# Design and Analysis of an Optimized CC–CV Charging Control Scheme for EV Batteries

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***Abstract*- This work investigated the dynamic performance of a constant current–constant voltage (CC–CV) battery charging strategy by comparing tuned and untuned control schemes for battery-supported electric vehicle applications. The primary objective was to evaluate how controller tuning influences voltage regulation, charging current behavior, state-of-charge evolution, settling time, and overshoot during the CC–CV transition. Simulation results confirmed that both control approaches satisfy the fundamental CC–CV charging requirements; however, the tuned CC–CV scheme consistently demonstrated superior dynamic performance. Improved voltage tracking, smoother current regulation, reduced overshoot, and faster settling time were observed in the tuned case, indicating enhanced transient response and improved charging stability. The SOC profiles further validated safe and efficient energy transfer without introducing abrupt charging dynamics. The comparative analysis highlights that appropriate controller tuning significantly enhances the effectiveness of the conventional CC–CV framework without increasing system complexity. By preserving the simplicity of the CC–CV structure while improving transient characteristics, the tuned strategy offers a practical and reliable solution for electric vehicle battery charging systems.**

**Overall, the outcomes of this study demonstrate that tuning-based enhancement of CC–CV control provides a balanced trade-off between performance improvement and implementation simplicity, making it well suited for real-world battery charging applications and future extensions toward intelligent and adaptive charging strategies.**

***Keywords-Constant Current Constant Voltage, Electrical Vehicle, PID, Pulse Width Modulation***

## I. Introduction

The global transportation sector is undergoing a significant transformation driven by the urgent need to reduce greenhouse gas emissions, improve energy efficiency, and decrease dependence on fossil fuels. Electric battery-supported vehicles have emerged as a promising alternative to conventional internal combustion engine vehicles due to their higher efficiency, lower environmental impact, and compatibility with renewable energy sources. The rapid adoption of electric vehicles (EVs) has placed increased emphasis on the development of reliable, efficient, and battery-friendly charging systems. At the core of every electric vehicle lies an electrochemical energy storage system, typically a lithium-ion battery, which determines the driving range, safety, cost, and overall performance of the vehicle. Proper charging of the battery is essential to ensure safe operation, maximize battery life, and maintain consistent performance. Among various charging strategies, the Constant Current–Constant Voltage (CC–CV) method has become the most widely used approach in electric vehicle charging systems due to its simplicity, effectiveness, and compatibility with battery characteristics. 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] analyzed 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], were 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.

## II. Methodology

### A. *Mathematical Modelling of the Converter*

- Inductor Current Dynamics

The inductor current dynamics can be expressed as equation (1): Inductor Current Dynamics

$$L\frac{di_L}{dt} = V_{in}D - V_{bat} \quad (1)$$

This equation describes the dynamic behavior of the inductor current. When the switch is ON, energy is stored in the inductor based on the difference between the input voltage scaled by duty cycle and the battery voltage. This equation forms the core of current control in CC mode. where (L) is the inductance, $V_{in}$ is the input voltage, and $V_{bat}$ is the battery voltage.

- Output Voltage Dynamics

The output voltage dynamics are governed by the capacitor equation (2):

$$C\frac{dV_{bat}}{dt} = i_L - i_{bat} \quad (2)$$

This equation governs the charging and discharging of the output capacitor. The capacitor voltage (battery terminal voltage) increases when the inductor current exceeds the battery current and decreases otherwise. It is critical for voltage regulation during CV mode. where (C) is the output capacitance and $i_{bat}$ is the battery charging current.

### B. *Battery Model*

The battery can be modelled using an equivalent circuit consisting of an open-circuit voltage and an internal resistance.

The battery terminal voltage is given by (3):

$$V_{bat} = V_{bat}(SOC) + i_{bat}R_{bat} \quad (3)$$

The battery is modeled using an open-circuit voltage dependent on SOC and an internal resistance. This model captures voltage drop due to internal resistance during charging and reflects realistic battery behavior.

The state of charge (SOC) evolution is described as (4):

$$SOC(t) = SOC(0) + \frac{1}{C_{bat}}\int i_{bat}(t)dt \quad (4)$$

This equation represents the continuous accumulation of charge inside the battery. SOC increases proportionally with the charging current over time and is normalized by battery capacity.

### C. *Closed-Loop Control*

Open-loop control of the converter is insufficient due to:

- Variations in battery internal resistance,
- Changes in SOC and temperature,
- Input voltage fluctuations,
- Load disturbances.

A closed-loop controller is therefore required to ensure precise tracking of current and voltage references under all operating conditions.

## III. PID-Based Control Strategy

### A. *Overview of PID Control*

The PID controller is widely used in industrial applications due to its simple structure and robust performance. The control law is expressed as (5):

$$u(t) = K_p e(t) + K_i\int e(t)dt + K_d\frac{de(t)}{dt} \quad (5)$$

This equation defines the PID controller used to generate the PWM duty cycle command. The proportional term improves response speed, the integral term eliminates steady-state error, and the derivative term enhances system damping. Each term contributes uniquely:

- Proportional control improves response speed,
- Integral control eliminates steady-state error,
- Derivative control enhances damping and reduces overshoot.

### B. *Current Control Loop (CC Mode)*

In CC mode, the objective is to regulate the battery charging current to a predefined constant value. The reference current is compared with the measured current, and the resulting error is processed by the PID controller. The controller output adjusts the duty cycle of the converter, ensuring accurate current tracking. A well-tuned current controller ensures:

- Minimal current ripple,
- Fast response to disturbances,
- Stable operation during high-current charging.

### C. *Voltage Control Loop (CV Mode)*

In CV mode, the objective shifts to maintaining the battery voltage at its rated value. The voltage error is processed by the PID controller, which regulates the converter duty cycle to hold the voltage constant while allowing the current to taper naturally. This mode is critical for:

- Preventing battery overvoltage,
- Reducing stress during the final stage of charging,
- Extending battery lifespan.

### D. *CC–CV Mode Transition Logic*

A logical switching mechanism determines the transition between CC and CV modes. When the battery voltage reaches the predefined threshold, control is smoothly transferred from the current loop to the voltage loop. Proper tuning ensures a seamless transition without abrupt changes in duty cycle.

### E. *PID Controller Tuning and Performance Improvement*

An untuned PID controller typically exhibits:

- Large overshoot,
- Longer settling time,
- Oscillatory response,
- Increased stress on battery and converter components.

The tuning the PID gains, the following improvements are achieved:

- Reduced current overshoot,
- Faster voltage stabilization,
- Improved transient response,
- Enhanced SOC smoothness.

The tuned controller demonstrates superior dynamic performance while preserving the simplicity of the CC–CV strategy.

## IV. PWM FOR DC–DC CONVERTER CONTROL

### A. *Introduction to Pulse Width Modulation*

Pulse Width Modulation (PWM) is a fundamental technique used in modern power electronic systems to control the output of switching converters. In applications such as battery chargers, electric vehicle power systems, and renewable energy interfaces, PWM provides an efficient and flexible means to regulate voltage, current, and power flow. Rather than relying on linear control methods that dissipate excess energy as heat, PWM enables high-efficiency operation by controlling semiconductor switches in an ON–OFF manner.

In a DC–DC converter-based battery charging system, PWM plays a critical role in regulating the duty cycle of the switching device, which directly determines the average output voltage and current delivered to the battery. By varying the width of the ON-time of the switching pulse while maintaining a fixed switching frequency, precise control over converter output can be achieved. This makes PWM particularly suitable for constant current–constant voltage (CC–CV) charging strategies, where accurate regulation of current and voltage is essential for battery safety and longevity.

### B. *Principle of PWM Operation*

PWM operates by comparing a low-frequency control signal with a high-frequency carrier signal. The control signal is typically derived from a feedback controller such as a PID controller, while the carrier signal is usually a triangular or sawtooth waveform. The result of this comparison determines the switching instants of the power semiconductor device.

When the control signal is greater than the carrier signal, the switch is turned ON; otherwise, it is turned OFF. The fraction of time for which the switch remains ON during one switching period is defined as the duty cycle. By varying the duty cycle, the average value of the output voltage can be controlled without changing the input voltage or switching frequency. In DC–DC converters, PWM ensures that energy transfer from the source to the load is regulated in a controlled manner. This switching-based operation minimizes power losses and enables compact converter design due to reduced heat dissipation.

### C. *PWM in DC–DC Converters*

In buck converters used for battery charging, PWM controls the energy stored in the inductor during each switching cycle. When the switch is ON, the inductor current increases, storing energy. When the switch is OFF, the stored energy is transferred to the battery through the freewheeling path. By adjusting the duty cycle, the rate of energy transfer is controlled, thereby regulating the charging current and voltage.

PWM enables smooth and continuous control over the converter output despite the discrete ON–OFF operation of the switch. This characteristic is particularly important in CC–CV charging, where smooth transitions between charging modes are required to avoid battery stress. PWM behavior differs depending on whether the converter operates in continuous conduction mode (CCM) or discontinuous conduction mode (DCM). In CCM, the inductor current never falls to zero, resulting in smoother current waveforms and easier control. In DCM, the inductor current reaches zero during part of the switching cycle, leading to more complex dynamics and higher current ripple. For battery charging applications, converters are generally designed to operate in CCM to ensure stable current delivery and reduced ripple. PWM control in CCM allows simpler modelling and more predictable dynamic behavior.

## V. RESULT AND DISCUSSIONS

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. 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. 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. During the CC phase, the SOC increases almost linearly due to constant charging current. After the transition to CV mode, the SOC increment rate decreases as the charging current tapers. 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. 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.

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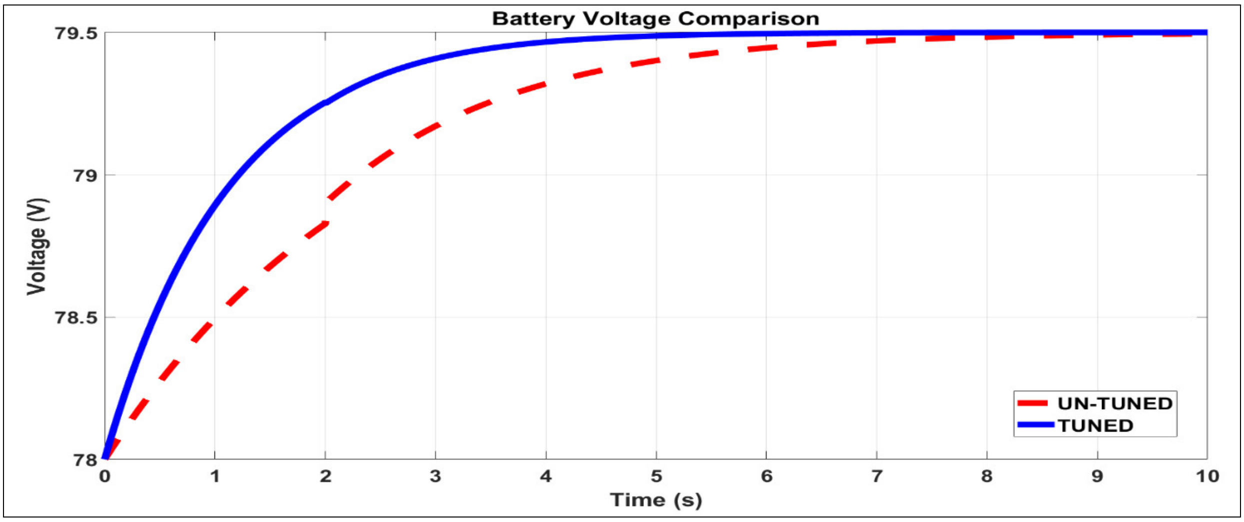


**Fig. 1 Battery Voltage Response**

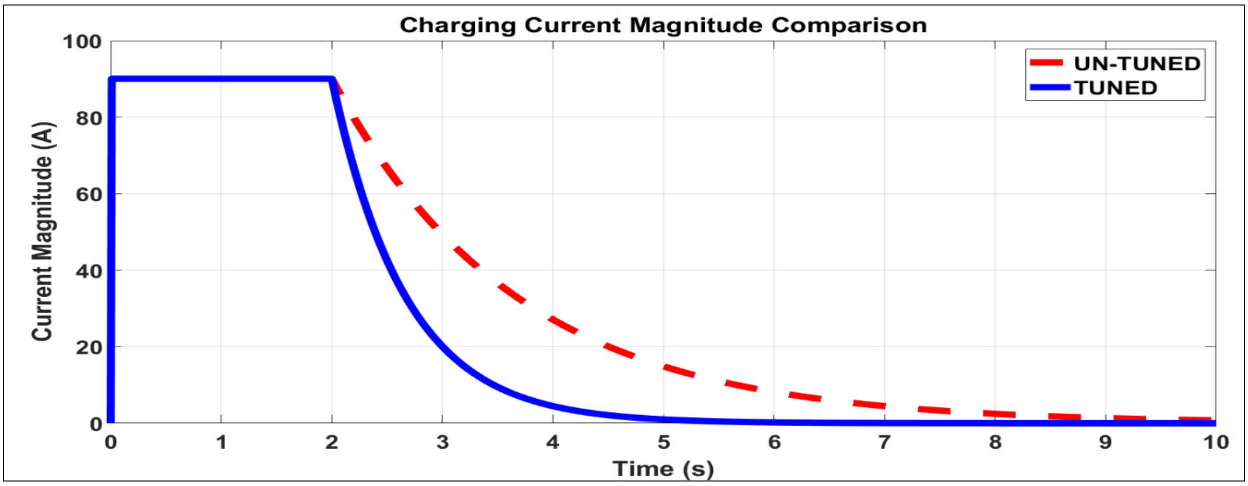


**Fig. 2 Charging Current Characteristics**

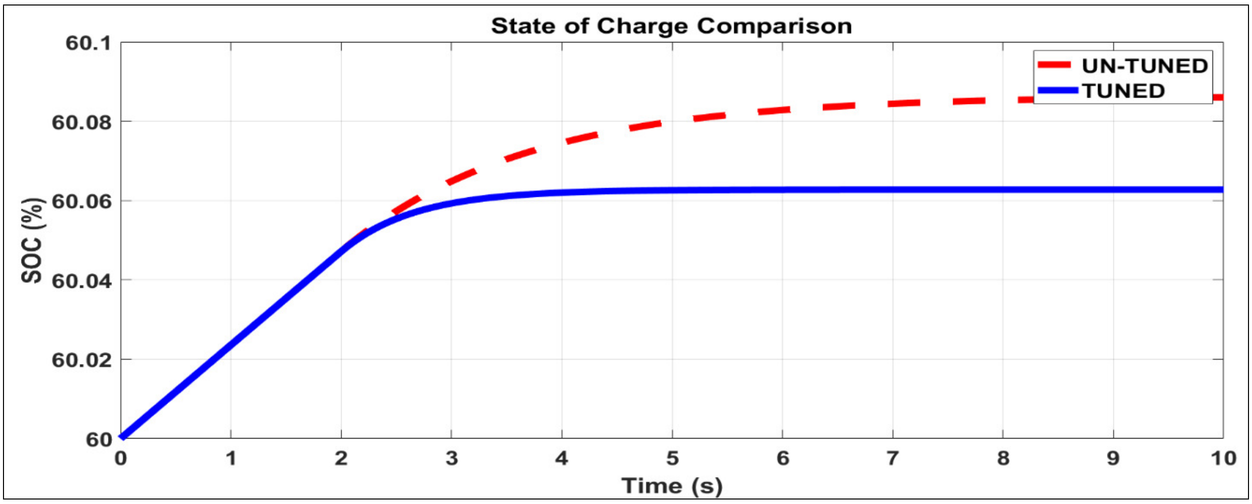


**Fig. 3 State of Charge (SOC) Evolution**

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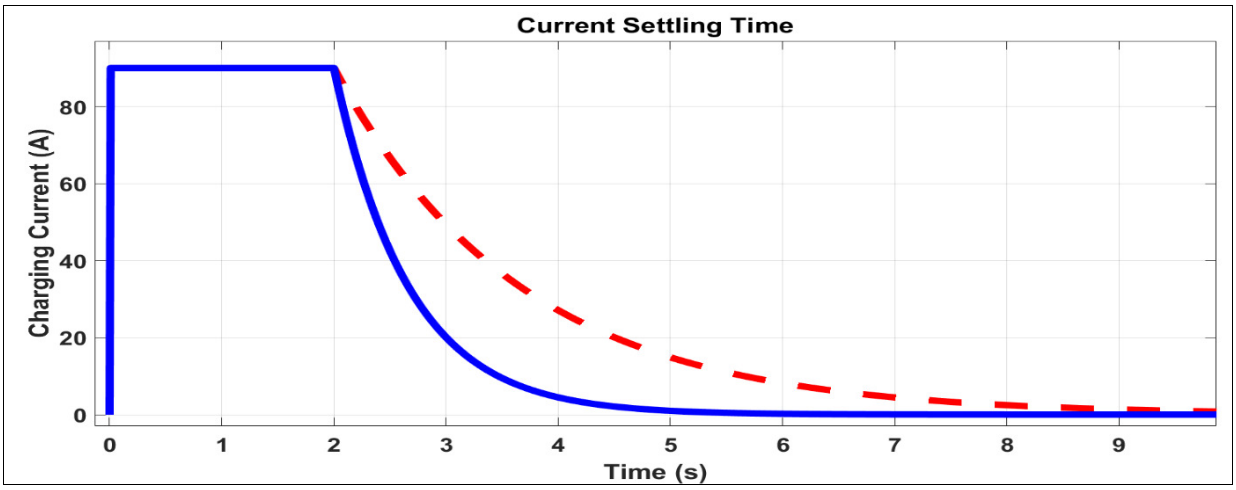


**Fig. 4 Current Settling Time Performance**

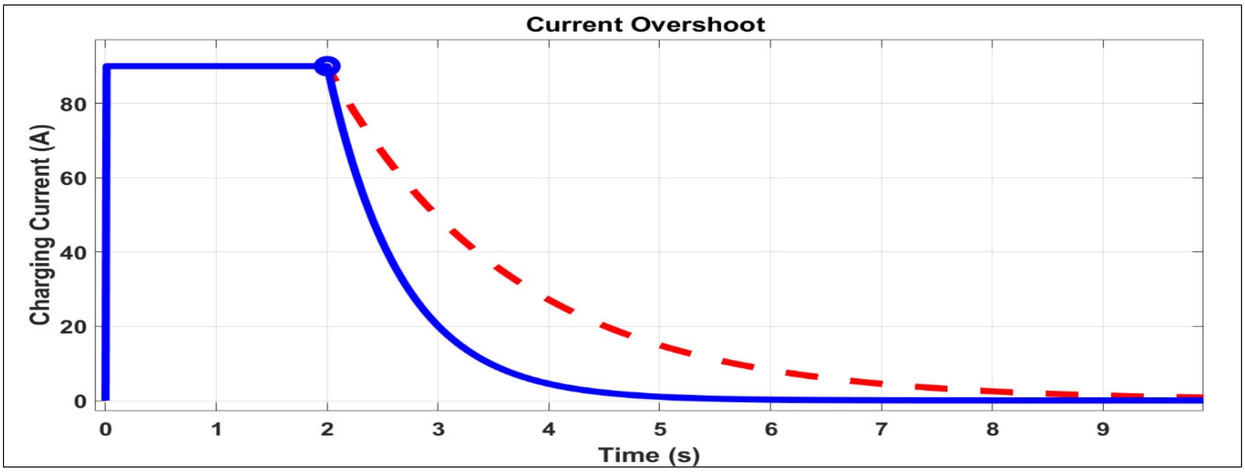


**Fig. 5 Current Overshoot Analysis**

TABLE I. 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 (%) | 60.09 % | 60.06 % | Comparable (stable in both cases) |
| SOC Stabilization Time (s) | 6.5 s | 3.5 s | 46% faster convergence |
| Current Overshoot | High | Very low | Significant reduction |
| Voltage Ripple | Moderate | Minimal | Improved regulation |
| Charging Efficiency | Moderate | High | Improved energy utilization |
| Dynamic Stability | Medium | High | Enhanced system robustness |

## VI.CONCLUSIONS

This paper 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. These improvements are achieved without modifying the fundamental CC–CV control structure, making the proposed tuning approach simple, practical, and easily implementable in real-world battery charging systems.

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