

Development of Bidirectional Battery Charging Scheduling System Considering SOC Level and Energy Price

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Abstract. Electric Vehicle (EV) technology has advanced to allow bidirectional power flow, enabling EVs to not only consume energy but also supply it back to the grid. However, research on time-based charging and discharging patterns is limited, particularly in Indonesia, where electricity tariffs remain constant throughout the day. This study proposes a time-based control strategy, assuming dynamic pricing with higher rates during peak hours, to create mutual benefits for EV users and utilities. The system integrates a State of Charge (SoC) management mechanism and a Proportional-Derivative (PD) controller to optimize battery performance and energy flow. Tests at initial SoC levels of 25%, 55%, and 85% reveal that the parameter combination $K_p = 0.02$ and $K_d = 1$ achieves the lowest error, ensuring efficient control. This strategy encourages EV users to sell energy during peak hours, providing financial rewards while helping utilities balance energy demand during critical periods.

Keywords: *Electrical Vehicle, Charging-Discharging, Converter AC-DC, Converter DC-AC, Bidirectional Charger.*

1 Introduction

Electric vehicles (EVs) are paving the way for a sustainable future by reducing emissions and revolutionizing energy use through Vehicle-to-Grid (V2G) technology. V2G empowers EVs to act as mobile energy storage units, balancing grid demand, reducing peak loads, and enhancing stability. With intelligent two-way charging systems and schedules tailored to user habits and energy costs, EVs are no longer just vehicles—they are key to building a cleaner, smarter energy system.

Recent studies on bidirectional chargers for EVs highlight their potential for enabling Vehicle-to-Grid (V2G) technology but also reveal key limitations: Bidirectional Charger Technology [1], supports fast and slow charging but neglects battery degradation, user behavior, and scheduling. G2V, V2G, V2H Technologies [2], explores multiple modes but inefficient transitions and high costs limit practicality. Controllable Charger for V2G [3], ensures stability with PI control but heavily depends on EMS accuracy. Bidirectional DC-DC

Converter [4], handles motoring and regenerative braking but struggles with transients and ignores capacity degradation. Charger Control in Microgrids [5], regulates power in microgrids but lacks analysis of charging patterns, impacting battery health. The conclusion is while advancements are evident, challenges like battery degradation, user behavior, and cost-effectiveness remain.

Research on V2G (Vehicle-to-Grid) and G2V (Grid-to-Vehicle) highlights key advancements in energy management: V2G Impact on Grids [6], enhances grid stability with smart charging, avoiding peak load risks. Battery Model [7], SoC-based dynamic model but overlooks thermal effects and self-discharge. Bidirectional Charger [8], ensures current stability, addressing harmonics and self-discharge. EV Grid Integration [9], proposes a 70% SoC limit for stable grid interaction using Opal-RT simulations. The conclusion is advances in smart charging and modeling are promising, but gaps like battery degradation, user behavior, and dynamic pricing require further attention for practical V2G adoption.

The studies reveal a gap in managing EV battery SoC with user behavior and tariffs. The proposed time-based scheduling integrates SoC control and dynamic pricing, encouraging EV users to sell energy during peak hours. This benefits users financially, supports utilities during peak demand, and optimizes bidirectional charger use.

The structure of this paper is as follows: SECTION II: Describes the proposed SoC control strategy. SECTION III: Details the Proportional-Derivative (PD) control testing methodology. SECTION IV: Presents the results and discussion of the testing in detail. SECTION V: Concludes with the key findings of the study.

2 Proposed Method

The method proposed in this study is shown in Figure 1. This flowchart illustrates the workflow of a battery charging and discharging system designed to optimize battery performance, safety, and lifespan. The system uses key parameters, namely State of Charge (SoC) and operating time, to control when the battery is charged or discharged. The main goal is to ensure the battery operates within a safe and efficient SoC range while minimizing the impact of degradation.

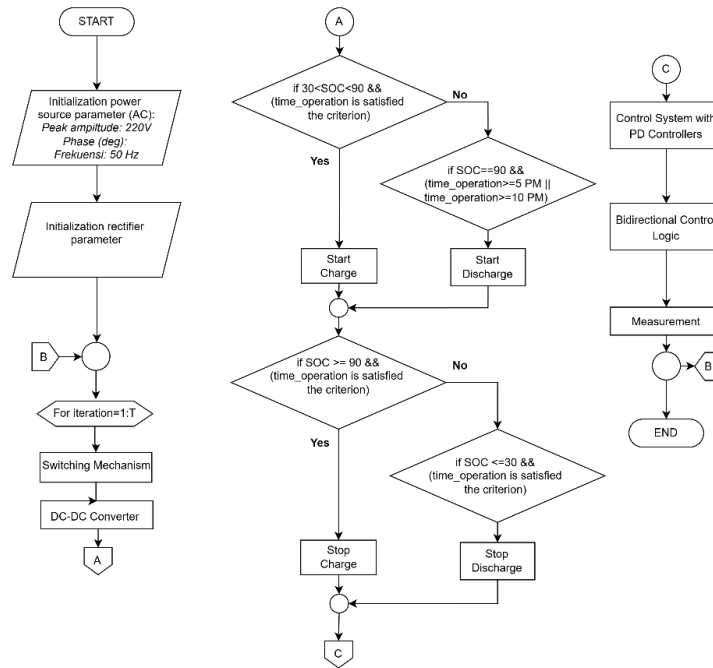


Figure 1 The flowchart of proposed method

The system starts with an initialization stage, setting power source parameters such as peak voltage (220V), operating frequency (50 Hz), and phase to ensure compatibility with the external source. Rectifier parameters are also configured to convert AC to DC for battery charging. The system then enters an iterative process from iteration 1 to T, where a switching mechanism, supported by a DC-DC converter, determines whether to charge or discharge. The DC-DC converter regulates current and voltage to meet the battery's requirements, ensuring efficient operation. Time operation criterion that proposed in this research are below:

1. 5PM-9PM: Discharging
2. 9PM-6AM: Charging
3. 6AM-7AM: Discharging
4. 7AM-4PM: Charging
5. 4PM-5PM: Discharging

The proposed system schedules specific times for battery discharging to meet high energy demand periods. From 5 PM to 9 PM, the battery discharges to support peak electricity usage during household and commercial activities. Similarly, discharging from 6 AM to 7 AM supports morning commutes, while 4 PM to 5 PM covers afternoon energy needs and vehicle preparation. This strategy maximizes the use of stored energy during critical times, with the system's control

logic based on the battery's SoC levels and predefined time slots. The system operates as follows: Charging starts when the SoC is between 30% and less than 90%, provided the time is suitable for charging. Discharging starts when the SoC reaches 90% during non-charging periods, ensuring energy is used effectively while avoiding overcharging. Charging stops automatically at 90% SoC, and discharging halts at 30% SoC to protect the battery from overcharging or excessive discharge. Key subsystems support this process, including a Proportional-Derivative (PD) Controller for stable charging and discharging, bidirectional control logic for seamless mode switching, and a real-time measurement system to monitor voltage, current, and SoC. Once the conditions are met, the system stops to keep the battery in an optimal state. This smart and efficient approach can be applied to electric vehicles and large-scale energy storage systems, ensuring safe and reliable battery management.

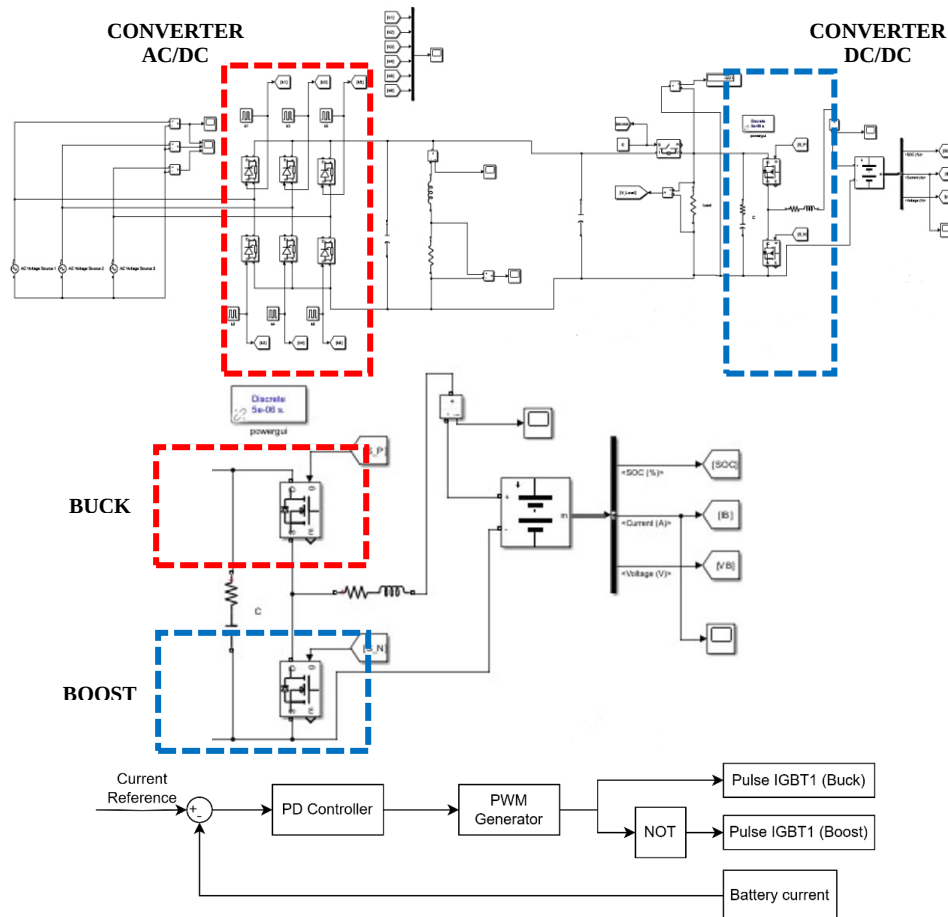


Figure 2 The battery charger configuration

Figure 2 illustrates the current flow direction, representing power flow control in a bidirectional converter used for Vehicle-to-Grid (V2G) applications. The system utilizes a DC current control technique with two MOSFET/IGBT switches managed by control signals to enable charging (G2V) and discharging (V2G). In charging mode (buck), the upper switch (IGBT 1) reduces the voltage for battery charging. When IGBT 1 is ON, current flows through the inductor to the battery. When OFF, current flows back via the lower switch diode (IGBT 2). In discharging mode (boost), the lower switch (IGBT 2) boosts the battery voltage to the DC bus. When IGBT 2 is ON, current flows through the inductor and the diode of IGBT 1, enabling power delivery from the battery to the grid. The control block diagram demonstrates a pulse-width modulation (PWM) mechanism. A voltage reference is compared to the actual battery voltage, and a Proportional-Integral (PI) controller processes the error to generate a current reference. A Proportional-Integral-Derivative (PID) controller then adjusts the PWM duty cycle to modulate the switches, ensuring safe and efficient battery operation. The system is modeled with a 220V, 50Hz grid, a 5.76×10^{-4} H inductor, and a 1000×10^{-6} F capacitor. A lithium-ion battery with a nominal voltage of 22V and 232 Ah capacity is used in the simulation. The control strategy employs a PI and PID controller to dynamically manage charging and discharging transitions. The proposed method has two key stages: (1) State of Charge (SoC) Management Cycle: Ensures the battery operates within an optimal SoC range to improve efficiency and extend its lifespan. (2) Proportional-Derivative (PD) Controller Design: Dynamically regulates switching between charging and discharging, maintaining system stability and accommodating changes in battery conditions. This approach optimizes battery performance, ensuring reliable and efficient management during transitions while preventing overcharging or deep discharging. The method is detailed in the control algorithm using reference voltage and current comparisons to dynamically adjust the PWM control signals.

A. SOC Management Cycle

This study examines the charging and discharging patterns of EV batteries over 24 hours, following a schedule that aligns charging with off-peak hours (LWBP) and discharging with peak hours (WBP). The test is based on daily human activities, where the EV is typically outside the home from 6:00 AM to 5:00 PM for work or other needs and returns home in the evening at 5:00 PM. During off-peak hours, the EV charges if the battery's SoC is below 90%. Charging stops automatically when the SoC reaches its maximum limit of 90%, meaning no further charging or discharging occurs. Conversely, during peak hours, if the battery's SoC drops to 30%, the EV discharges to provide energy to the grid, helping reduce the load during high-demand periods between 5:00 PM and 10:00 PM. This method optimizes battery use, prevents overloading the grid during

peak times, and supports efficient energy management. The process is detailed in Algorithm 1.

Algorithm 1. SOC Management Over 24 Hours
Input: - Initial_SOC: Starting SOC percentage (e.g., 85%) - DischargeRate: SOC decrease rate per hour (e.g., 10%) - ChargeRate: SOC increase rate per hour (e.g., 8%) - SimulationTime: Total simulation duration (e.g., 24 hours) - SamplingTime: Time step for simulation (e.g., 1 second) SOC_Limits: SOC thresholds: - Minimum_SOC = 30% (SOC enters idle when discharging drops below this level) - Maximum_SOC = 90% (SOC switches to discharging if charging exceeds this level) Output: - SOC(t): SOC values over the simulation time.
Algorithm Steps: Define time intervals: 5:00 PM - 9:00 PM (Discharging): SOC decreases until $SOC \leq 30\%$. 9:00 PM - 6:00 AM (Charging): SOC increases until $SOC \geq 90\%$. 6:00 AM - 7:00 AM (Discharging): SOC decreases until $SOC \leq 30\%$. 7:00 AM - 4:00 PM (Charging): SOC increases until $SOC \geq 90\%$. 4:00 PM - 5:00 PM (Discharging): SOC decreases until $SOC \leq 30\%$.
Simulation Loop: For each time step (t) in SimulationTime: Determine the current time period: If 5:00 PM - 9:00 PM: If Current_SOC > Minimum_SOC: Reduce SOC by $(DischargeRate / 3600) \times SamplingTime$. Else: Keep SOC constant (idle state). If 9:00 PM - 6:00 AM: If Current_SOC < Maximum_SOC: Increase SOC by $(ChargeRate / 3600) \times SamplingTime$. Else: Switch to discharging: Reduce SOC by $(DischargeRate / 3600) \times SamplingTime$. If 6:00 AM - 7:00 AM: If Current_SOC > Minimum_SOC: Reduce SOC by $(DischargeRate / 3600) \times SamplingTime$. Else: Keep SOC constant (idle state). If 7:00 AM - 4:00 PM: If Current_SOC < Maximum_SOC: Increase SOC by $(ChargeRate / 3600) \times SamplingTime$. Else: Switch to discharging: Reduce SOC by $(DischargeRate / 3600) \times SamplingTime$. If 4:00 PM - 5:00 PM:

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If Current_SOC > Minimum_SOC:
    Reduce SOC by (DischargeRate / 3600) × SamplingTime.
Else:
    Keep SOC constant (idle state).
SOC Constraints:
    Ensure Current_SOC remains within [0%, 100%].
Record SOC:
    Save the SOC value for the current time step.
End Simulation:
    When t reaches the end of SimulationTime, stop.
    
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B. Proportional-Derivative (PD) Control

The Proportional-Derivative (PD) controller is designed to manage the transition between charging and discharging processes in batteries, ensuring smooth and stable operation. It works by comparing the reference current with the actual current, using this error to adjust the system. The K_p (proportional gain) addresses the current error directly, while the K_d (derivative gain) reduces oscillations by considering how the error changes over time. In battery management, the PD controller adjusts the charging and discharging process based on the battery's State of Charge (SoC). With well-tuned parameters, it keeps the actual current close to the reference, helping to optimize charging, extend battery life, and prevent discharging beyond safe limits. PD controllers are often preferred because they are simple to implement and effective at handling transitions between modes. This makes them a practical and cost-efficient choice for managing battery energy systems. The steps for implementing the PD controller are shown in Algorithm 2.

Algorithm 2: Proportional-Derivative (PD) Controller

Initialization:

- Set the simulation parameters such as battery capacity, voltage, SOC, PID controller parameters, time markers, and discharge/charge rates.
 - Define Simulation Time: Create a time vector t representing 24 hours, sampled at the desired simulation interval.
 - Battery Model Initialization:
 - Set initial SOC to 55%.
 - Initialize vectors for battery current, reference current, and SOC.
 - PID Controller Initialization:
 - Set proportional, integral, and derivative gains (K_p , K_i , and K_d).
-

Simulation Loop:

- For each time step, calculate the error as the difference between the reference and actual battery current.
 - Update the PID terms:
 - Add the current error to the integral term.
 - Calculate the derivative of the error.
 - Compute the PID output using K_p , K_i , and K_d .
 - Determine the battery's operating state (charging/discharging/idle) based on the current time.
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- Update SOC and currents based on the operating state and PID output.
- Ensure SOC and currents are bounded between their respective limits.

Plot Results:

- Plot the SOC over the 24-hour period.
- Plot the comparison of reference and actual battery currents.
- Calculate and display the mean squared error (MSE) between the reference and actual currents.

3 Result and Discussion

A. The first test conducted was to examine the SOC Management section
With three case studies, namely:

- SOC 25%
- SOC 55%
- SOC 85%

The graphs show how the battery's SoC changes during charging and discharging periods. Charging periods, marked in green, show a steady increase in SoC, while discharging periods, marked in red, show a decrease, following the expected behavior of the battery. During discharging, the SoC drops significantly, especially in the early cycles, where it falls below 50%. This indicates a high energy demand or large current draw. In charging, the SoC rises consistently but doesn't always reach full capacity (100%). This could be due to less efficient charging or signs of battery wear. These patterns highlight the need to optimize charging methods to improve battery performance and lifespan.

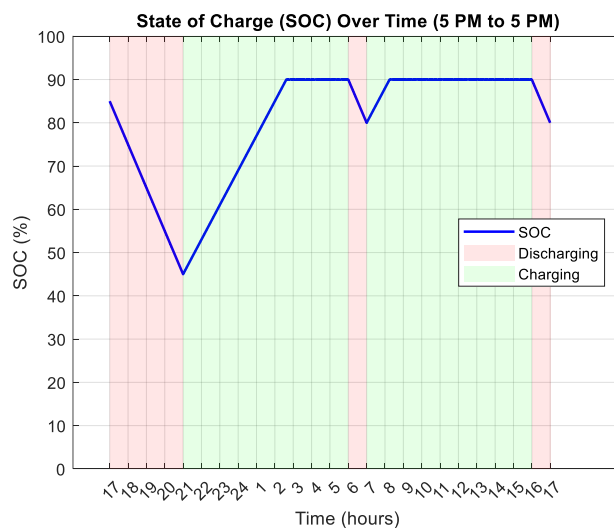


Figure 3 The Soc performance with initialization = 85%

Figure 3 demonstrates battery SoC management starting at 85%, aligned with human activity patterns. During the peak load period (17:00–21:00), the battery discharges, allowing EV users to sell electricity to the utility for profit while supporting high demand. By 21:00, the SoC remains within the allowable range at approximately 45%. Charging resumes during the off-peak period, reaching the maximum SoC of 90% by 02:00, after which charging stops to prevent battery degradation. From 02:00 to 06:00, the EV remains inactive with no charge-discharge processes. During the morning commute (06:00–07:00), the battery discharges to 80%. Charging resumes at the workplace, restoring the SoC to 90%. In the evening (16:00–17:00), the EV is used again, reducing the SoC back to 80%. During off-peak periods, electricity is used for personal needs, as low tariffs make selling to the utility uneconomical. This pattern reflects efficient battery management that balances user needs and system longevity.

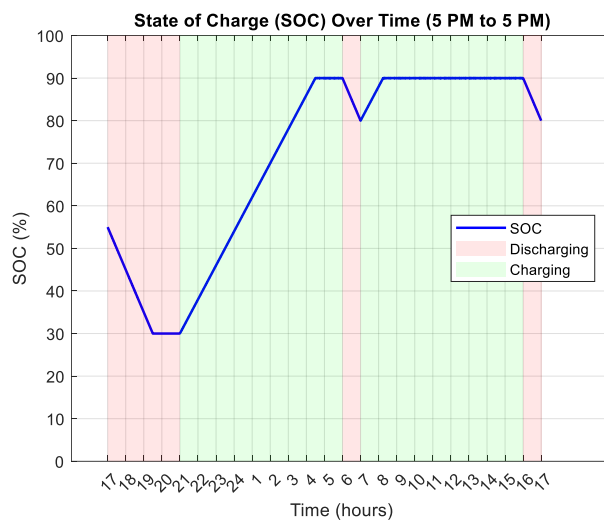


Figure 4 The Soc performance with initialization = 55%

Figure 4 illustrates battery SoC management starting at 55%, aligned with daily user patterns. During the peak load period (17:00–21:00), the battery discharges, allowing EV users to sell electricity to the utility for profit, while supporting high demand. By 19:00, the SoC reaches the minimum threshold of 30%, halting further discharge. From 19:00 to 21:00, no charge-discharge occurs due to high tariffs. In the off-peak period (21:00–04:00), the battery charges to 90%, then remains idle until 05:00. During morning use (06:00–07:00), the EV discharges to 80%, followed by charging at work to restore SoC to 90%. Evening use (16:00–17:00) reduces the SoC to 80%. Off-peak electricity is reserved for personal use, as selling to the utility during low tariffs is not economically beneficial.

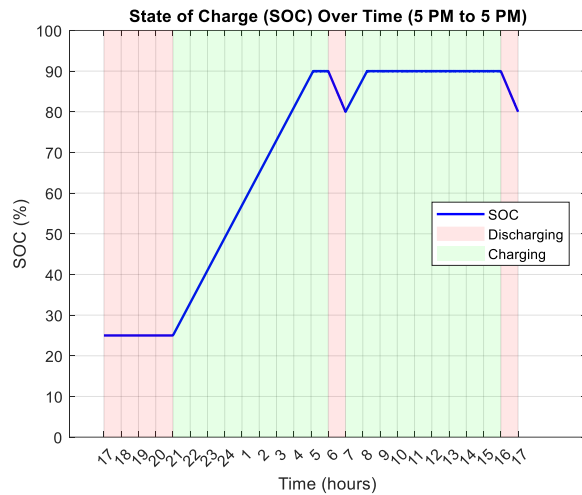


Figure 5 The Soc performance with initialization = 25%

Figure 5 shows battery SoC management starting at 25%, following daily user patterns. During peak load (17:00–21:00), no charge-discharge occurs as the SoC is below 30%, preventing electricity sales to the utility. In the off-peak period (21:00–04:00), the battery charges to 90%, then remains idle until 05:00. Morning use (06:00–07:00) discharges the battery to 80%, followed by charging at work back to 90%. Evening use (16:00–17:00) reduces the SoC to 80%. Off-peak electricity is stored for personal use, as low tariffs make sales to the utility uneconomical.

A. Propotional–Derivative Controller

Table 1 summarizes the performance of the Proportional-Derivative (PD) controller across various initial State of Charge (SoC) conditions (25%, 55%, and 85%) using Mean Squared Error (MSE) as a metric. Among the tested configurations, $K_p = 0.02$, $K_d = 1$ achieved the best performance, with the lowest MSE across all SoC levels, particularly at 85% SoC (MSE = 0.195255). Reducing K_d to 0.9 increased MSE, with the highest value at 85% SoC (MSE = 0.336407), indicating decreased controller performance. Increasing K_p to 0.1 resulted in slightly higher MSE values, with the highest at 25% SoC (MSE = 0.250718), showing limited benefit. A larger K_p of 0.2 further degraded performance, producing the worst MSE at 25% SoC (MSE = 0.341187). Adding an integral element ($K_i = 0.01$) drastically increased MSE, with the highest value at 25% SoC (MSE = 3.106336), significantly reducing controller effectiveness. The findings conclude that the combination of $K_p = 0.02$, $K_d = 1$ is the most effective, delivering the lowest MSE. Adjusting K_d or K_p negatively impacts performance, and incorporating K_i leads to substantial degradation. A PD controller without an integral element is optimal for this system.

Table 1 Performance comparison of PD controller

Soc initial condition	Soc = 25%	Soc = 55%	Soc = 85%
Kp = 0.02; Kd = 1;			
MSE	0.185716	0.207647	0.195255
Kp = 0.02; Kd = 0.9;			
MSE	0.234374	0.314329	0.336407
Kp = 0.1; Kd = 1;			
MSE	0.250718	0.249669	0.210818
Kp = 0.2; Kd = 1;			
MSE	0.341187	0.319548	0.252096
Kp = 0.02; Ki = 0.01; Kd = 1			
MSE	3.106336	2.226128	1.239318

The upper graph in Figure 4(a) depicts the SoC changes over a 24-hour period, showing an increase during charging and a decrease during discharging phases. The lower graph in Figure 4(b) compares the reference current (green line) with the actual battery current (magenta line), demonstrating the system's response to switching between charging and discharging processes. The actual current closely follows the reference current, with minor deviations due to the control parameters. These results highlight the PD controller's effectiveness in maintaining system stability and reliability.

Figures 6 to 8 present the simulation results of State of Charge (SoC) management and battery current response over 24 hours with initial SoC levels of 25%, 55%, and 85%. The simulation uses a Proportional-Derivative (PD) controller with $K_p = 0.02$ and $K_d = 1$. Each figure includes two parts: (a) the SoC variation over time in the upper graph and (b) the comparison of reference current (green line) with actual current (magenta line) in the lower graph. In Figures 6(a) to 8(a), the SoC changes dynamically based on the designed management cycle. Starting from initial SoC levels, such as 25%, the SoC significantly decreases during the discharging phase, then steadily increases during charging, approaching 90%. This cycle repeats, reflecting the planned operating pattern of the battery. Figures 6(b) to 8(b) show the reference and actual current comparison. The actual current closely follows the reference, with minor deviations during transitions between charging and discharging. These deviations are influenced by the PD controller parameters ($K_p = 0.02$ and $K_d = 1$). Overall, the PD controller effectively regulates battery current and maintains SoC within the desired range, though further parameter optimization could enhance precision and stability. Battery current behavior corresponds to the SoC. During charging, the current decreases (negative), while it increases (positive) during discharging. The current drops to zero when no charging or discharging occurs.

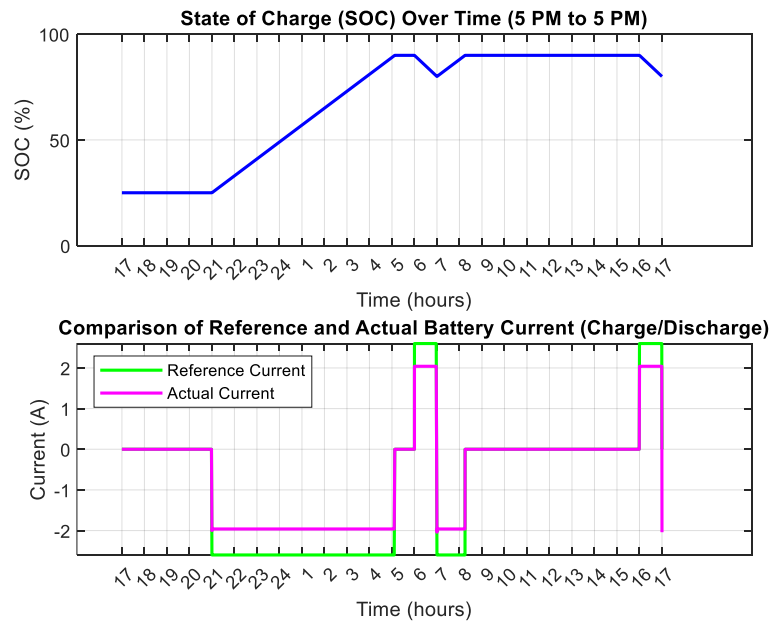


Figure 6 (a) Soc 25%'s performance (b) The comparison of Reference and Actual Battery Current with the $K_p = 0.02$ and $K_d = 1$

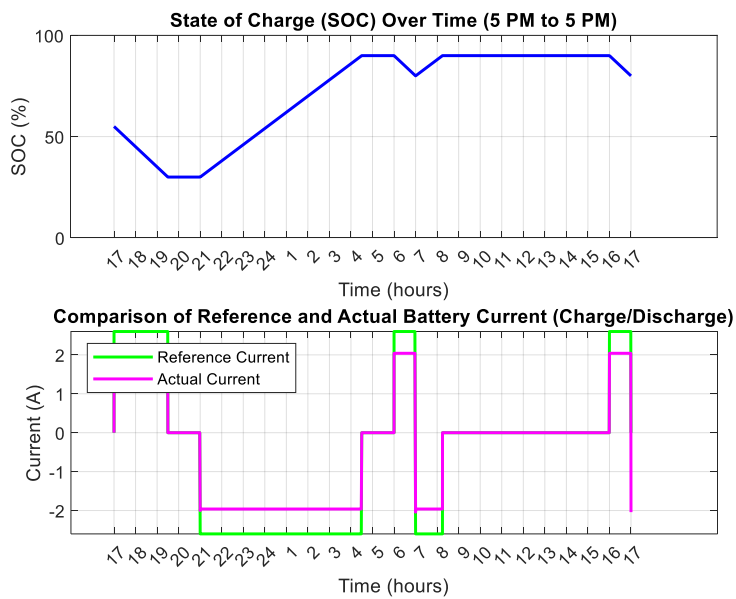


Figure 7 (a) Soc 55%'s performance (b) The comparison of Reference and Actual Battery Current with the $K_p = 0.02$ and $K_d = 1$

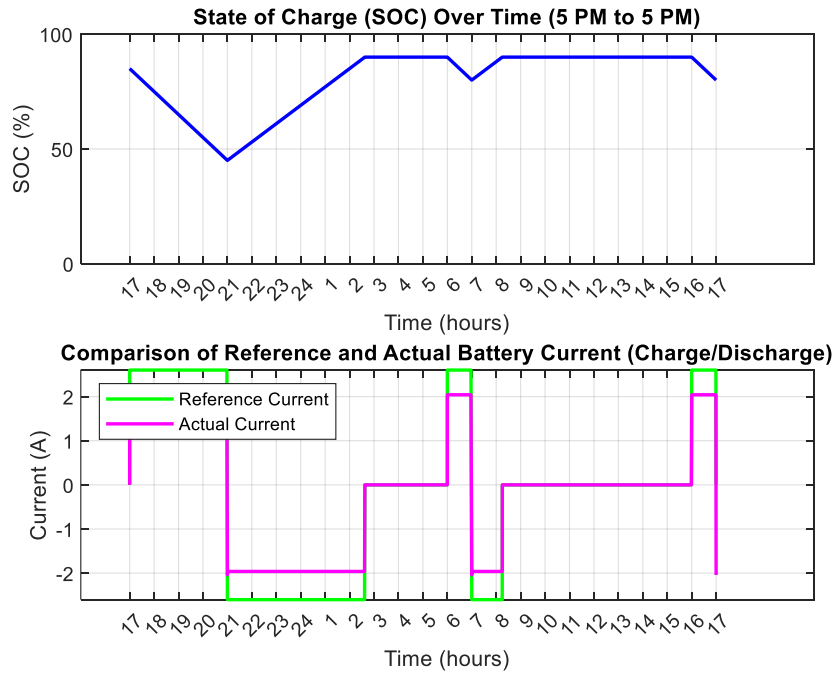


Figure 8 (a) Soc 85%'s performance (b) The comparison of Reference and Actual Battery Current with the $K_p = 0.02$ and $K_d = 1$

4 Conclusion And Future Work

This research focuses on developing a time-based State of Charge (SOC) management system and designing a Proportional-Derivative (PD) controller to optimize battery charging and discharging based on EV usage patterns. The study has two main stages: (1) creating an SOC management cycle to maintain the battery within an optimal range, and (2) designing a PD controller to regulate the switching between charging and discharging dynamically. Tests were conducted with initial SOC levels of 25%, 55%, and 85%. Results showed that using $K_p = 0.02$ and $K_d = 1$ achieved the lowest Mean Squared Error (MSE), indicating optimal controller performance. Time-based EV scheduling encourages users to export stored energy during peak utility demand, benefiting both EV owners and utilities. However, challenges arose from mismatched reference and actual currents due to PD parameter tuning. Future research should explore a theoretically designed PID controller to further reduce errors.

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