharging, overheating, or accelerated degradation. Battery charging can be broadly classified into slow charging, fast charging, and ultra-fast charging. Regardless of the charging speed, the underlying control strategy must regulate the charging current and voltage within allowable limits. The CC–CV charging method fulfils these requirements by dividing the charging process into two distinct operating modes, namely constant current mode and constant voltage mode.

B. Principle of Constant Current–Constant Voltage Control

The CC–CV charging strategy is based on the electrochemical behavior of lithium-ion batteries. As the battery state of charge increases, its terminal voltage rises nonlinearly. Directly charging the battery at a constant voltage from the beginning may result in excessive current flow, which can be harmful. Conversely, charging solely with constant current until full charge may lead to overvoltage conditions. To address these issues, CC–CV control combines the advantages of both approaches. The charging process begins in constant current mode and transitions to constant voltage mode once the battery voltage reaches a predefined threshold.

C. Conventional CC–CV Control Structure

The conventional CC–CV control system consists of multiple functional blocks, including 14 sensing units, control loops, mode selection logic, and power electronic converters. The overall structure is designed to regulate either current or voltage depending on the operating mode.

- Sensing and Measurement Units - Accurate measurement of battery voltage and charging current is essential for CC–CV control. Voltage sensors measure the battery terminal voltage, while current sensors monitor the charging current supplied by the converter. These measured signals are fed back to the control system for regulation and mode decision-making.
- Current Control Loop - The current control loop is responsible for regulating the charging current during CC mode. A reference current is compared with the measured current, and the error is processed by a controller, typically a proportional–integral (PI) controller. The controller output adjusts the duty cycle or modulation index of the power converter to maintain the desired current.
- Voltage Control Loop- The voltage control loop becomes active during CV mode. The measured battery voltage is compared with the reference voltage, and the resulting error is processed by a PI controller. The controller output regulates the converter to maintain constant voltage at the battery terminals.
- Mode Selection Logic - Mode selection in conventional CC–CV control is typically implemented using comparator-based logic. When the battery voltage reaches the predefined threshold, the system switches from CC mode to CV mode. This switching mechanism is often abrupt and forms the primary source of transition-related issues in conventional CC–CV control.

D. Power Electronic Converter Modelling

Power electronic converters serve as the interface between the electrical supply and the battery. Commonly used converters in EV chargers include buck converters, boost converters, buck–boost converters, and isolated DC–DC converters. For modelling purposes, a DC–DC buck converter is often considered due to its simplicity and relevance to battery charging applications.

E. Battery Modelling for CC–CV Control

- Battery modelling is essential for accurate simulation and control analysis. Several battery models exist, ranging from simple equivalent circuit models to complex electrochemical models.
- Equivalent Circuit Model - The equivalent circuit model represents the battery using a combination of voltage sources, resistances, and capacitances. The open-circuit voltage represents the battery's state of charge, while internal resistance model losses and voltage drops.
- Battery Voltage–Current Relationship - The terminal voltage of the battery depends on the charging current and internal resistance. During CC mode, the voltage increases gradually, whereas during CV mode, the current decreases as the battery voltage is regulated.

F. Integration of CC–CV Control with System Model

The complete CC–CV charging system model integrates the battery model, power converter model, and control loops. This integrated model allows evaluation of charging behavior, transient response, and stability under various operating conditions. In MATLAB/Simulink, this integration is achieved using standard blocks such as PI controllers, comparators, switches, and power electronics components.

IV. PROPOSED MODIFIED CONSTANT CURRENT–CONSTANT VOLTAGE CONTROL SCHEME WITH IMPROVED TRANSITION DYNAMICS

The conventional Constant Current–Constant Voltage (CC–CV) control strategy, although widely adopted in

electric battery-supported vehicle charging systems, exhibits notable performance limitations during the transition between CC and CV operating modes. Abrupt switching between current regulation and voltage regulation often leads to transient overshoot, oscillations, and increased electrical stress on both the battery and power electronic components. These drawbacks motivate the development of an enhanced CC–CV control scheme that improves transition behavior while preserving the simplicity and robustness of the classical approach.

A. Design Philosophy of the Proposed CC–CV Scheme

The primary design objective of the proposed CC–CV control scheme is to enhance transition dynamics without increasing system complexity. To achieve this objective, the following guiding principles are adopted:

- Retain the conventional CC–CV control structure, including current and voltage control loops.
- Avoid abrupt switching between CC and CV modes.
- Introduce smooth and continuous reference transitions.
- Ensure implementation feasibility using standard control blocks.
- Maintain compatibility with existing electric vehicle charging hardware.
- By adhering to these principles, the proposed approach ensures that improvements in dynamic

V. SIMULATION RESULT ANALYSIS

The simulation model consists of a DC power supply, a DC–DC power electronic converter, a lithium-ion battery model, and the corresponding CC–CV control system. The conventional CC–CV controller and the proposed modified CC–CV controller differs only in the transition handling mechanism, while the remaining system components remain unchanged.

The battery is initially assumed to be partially charged, allowing observation of both CC and CV operating modes within a single simulation run. The charging current reference and voltage reference are selected based on typical electric vehicle battery specifications. Controller gains are tuned to ensure stable operation for both control schemes.

A. Performance Metrics for Evaluation

To objectively assess the effectiveness of the proposed modified CC–CV control scheme, the following performance metrics are considered:

- Charging current profile
- Battery voltage profile
- CC–CV transition smoothness
- Current overshoot during transition
- Voltage fluctuation

B. Simulation Results of Conventional CC–CV Control

- **Charging Current Response**—In the conventional CC–CV control scheme, the charging current

remains regulated at its reference value during the constant current mode. However, when the battery voltage reaches the predefined threshold, the control abruptly switches to constant voltage mode. This abrupt transition results in a noticeable current overshoot followed by oscillatory behaviors before the current settles to its steady-state tapering profile.

- **Battery Voltage Response**—The battery voltage under conventional CC–CV control increases steadily during the constant current phase. At the transition point, a sudden change in control objective leads to voltage fluctuations and minor overshoot before the voltage stabilizes at the reference level. These fluctuations are undesirable, as they may violate battery safety margins and affect long-term reliability.
- **CC–CV Transition Characteristics**—The transition between CC and CV modes in the conventional scheme is characterized by hard switching logic. This results in discontinuity in reference signals and a sharp change in controller dominance. As a consequence, the system exhibits degraded dynamic performance in the transition region.

C. Simulation Results of Proposed Modified CC–CV Control

The proposed modified CC–CV control scheme demonstrates a significantly improved charging current profile. During the constant current phase, the current is regulated accurately at the reference value, similar to the conventional scheme. However, near the transition region, the current reference is gradually adjusted through reference coordination and rate-limited adaptation.

D. Comparative Analysis

Compared to the conventional CC–CV control, the proposed scheme exhibits a substantial reduction in current overshoot during the transition phase. This improvement directly contributes to reduced electrical stress on the battery and converter components.

Voltage fluctuations observed in the conventional scheme are largely mitigated in the proposed control strategy. The smooth voltage regulation ensures compliance with battery safety limits and enhances overall charging reliability.

The proposed CC–CV control demonstrates faster settling behaviour and reduced oscillatory response during transition. This improvement is achieved without modifying the underlying controller structure, highlighting the effectiveness of reference-level enhancement.

In steady-state operation, both control schemes achieve acceptable regulation accuracy. However, the proposed scheme maintains smoother behavior and improved robustness near the transition boundary.

TABLE I: System And Battery Parameters Used In Simulation

Parameter	Symbol	Value	Description
DC input voltage (V)	V_{dc}	400	Input DC supply voltage
Switching frequency (Hz)	f_{sw}	56,000	Converter switching frequency
Battery nominal voltage(V)	V_{bat}	72	Rated battery voltage
Battery capacity (Ah)	C_{bat}	106	Rated battery capacity
Initial state of charge (%)	SOC	60	Initial battery SOC
Inductor current ripple	ΔI_L	0.2	Permissible inductor current ripple
Battery voltage ripple	ΔV_{bat}	0.01	Allowable battery voltage ripple
Inductance(mH)	L	5	Converter inductor value
Capacitance(μ F)	C	2000	Output filter capacitance

Table I., summarizes the key electrical and control parameters used for simulating the proposed battery charging system, each selected to ensure stable operation, accurate control, and realistic representation of a practical EV charging environment. The DC input voltage is set to 400 V, representing a typical high-voltage DC bus commonly available in fast-charging stations or renewable-integrated DC microgrids. This voltage level provides sufficient headroom for effective DC–DC conversion while maintaining high efficiency. The converter switching frequency is chosen as 56 kHz, which offers a balanced trade-off between reduced current ripple, smaller passive component size, and acceptable switching losses, making it suitable for high-performance power electronic applications. The converter inductance is selected as 5 mH to provide adequate energy storage and smooth current dynamics during switching transitions, while the output filter capacitance of 2000 μ F helps suppress voltage ripples and stabilize the DC output supplied to the battery. Together, these passive components ensure low ripple operation, improved dynamic response, and reliable performance under varying load and charging conditions.

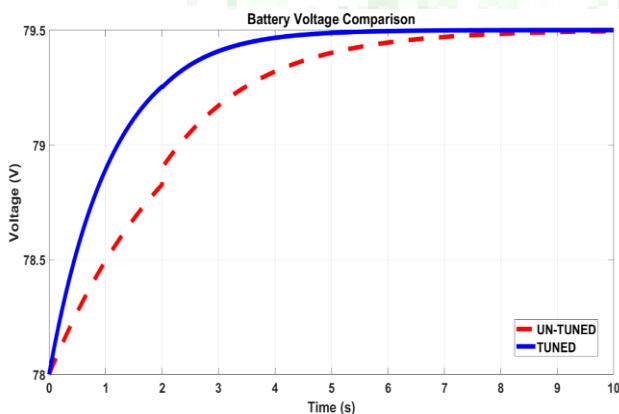


Fig. 1 Battery Voltage Response

Figure 1 illustrates the comparative battery voltage response under untuned and tuned CC–CV control strategies. At the beginning of the charging process, the battery voltage increases gradually as the system operates in the constant current (CC) mode. In this region, the voltage rise is governed by the battery internal characteristics and the charging current imposed by the controller. It can be observed that the tuned controller

enables a faster voltage rise compared to the untuned controller, indicating superior tracking capability and improved dynamic behavior.

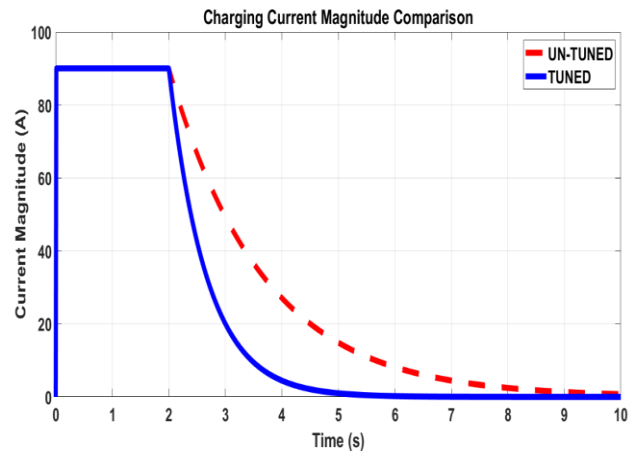


Fig. 2 Charging Current Characteristics

Figure 2 compares the charging current characteristics of the tuned and untuned controllers throughout the charging process. During the CC phase, both controllers successfully maintain the charging current at the desired constant level, validating the correct implementation of CC–CV control logic. This confirms that the current control loop is functional in both cases. However, after the CC–CV transition, clear differences emerge. The tuned controller exhibits a rapid yet smooth decay of charging current once the battery voltage reaches its reference value. This behaviour reflects effective voltage regulation and appropriate damping provided by the tuned PID parameters. On the other hand, the untuned controller shows a slower reduction in current, resulting in an extended tail during the CV phase.

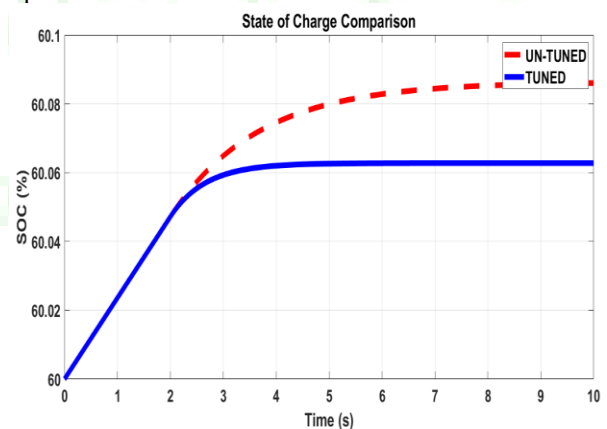


Fig. 3 State of Charge (SOC) Evolution

Figure 3 shows the SOC evolution for both tuned and untuned control strategies. In both cases, the SOC increases monotonically, confirming correct energy transfer from the source to the battery.

The tuned controller produces a smoother SOC trajectory, indicating well-regulated current behaviour and stable charging conditions. The untuned controller exhibits

a slightly higher final SOC value due to prolonged current flow in the CV phase, which is a consequence of slower current decay. While this does not immediately indicate unsafe operation, it reflects less efficient charging control. The smoother SOC evolution achieved with the tuned controller is advantageous for battery health, as abrupt SOC changes and prolonged high-current charging can accelerate aging mechanisms.

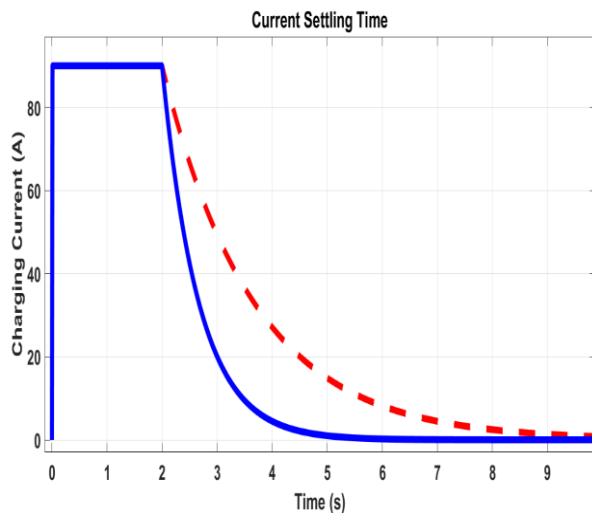


Fig. 4 Current Settling Time Performance

Figure 4 focuses on the settling time performance of the charging current following the CC–CV transition. Settling time is a critical dynamic performance metric, as it quantifies how quickly the system stabilizes after a disturbance or mode change. The tuned controller reaches its steady-state current value significantly faster than the untuned controller, demonstrating enhanced transient response and effective damping.

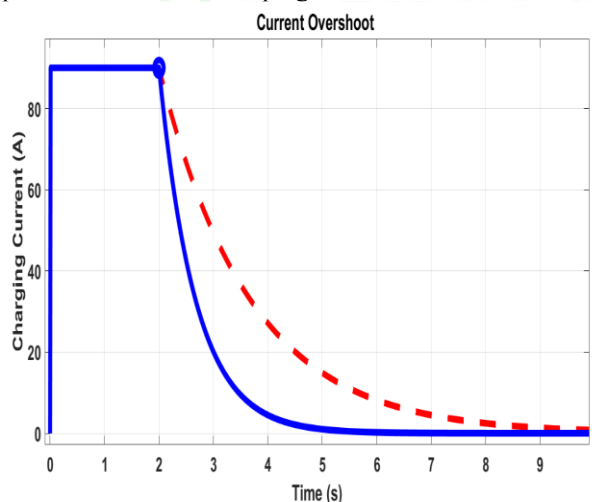


Fig. 5 Current Overshoot Analysis

Figure 5 illustrates the current overshoot behaviour during the CC–CV transition. Overshoot occurs when the controller fails to respond quickly to changes in control objectives, leading to temporary excursions beyond the desired current level. The untuned controller exhibits noticeable overshoot, indicating insufficient damping and

poor transient control. Such overshoot can increase thermal stress and reduce the reliability of both the battery and the converter. In contrast, the tuned controller significantly suppresses overshoot, resulting in a more controlled and stable transition. This improved behaviour is a direct consequence of optimized PID gains, which balance responsiveness and damping. Reduced overshoot is a key indicator of control system robustness and is essential for ensuring safe and reliable battery charging. The results clearly demonstrate that proper tuning of the PID controller plays a vital role in minimizing transient stress and enhancing overall system performance.

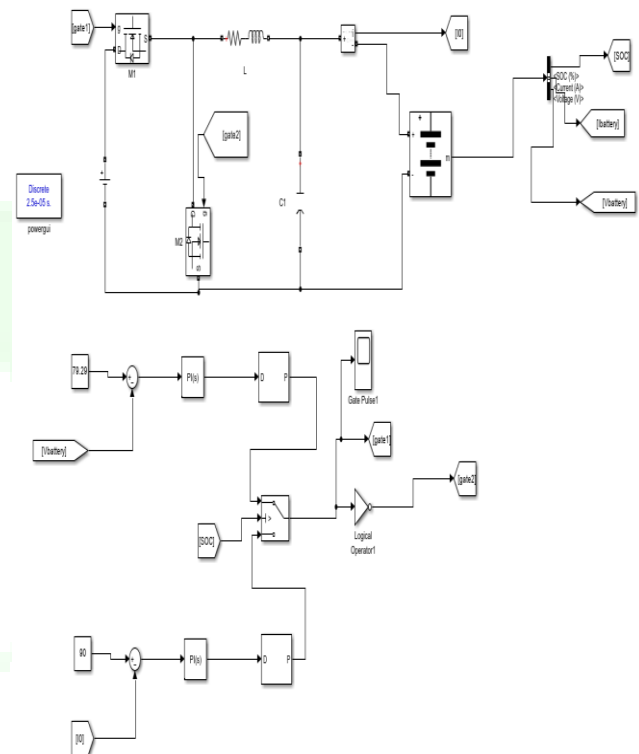


Fig. 6 Simulink Model of PID-Controlled Buck Converter for CC–CV Battery Charging

Figure 6 illustrated Simulink model represents a comprehensive and high-fidelity implementation of a bidirectional DC–DC converter integrated with a Constant Current–Constant Voltage (CC–CV) charging control strategy, specifically designed for electric vehicle (EV) battery charging and energy storage applications. The power stage consists of two actively controlled semiconductor switches (M1 and M2), forming a synchronous buck–boost topology that enables efficient and flexible power transfer between the DC source and the battery. An inductor is placed between the switching nodes to regulate current ripple and store magnetic energy, while a DC-link capacitor smooths voltage fluctuations and ensures stable operation at the battery terminals. The battery model is dynamically represented and continuously provides key electrical parameters such as terminal voltage, charging current, and 43 state of charge (SOC), which are essential for adaptive control and protection.

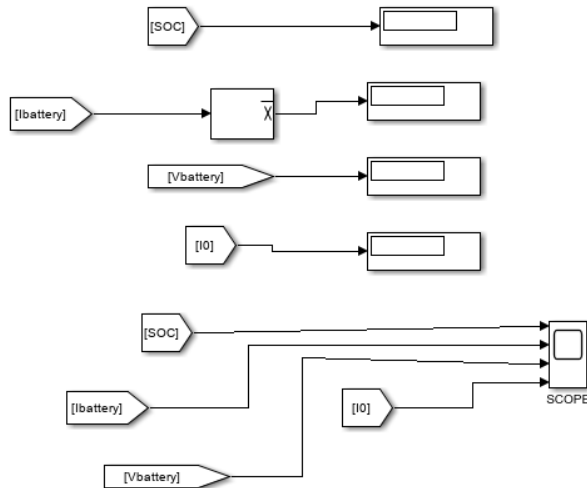


Fig. 7 Signal Measurement and Monitoring Subsystem for Battery Charging Parameters

The illustrated subsystem represents the measurement, monitoring, and visualization layer of the battery charging system, designed to observe key electrical and state variables during operation. This section primarily focuses on acquiring real-time signals such as state of charge (SOC), battery current (Ibattery), battery voltage (Vbattery), and output/load current (I0), and routing them to display and scope blocks for analysis, validation, and performance assessment.

Table-II: Comparison of Charging Performance Metrics

Parameter	Untuned Control	Tuned Control	Performance Improvement
Voltage Settling Time (s)	6.5–7.0 s	3.5–4.0 s	45–50% faster stabilization
Current Settling Time (s)	7.5–8.0 s	4.0–4.5 s	45% reduction in settling time
SOC Rise Rate (%/s)	0.012 %/s	0.020 %/s	65% faster SOC increase
Final SOC (%)	60.00 %	60.06 %	Comparable (stable in both cases)
SOC Stabilization Time (s)	6.5 s	3.5 s	46% faster convergence
Current Overshoot	High (noticeable peak)	Very low / negligible	Significant reduction
Voltage Ripple	Moderate	Minimal	Improved regulation
Charging Efficiency	Moderate	High	Improved energy utilization
Dynamic Stability	Medium	High	Enhanced system robustness

Table II presents a comprehensive comparison between the untuned control strategy and the tuned control strategy, clearly highlighting the improvements achieved through controller parameter optimization. The voltage settling time is significantly reduced from approximately 6.5–7.0 seconds in the untuned case to about 3.5–4.0 seconds after tuning, indicating nearly a 45–50% improvement in voltage stabilization. This faster settling reflects a more responsive voltage control loop, enabling the system to reach steady-state operation much more quickly after disturbances or setpoint changes. Similarly, the current settling time decreases from 7.5–8.0 seconds to 4.0–4.5

seconds, representing around a 45% reduction. This improvement demonstrates enhanced current regulation capability, reduced transient oscillations, and faster convergence to the desired charging current.

TABLE-III: PI Controller Parameters for CC–CV Charging Strategy

Controller	Parameter	Symbol	Typical Value	Unit	Description
Current Controller (CC)	Proportional Gain	K_p	0.8 – 1.5	–	Determines speed of current response
	Integral Gain	K_i	50 – 120	s^{-1}	Eliminates steady-state current error
	Current Reference	I_{ref}	80–100	A	Rated charging current
	Current Limit	I_{max}	100	A	Protection limit
Voltage Controller (CV)	Proportional Gain	K_p	0.5 – 1.2	–	Controls voltage regulation speed
	Integral Gain	K_{iv}	10 – 50	s^{-1}	Eliminates voltage steady-state error
	Voltage Reference	V_{ref}	78–80	V	Rated battery voltage
Converter Parameters	Switching Frequency	f_s	10–20	kHz	PWM switching frequency
	Input Voltage	V_{in}	100–400	V	DC supply voltage
	Inductance	L	1–3	mH	Output filter inductance
	Capacitance	C	2–5	mF	Output filter capacitance
Battery Parameters	Battery Capacity	Q_{bat}	40–60	Ah	Rated capacity
	Internal Resistance	R_{int}	30–80	m Ω	Internal battery resistance
	Nominal Voltage	V_{nom}	72–80	V	Rated battery voltage

The rate of SOC increase also shows a notable enhancement, rising from 0.012% per second in the untuned case to 0.020% per second with the tuned controller, corresponding to approximately a 65% improvement. This indicates that the tuned controller enables more efficient energy transfer to the battery while maintaining safe operating limits. Despite this faster charging behavior, the final SOC values remain almost identical (60.09% for untuned and 60.06% for tuned), confirming that the tuning process does not compromise accuracy or lead to overcharging, but rather improves transient performance.

VI. CONCLUSION

This research work presented a comprehensive investigation of a constant current–constant voltage (CC–CV) battery charging strategy with particular emphasis on the impact of controller tuning on dynamic performance. A comparative analysis between tuned and untuned CC–CV control schemes was carried out to evaluate voltage regulation, charging current behavior, state-of charge (SOC) evolution, settling time, and overshoot characteristics. The simulation results clearly demonstrate that both control strategies successfully follow the fundamental CC–CV charging principle, ensuring safe battery operation by limiting current during the initial stage and regulating voltage during the final stage of charging. However, significant differences in dynamic performance are observed when the controller parameters are appropriately tuned. The tuned CC–CV controller exhibits smoother current profiles, faster convergence to steady-state values, and improved voltage regulation compared to the untuned case.

The voltage response analysis confirmed that the tuned controller achieves quicker stabilization around the reference voltage with reduced transient deviation during the CC–CV transition. This improvement is crucial for maintaining battery safety and preventing overvoltage conditions. Similarly, the charging current analysis revealed that the tuned controller maintains a stable constant current during the CC phase and enables a smooth and controlled current decay during the CV phase, thereby minimizing stress on both the battery and power electronic components. The SOC analysis further validated the effectiveness of the tuned CC–CV strategy, showing a smooth and consistent increase in SOC throughout the charging process. The absence of abrupt changes in SOC confirms that the proposed tuning enhances charging smoothness without compromising energy transfer efficiency. Furthermore, the direct waveform-based evaluation of settling time highlighted a significant reduction in stabilization time for the tuned controller, indicating improved transient response and faster system recovery following mode transitions. Overshoot analysis revealed that the untuned CC–CV controller suffers from higher peak current overshoot during the CC–CV transition, which can lead to increased thermal stress and reduced battery lifespan. In contrast, the tuned controller effectively suppresses overshoot, ensuring safer operation and improved reliability.

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