

# Two-Stage PID-Controlled Thermal Management and Chaotic Phase Space-Based Dynamic Analysis of Lithium-Ion Batteries under Fast Charging Conditions

Nihat Pamuk<sup>1</sup>, Erdem Girgin<sup>1</sup>

<sup>1</sup> Zonguldak Bulent Ecevit University, Electrical and Electronics Engineering, Zonguldak, Türkiye

**Abstract** – Temperature rise in lithium-ion batteries during fast charging is a critical factor that directly affects battery performance, service life, and operational safety. In this study, an Arduino Mega-based experimental system was developed for real-time battery temperature monitoring and active cooling control. Battery temperature, current, and voltage were monitored simultaneously, while active cooling was provided by a TEC1-12706 Peltier module. In the proposed control approach, the Peltier module was operated at the maximum PWM duty cycle until the battery temperature came within 1 °C of the specified target temperature, after which PID control was activated to achieve more precise temperature regulation. The developed method was experimentally evaluated under three operating conditions: no cooling, hysteresis-based control, and two-stage PID-based control. The acquired temperature data were analysed in phase space using the Lorenz, Rössler, Duffing, and Chua chaotic attractors in MATLAB to investigate the dynamic characteristics of the thermal response. Experimental results demonstrated that the two-stage PID-based control approach provided more stable temperature regulation than the other methods and enabled more effective thermal management under fast-charging conditions.

**Keywords** – fast charging, lithium-ion battery, two-stage PID control, peltier cooling, chaotic attractors.

DOI: 10.18421/SAR93-03

<https://doi.org/10.18421/SAR93-03>

**Corresponding author:** Nihat Pamuk,  
Zonguldak Bulent Ecevit University, Electrical and Electronics Engineering, Zonguldak, Türkiye  
**Email:** [nihatpamuk@beun.edu.tr](mailto:nihatpamuk@beun.edu.tr)

Received: 09 August 2026.

Revised: 14 September 2026.

Accepted: 20 September 2026.

Published: 27 September 2026.



©2026 Nihat Pamuk & Erdem Girgin; published by UIKTEN. This work is licensed under the Creative Commons Attribution-NonCommercial 4.0 International License.

The article is published with Open Access at <https://www.sarjournal.com/>

## 1. Introduction

Lithium-ion batteries have found widespread use in applications ranging from portable electronic devices to electric vehicles and grid-scale energy storage systems due to their high energy density and rechargeable characteristics [1]. This widespread adoption has increased the demand for shorter charging times; however, fast-charging processes conducted at high current rates require the simultaneous consideration of their effects on ion transport, electrochemical reactions, material degradation, and safety within the cell [2]. The fast-charging performance of batteries depends not only on electrode properties but is also significantly influenced by the ionic conductivity of the electrode, interfacial stability, and ion transport behavior [3]. Furthermore, heat generation and temperature distribution within the cell under high charging currents are among the key factors that directly affect battery performance, operational stability, and safety [4]. Therefore, reliable monitoring of battery temperature during fast-charging applications and the effective removal of generated heat using appropriate cooling methods are considered fundamental requirements of battery thermal management systems [5]. Recent studies have demonstrated that various thermal management methods, including air and liquid cooling, phase-change materials, heat pipes, and thermoelectric systems, can be employed to limit battery temperature and temperature differences between cells [6].

In lithium-ion batteries, adverse operating conditions such as overcharging, external heating, short circuits, and mechanical damage can initiate a sequence of mutually triggering exothermic reactions within the cell, ultimately leading to thermal runaway [7]. During thermal runaway, the rapid increase in cell temperature may give rise to serious safety risks, including the release of flammable gases, loss of structural integrity of the cell, fire, and explosion [8].

To enable the early detection of thermal degradation, various early-warning methods have been developed based on the monitoring of physical and electrochemical parameters such as temperature, voltage, current, gas concentration, and mechanical expansion of the cell [9]. However, due to variations in cell chemistry and operating conditions, a single measurement parameter may not be sufficient to represent all stages of the thermal degradation process with adequate accuracy. Therefore, recent studies have increasingly focused on multi-parameter approaches that jointly evaluate data obtained from multiple sensors and determine thermal runaway thresholds based on real-time measurement data [10]. These developments highlight the need, particularly under fast-charging conditions, for continuous monitoring of temperature variations and the development of effective control systems capable of responding promptly to critical thermal trends.

Changes in battery temperature may exhibit nonlinear dynamic characteristics, particularly under fast-charging conditions. Therefore, assessments based solely on the time domain may not always be sufficient to reveal all characteristics of the system behavior [11]. Chaotic time-series analysis and phase-space methods, which are commonly employed in the analysis of nonlinear systems, constitute important mathematical approaches for investigating complex dynamic behavior.

In this context, the Lorenz [12], Rössler [13], Duffing [14], and Chua [15] models are among the fundamental mathematical approaches widely used to examine the phase-space behavior of nonlinear dynamic systems. In this study, these models were not incorporated into the control algorithm; rather, they were used solely to analyze the dynamic behavior of the system in phase space by applying values derived from the experimental temperature data to the respective models. Accordingly, the dynamic characteristics of the temperature variations observed under different control scenarios were visually analyzed in MATLAB using the Lorenz, Rössler, Duffing, and Chua attractors.

In battery thermal management systems, various control algorithms are employed in addition to passive and active cooling methods to maintain battery temperature within a safe operating range [16]. Among these methods, the PID (Proportional-Integral-Derivative) control algorithm is widely preferred in temperature control applications due to its simple structure, ease of implementation, and adaptability to different systems [17]. The PID control algorithm continuously evaluates the error signal between the measured and target temperatures and dynamically updates the control output, thereby enabling the system to respond to temperature variations in a stable manner.

However, the rapid temperature increases that may occur during fast charging of lithium-ion batteries can directly affect the response time of the control system and the cooling performance. Therefore, recent studies have increasingly investigated PID-based control approaches in combination with active cooling methods based on air, liquid, and thermoelectric (Peltier) systems to develop thermal management strategies capable of controlling battery temperature more rapidly, stably, and effectively [18].

In this study, an experimental thermal management system was developed to monitor and effectively manage the temperature of a lithium-ion battery in real time under fast-charging conditions. Within the developed system, temperature, current, and voltage data were monitored simultaneously, while temperature control was achieved using a TEC1-12706 thermoelectric (Peltier) module driven by a PWM signal. In the proposed control strategy, when the battery temperature was considerably higher than the target temperature, the Peltier module was operated at the maximum PWM value. Once the temperature approached approximately 1 °C above the target value, control was transferred to the PID algorithm. At this stage, the cooling capacity was dynamically adjusted according to the temperature variation and the error signal [19]. In this way, the initial cooling stage, which requires rapid intervention, and the stable and precise temperature control around the target temperature were integrated into a single control structure.

Within the scope of this study, a two-stage PID-based thermal management system was experimentally implemented to monitor and effectively regulate the temperature of a lithium-ion battery in real time under fast-charging conditions. In the developed experimental setup, three different control scenarios were comparatively evaluated: operation without active control, hysteresis-controlled operation, and two-stage PID-controlled operation. In addition, the temperature data obtained from the experiments were analyzed in phase space using the Lorenz, Rössler, Duffing, and Chua chaotic attractor models in MATLAB, and the dynamic behavior associated with the different control scenarios was investigated. Thus, while the temperature regulation performance of the proposed control approach was evaluated based on the experimental results, the dynamic characteristics of the temperature variations were also analyzed through different nonlinear mathematical models.

## 2. Methodology

In this study, an experimental thermal management system based on a two-stage PID control approach was developed to monitor changes in lithium-ion battery temperature in real time under fast-charging conditions and to activate cooling before the temperature reached critical levels. In the experimental setup, temperature, current, and voltage data were measured simultaneously and continuously recorded at predefined sampling intervals. To reduce instantaneous fluctuations and noise in the measurement data, a moving average filter was applied, and the filtered temperature data were subsequently provided as input to the control algorithm. Based on the output values generated by the control algorithm, the duty cycle of the PWM signal was dynamically adjusted. Accordingly, the cooling capacity of the TEC1-12706 thermoelectric (Peltier) module was controlled in real time in response to changes in battery temperature.

### 2.1. Hardware Architecture

The developed experimental system was built on an Arduino Mega 2560-based hardware architecture to enable real-time monitoring of lithium-ion battery temperature under fast-charging conditions and, when necessary, the implementation of active cooling through the proposed two-stage PID control approach. The selection of the system components was based on the requirements of stable operation under high-current conditions, reliable data acquisition, high measurement accuracy, and real-time control. The main components constituting the hardware architecture of the experimental system are described below.

- **Arduino Mega 2560 (ATmega2560):** used as the main control unit of the experimental system. The Arduino Mega 2560 was responsible for acquiring and processing sensor data, executing the two-stage PID control algorithm, generating the PWM signal required to drive the Peltier module, and managing the graphical display.

- **AHT10 Temperature Sensor:** used for real-time measurement of the battery surface temperature. The digital I<sup>2</sup>C communication protocol enabled stable and reliable transmission of temperature data to the microcontroller.

- **ACS712 30 A Current Sensor:** used to continuously monitor the charging current applied to the battery during the fast-charging process. To improve measurement accuracy and minimize sensor-induced zero-point deviations, offset calibration was performed during system initialization.

- **Sony VTC6 18650 Battery:** a battery pack consisting of two Sony VTC6 18650 cells connected in parallel was used in the experimental studies. The parallel configuration increased the total capacity and enabled the charging current to be shared between the cells.

- **TP4056 Charging Module:** four TP4056 charging modules were used in a parallel configuration to charge the battery pack. This configuration was intended to increase the total charging current and provide a more stable charging process.

- **TEC1-12706 Peltier Module:** used as an active thermoelectric cooling element for controlling the battery temperature. The cooling capacity of the Peltier module was dynamically adjusted according to the duty cycle of the PWM signal generated by the control algorithm.

- **IRFP264 MOSFET:** used to transfer the PWM control signal generated by the Arduino Mega 2560 to the power stage and to drive the TEC1-12706 Peltier module at the required power level.

- **Aluminum Heat Sink Block (20 × 10 cm):** used to enhance heat transfer from the hot side of the Peltier module to the ambient air and to maintain the thermal performance of the module.

- **Two-Channel Relay Module:** used to perform the switching operations of the active cooling system and to control the associated power circuits.

- **128 × 64 Graphical LCD:** used to display real-time information on temperature, current, voltage, battery state of charge, and system operating status throughout the experiments.

- **600 W Dual-Output Laboratory Power Supply:** used to provide stable voltage and power levels required by the Arduino Mega 2560, Peltier module, Mosfet power stage, relay module, graphical LCD, and cooling fans.

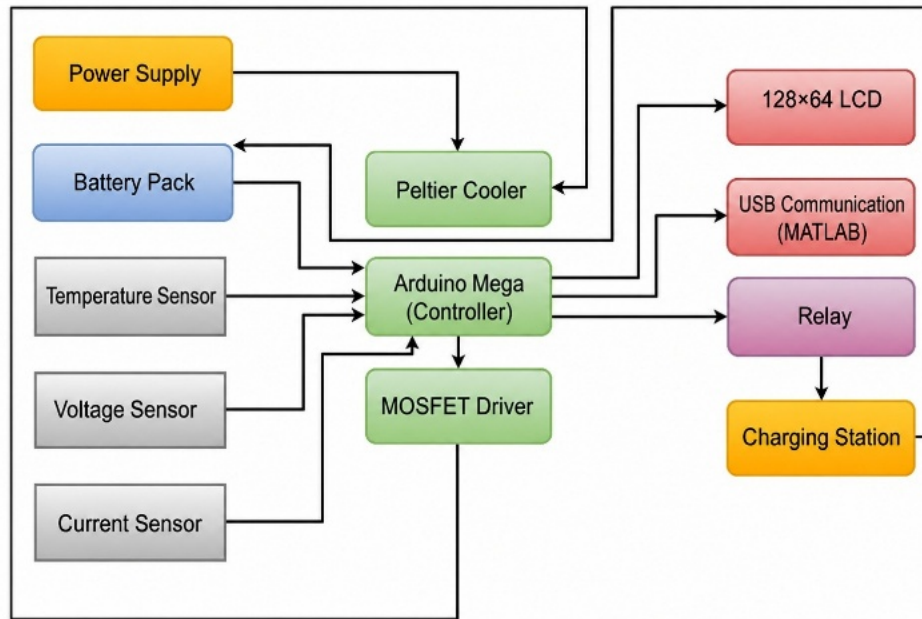


Figure 1. Main hardware components and connection architecture of the thermal management system

Figure 1 illustrates the main hardware components used in the developed experimental system and the interconnection structure among these components.

Figure 2 presents an overall view of the experimental test setup established based on the main hardware components and connection architecture of the thermal management system.

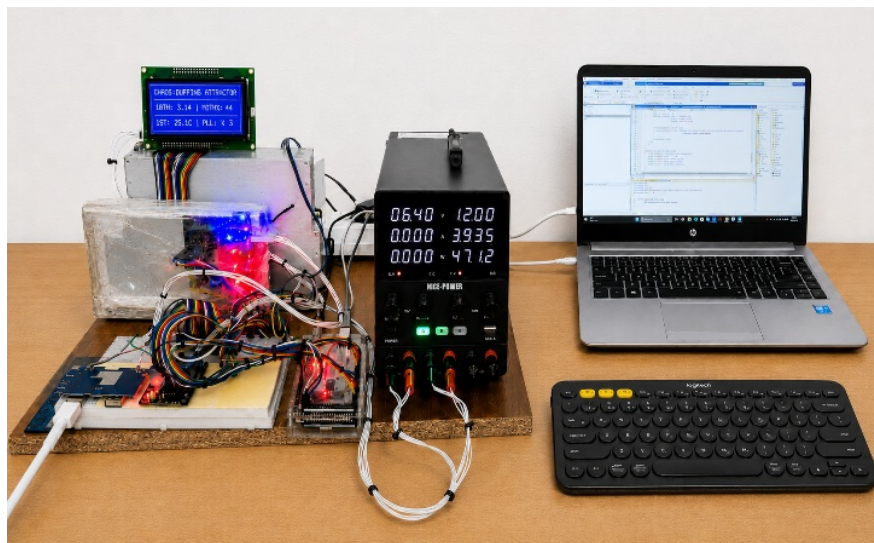


Figure 2. Overall view of the experimental test setup, including the Arduino control system, Peltier cooling unit, sensors, LCD, power supply, and monitoring interface

In the experimental setup, the measurement, control, power, and active cooling units were integrated within a unified system architecture. This configuration enabled real-time monitoring of temperature, current, and voltage data, as well as the operation of the TEC1-12706 Peltier module in accordance with the developed control algorithm.

## 2.2. Sensor Calibration and Data Filtering Process

To improve the accuracy and reliability of the measurements obtained from the sensors used in the experimental system, calibration and filtering procedures were applied to the temperature, current, and voltage data. During the measurement process, the raw sensor data were not directly transferred to the control algorithm due to instantaneous fluctuations that could arise from environmental effects and electronic components.

Therefore, a moving average filter was employed to reduce short-term measurement fluctuations and high-frequency noise components that could adversely affect the control performance. For the ACS712 current sensor, an initial offset value corresponding to the zero-current condition was determined during system startup, and subsequent measurements were corrected with respect to this reference value. For voltage measurements, the values read by the microcontroller were converted to actual voltage levels using the conversion coefficient of the voltage-divider circuit.

The battery surface temperature was measured using the AHT10 digital temperature sensor, and the resulting temperature data were transferred to the control algorithm after being subjected to the filtering process. The filtered temperature, current, and voltage data were continuously updated by the Arduino Mega 2560 at predefined sampling intervals. The acquired data were simultaneously displayed on the graphical LCD, while the relevant measurement values were used as input parameters for the control algorithm. In this manner, the stability of the measurement data was improved, with the aim of reducing control errors that could arise from sensor noise and transient measurement fluctuations.

### 2.3. Two-Stage PID-Controlled Rapid Cooling System

The temperature rise that occurs during fast charging of lithium-ion batteries is one of the key parameters directly affecting battery performance, service life, and safety. Therefore, a two-stage control approach capable of responding rapidly and stably to temperature variations was implemented in the developed experimental system. In the first stage of the control algorithm, if the battery temperature remained sufficiently far from the predefined target value, the Peltier module was operated at the maximum PWM duty cycle to achieve the highest possible cooling capacity. Once the battery temperature approached within approximately 1 °C of the target value, control was transferred to the PID algorithm, and the PWM duty cycle was continuously updated according to the temperature error and the instantaneous thermal behavior of the system. Thus, rapid cooling was achieved during the first stage, while overshoot and oscillations around the target temperature were limited during the second stage, enabling more stable and precise temperature control. Figure 3 illustrates the control steps followed by the developed two-stage PID-controlled cooling approach as a function of battery temperature.

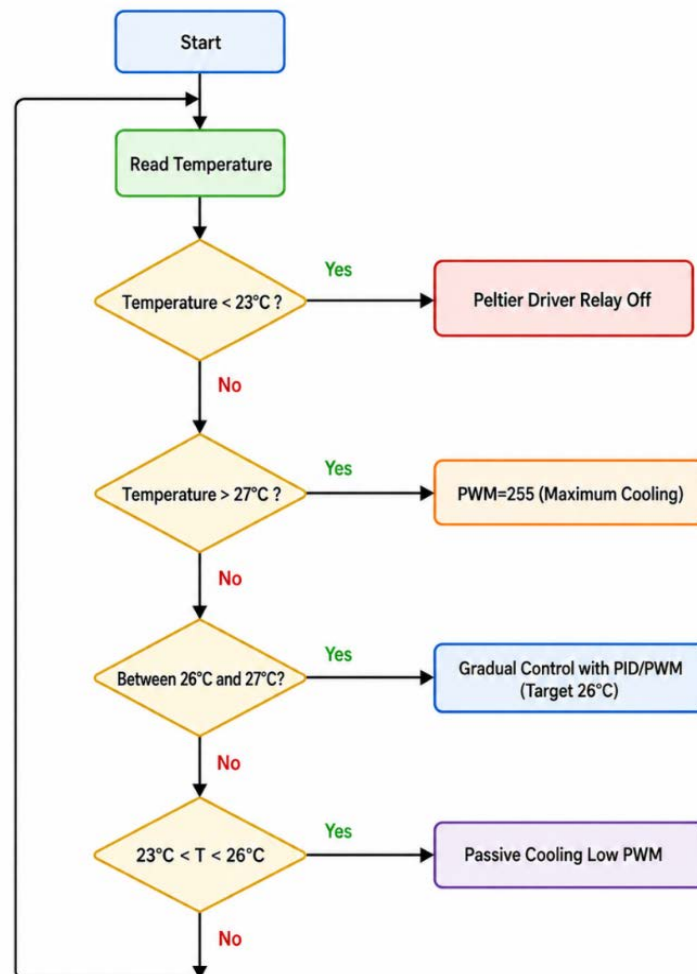


Figure 3. Flowchart of the two-stage PID-controlled rapid cooling algorithm

With the developed two-stage control approach, changes in battery temperature can be addressed within a short response time. As the temperature approaches the target value, the cooling capacity is gradually adjusted to maintain the system within a stable temperature range. While this approach provides a rapid temperature reduction through high cooling capacity during the initial stage of the control process, it also contributes to reducing overshoot and oscillations around the target temperature and achieving more stable thermal behavior.

### 2.3.1. PID Control Equations

In the second stage of the two-stage control approach, once the temperature approaches within approximately 1 °C of the target value, the control process is governed by the PID algorithm. The PID control algorithm continuously calculates the error between the target temperature and the measured temperature to generate the control signal [20]. The objective of this control structure is to maintain the temperature stably around the target value while responding rapidly to sudden changes and reducing unnecessary temperature oscillations. The PID control output is expressed by Equation (1).

$$u(t) = K_p e(t) + K_i \int e(t) dt + K_d \frac{de(t)}{dt} \quad (1)$$

In Equation (1),  $u(t)$  represents the PID control output,  $e(t)$  denotes the error between the target temperature and the measured temperature,  $K_p$  represents the proportional gain,  $K_i$  represents the integral gain, and  $K_d$  represents the derivative gain. In this study, the error term was calculated using Equation (2).

$$e(t) = T_{target} - T_{measured} \quad (2)$$

In Equation (2),  $T_{target}$  represents the target temperature, while  $T_{measured}$  denotes the temperature value obtained in real time from the temperature sensor. The calculated PID control output is used to determine the PWM duty cycle, thereby enabling the cooling capacity of the Peltier module to be dynamically adjusted. In this configuration, the temperature data acquired from the sensor directly constitute the input to the PID controller.

### 2.3.2. Two-Stage Control Strategy

The control algorithm developed in this study was structured as a two-stage control strategy to provide a rapid response to the temperature rise occurring during fast charging and to ensure stable operation around the target temperature.

In the first stage of the control algorithm, when the measured battery temperature differed from the target temperature by approximately 1 °C or more, the Peltier module was operated at the maximum PWM duty cycle. In this manner, a high cooling capacity was provided to bring the battery temperature as close as possible to the target value within the shortest possible time. Once the measured temperature approached within approximately 1 °C of the target value, the control process was switched to the second stage, in which the PWM duty cycle was dynamically adjusted by the PID control algorithm. At this stage, the control output generated by the PID algorithm was applied to the MOSFET power circuit driving the Peltier module, thereby enabling the cooling capacity to be continuously updated according to the instantaneous temperature variation of the battery. With the proposed two-stage control strategy, the rapid temperature increase observed during the initial phase of fast charging was effectively suppressed by applying a high cooling capacity. Subsequently, as the temperature approached the target value, the PID algorithm dynamically adjusted the PWM duty cycle, enabling more stable and precise temperature regulation around the desired setpoint.

### 2.4. Experimental Test Scenarios

To evaluate the performance of the developed two-stage control approach, the experimental studies were conducted under three different operating scenarios. In all experiments, the same hardware infrastructure, battery pack, and data acquisition method were used, while only the applied temperature control strategy was changed. This enabled a comparative investigation of the effects of different control approaches on the thermal behavior of the battery.

In the first scenario, no active cooling method was applied, and the natural temperature variation of the battery during the fast-charging process was recorded. This scenario was used to determine the thermal behavior of the system in the absence of temperature control and to establish a reference for comparison with the other control methods.

In the second scenario, a temperature-based hysteresis control method was implemented. In this method, the Peltier module was operated according to an on-off control principle based on predefined lower and upper temperature threshold values, and the variation in battery temperature was monitored under this control structure.

In the third scenario, the two-stage PID-controlled cooling approach developed in this study was applied. When the battery temperature deviated from the target temperature by approximately 1 °C or more, the Peltier module was operated at the maximum PWM duty cycle. Once the temperature approached within approximately 1 °C of the target value, the control process was transferred to the PID algorithm. Thus, rapid thermal intervention was achieved through high cooling capacity in the first stage, while more stable and precise temperature control around the target temperature was achieved in the second stage. For each experimental scenario, temperature, current, and voltage data were recorded under identical sampling conditions. The acquired data were subsequently used in the analysis stages to comparatively evaluate the thermal performance of the different control strategies.

## 2.5. Types of Chaotic Attractors

In this study, the Lorenz, Rössler, Duffing, and Chua chaotic attractor models were employed in MATLAB to investigate the phase-space dynamic behavior of the temperature data obtained during the experimental process. Values derived from the experimental temperature data were applied to the corresponding mathematical models to generate phase-space trajectories. These chaotic attractor models were not incorporated into any stage of the control algorithm; rather, they were used solely for the visual and comparative evaluation of the dynamic characteristics of the temperature data obtained under different control scenarios. The mathematical expressions of the chaotic attractor models used in this study are presented in the following equations. In this context, the system of differential equations describing the dynamic behavior of the Lorenz attractor is given in Equation (3).

$$\begin{cases} \dot{x} = \sigma(y - x) \\ \dot{y} = x(\rho - z) - y \\ \dot{z} = xy - \beta z \end{cases} \quad (3)$$

In Equation (3),  $x$ ,  $y$  and  $z$  represent the state variables of the system, while  $\sigma$ ,  $\rho$  and  $\beta$  denote the parameters governing the system behavior. The system of differential equations describing the dynamic behavior of the Rössler attractor is given in Equation (4).

$$\begin{cases} \dot{x} = -y - z \\ \dot{y} = x + ay \\ \dot{z} = b + z(x - c) \end{cases} \quad (4)$$

In Equation (4),  $a$ ,  $b$  and  $c$  represent the system parameters, while  $x$ ,  $y$  and  $z$  denote the state variables in phase space. The system of differential equations describing the dynamic behavior of the Duffing attractor is given in Equation (5).

$$\ddot{x} + \delta\dot{x} + \alpha x + \beta x^3 = \gamma \cos(\omega t) \quad (5)$$

In Equation (5),  $\delta$  represents the damping coefficient,  $\alpha$  and  $\beta$  denote the linear and nonlinear coefficients, respectively,  $\gamma$  represents the amplitude of the external forcing term, and  $\omega$  denotes the angular frequency. The system of differential equations describing the dynamic behavior of the Chua attractor is given in Equation (6).

$$\begin{cases} \dot{x} = \alpha(y - x - f(x)) \\ \dot{y} = x - y + z \\ \dot{z} = -\beta y \end{cases} \quad (6)$$

In Equation (6),  $f(x)$ , represents the nonlinear function characterizing the Chua system, while  $\alpha$  and  $\beta$  denote the system parameters. In this study, the same temperature dataset was used for all chaotic models, and the resulting phase-space behaviors were comparatively evaluated under different control scenarios.

## 3. Results and Discussion

The temperature, current, and system-state data obtained under the three different test scenarios were evaluated together to investigate the effect of the developed rapid cooling approach on the thermal behavior during the fast-charging process. The findings were first assessed based on the temperature-time curves obtained in the time domain and were subsequently supported by chaotic attractor visualizations generated in MATLAB using the same datasets. The chaotic attractor analyses were employed to visualize the dynamic trends of the temperature variations in phase space and to comparatively examine the behavioral differences among the different test scenarios. However, these analyses did not directly contribute to the decision-making mechanism of the control algorithm.

### 3.1. Thermal Behavior and Results with the Cooling System Disabled (Scenario 1)

In this scenario, in which the cooling system was completely disabled, the battery exhibited its natural thermal behavior throughout the fast-charging process. At the beginning of the test, the battery surface temperature was approximately 25 °C, and only a limited and gradual temperature increase was observed during the initial stage of charging.

However, as the charging process progressed, the rate of temperature increase became noticeably higher, and the temperature curve exhibited increasingly nonlinear behavior over time. Particularly during the middle stage of the charging process, the temperature rise accelerated, and the battery surface temperature reached approximately 31–32 °C within a relatively short period. This observed increase indicates that the heat generated within the cell during fast charging could not be dissipated sufficiently through natural heat transfer mechanisms, resulting in a gradual accumulation of heat and a corresponding increase in battery temperature.

The absence of an active cooling or temperature control mechanism allowed the generated heat to accumulate throughout the charging process, causing the battery temperature to continue rising. Therefore, the temperature trend observed under uncontrolled conditions highlights the necessity of an effective thermal management system during fast charging. Figure 4 shows the time-dependent variation in battery temperature recorded throughout the fast-charging process under Scenario 1, in which the cooling system was disabled.

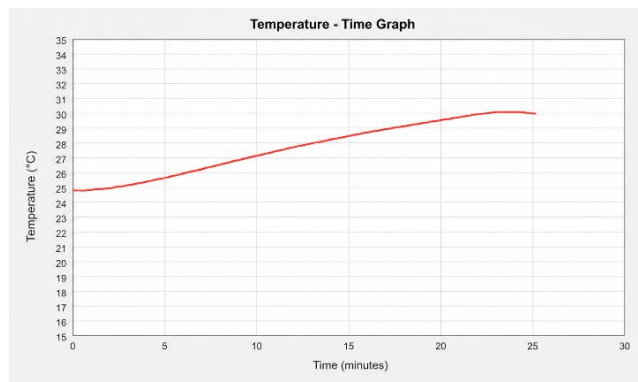


Figure 4. Temperature–time curve with the cooling system disabled

Examination of the slope of the temperature-time curve shows that the rate of temperature increase became markedly higher during the later stages of the test. This finding indicates that, under fast-charging conditions, battery temperature may rise in an uncontrolled manner in the absence of active cooling, potentially leading to thermal instability. The obtained results clearly support the necessity of implementing active cooling strategies.

### 3.2. Thermal Behavior and Results under Hysteresis-Controlled Cooling (Scenario 2)

In this scenario, the PID control structure was disabled, and only a hysteresis-based cooling strategy was applied. This approach aimed to investigate the behavior of the control system under a simple and stable switching logic while maintaining the battery temperature within predefined limits.

In the hysteresis control scheme, the cooling system was activated at a battery temperature of 26 °C and deactivated when the temperature decreased below 24 °C. This 2 °C hysteresis range minimized frequent switching of the relay and enhanced the overall stability of the thermal management system. Figure 5 shows the time-dependent variation in battery temperature recorded during fast charging under Scenario 2, in which hysteresis-controlled cooling was applied.

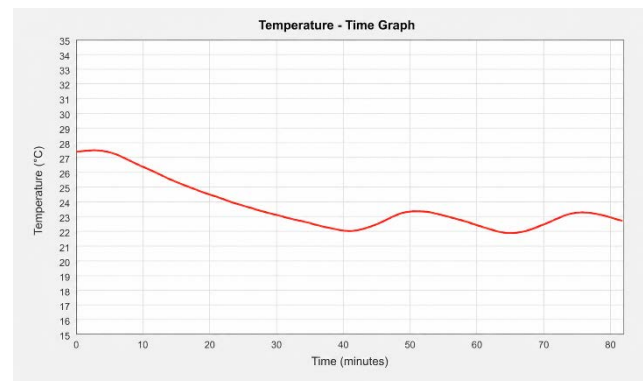


Figure 5. Temperature–time curve under hysteresis-controlled cooling

Examination of the temperature–time curve showed that the battery temperature fluctuated within the predefined hysteresis limits and that no uncontrolled temperature rise occurred. During the periods in which the cooling system was active, the upward temperature trend was suppressed, whereas after the cooling system was deactivated, the temperature gradually began to rise again. This behavior indicates that the hysteresis-based control approach could maintain the battery temperature within a defined operating range under fast-charging conditions. However, the temperature fluctuation range was observed to be wider than that obtained under the two-stage PID/PWM-controlled scenario.

### 3.3. Thermal Behavior and Results under PID-Controlled Cooling (Scenario 3)

In this scenario, the battery temperature was regulated using a two-stage control strategy. The primary objective of the developed approach was to provide a rapid response to the temperature rise occurring during fast charging and to achieve more stable and precise control as the battery temperature approached the target operating value. Accordingly, if the battery temperature remained sufficiently far from the predefined target temperature, the Peltier module operated at the maximum PWM duty cycle. Once the battery temperature approached within 1 °C of the predefined target value, the control process was transferred to the PID algorithm, and the PWM duty cycle was dynamically adjusted according to the PID output.

In this manner, rapid thermal intervention was achieved through high cooling capacity during the first stage of control, while the second stage was intended to regulate the battery temperature more stably and precisely around the target value.

Examination of the experimental results showed that the first control stage, implemented at the maximum PWM duty cycle, suppressed the temperature rise within a short period. As a result, the battery surface temperature rapidly approached the predefined target value, while further temperature increase to higher levels was limited. Once the battery temperature approached within approximately 1 °C of the target value, the PID controller was activated, the PWM duty cycle was continuously recalculated, and the cooling capacity of the Peltier module was dynamically adjusted in response to instantaneous temperature variations. In this manner, excessive cooling and unnecessary temperature oscillations that could result from continuous operation of the Peltier module at maximum power were reduced.

Examination of the temperature curve during the PID-controlled stage indicated that fluctuations around the target value remained limited and that the system reached a stable operating region within a relatively short period. The periodic temperature variations observed in the hysteresis-controlled scenario due to threshold-based switching were substantially reduced under the two-stage PID control approach, and the battery temperature exhibited a more balanced behavior around the target operating point. This improvement can be attributed to the PID controller continuously updating the PWM duty cycle by considering not only the instantaneous temperature error but also its accumulated value over time and its rate of change. Figure 6 shows the time-dependent variation in battery temperature recorded during fast charging under Scenario 3, in which two-stage PID/PWM-controlled cooling was applied.

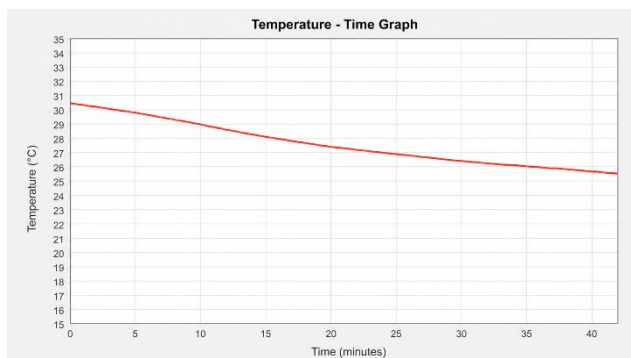


Figure 6. Temperature–time curve under PID-controlled cooling

Figure 6 shows that the developed two-stage control approach integrates rapid cooling and precise temperature regulation within a single control structure. In the first stage, the temperature rise was rapidly suppressed by applying the maximum PWM duty cycle, whereas in the second stage, activation of the PID algorithm enabled the battery temperature to be maintained more stably around the target value. The obtained findings indicate that the proposed approach is effective not only in limiting temperature rise but also in maintaining the target operating temperature and reducing temperature fluctuations.

### 3.4. Comparative Evaluation of the Three Control Strategies

In this study, the three control scenarios were evaluated collectively in terms of the applied control strategy, variations in battery temperature, and the overall thermal behavior of the system. The no-cooling condition, hysteresis-controlled cooling, and the two-stage PID-controlled approach were investigated under the same experimental conditions, and the effects of each method on battery temperature regulation were comparatively analyzed. In the first scenario, in which no cooling was applied, the battery temperature was observed to increase continuously throughout the charging process. In the absence of an active temperature control mechanism, the heat generated within the battery was dissipated only through natural heat transfer mechanisms.

This finding indicates that, particularly under fast-charging conditions, passive heat dissipation alone may be insufficient to maintain the battery temperature within the desired operating range, highlighting the need for an effective thermal management approach. In the second scenario, employing hysteresis-controlled cooling, the battery temperature was maintained between predefined lower and upper threshold values. However, because the control structure was based on an on-off switching principle, the Peltier module was activated or deactivated only when the corresponding threshold temperatures were reached. Consequently, recurring temperature oscillations were observed at regular intervals, and a fully stable operating regime around the target temperature could not be achieved.

In the two-stage PID-controlled method, the control process was implemented using a more flexible and dynamic structure. Until the battery temperature approached the target value, the Peltier module operated at the maximum PWM duty cycle to provide rapid cooling. Once the temperature approached within approximately 1 °C of the target value, the control process was transferred to the PID algorithm.

From this point onward, the PWM duty cycle was continuously updated according to the temperature error, and the cooling capacity was adjusted in response to the instantaneous thermal behavior of the battery. As a result, the system was able to respond rapidly to temperature increases while maintaining a more stable and precise operating behavior around the target temperature.

When the temperature–time curves obtained from the three scenarios were evaluated together, it became evident that the applied control method had a decisive influence on the thermal behavior of the battery. In the absence of cooling, the battery temperature exhibited a continuous increasing trend, whereas hysteresis control maintained the temperature within predefined limits. However, due to the threshold-based on–off control mechanism, temperature fluctuations could not be eliminated. In contrast, the two-stage PID-controlled approach produced a more balanced and stable profile by providing a rapid response to temperature rise and switching to a precise control stage as the temperature approached the target operating point.

A comparative evaluation of Figures 4 and 6 demonstrates the effects of the different control strategies on the thermal performance of the battery. The obtained findings indicate that the developed two-stage control approach combines rapid thermal response capability with stable operation around the target temperature within a single control structure. Based on these results, the proposed method can be considered a practical thermal control approach for the effective and stable management of battery temperature under fast-charging conditions.

### 3.5. Chaotic Phase-Space Analyses

In this study, values derived from the instantaneous temperature data obtained during the experiments were applied to the corresponding chaotic attractor equations to investigate the dynamic behavior of the system in phase space using different mathematical models. The Lorenz, Rössler, Duffing, and Chua attractors were not used to generate the control signal; rather, they were employed solely for the visual and comparative evaluation of the dynamic characteristics of the experimental results. In this way, the time-dependent trends of the temperature variations were analyzed not only through conventional temperature–time curves but also from a phase-space perspective. Figure 7 presents the phase-space representation generated using the Lorenz chaotic attractor model based on the temperature data obtained from the scenario in which the cooling system was disabled.

Figure 7 shows that the phase trajectories of the Lorenz attractor generated from the temperature data obtained under the no-cooling scenario are distributed over a relatively broad region. Although the characteristic two-lobed structure of the attractor is preserved, the trajectories form wider loops in the outer regions.

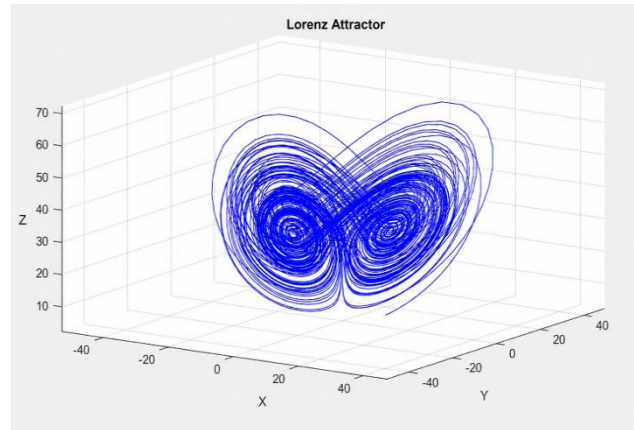


Figure 7. Lorenz attractor representation of the temperature data obtained with the cooling system disabled

This distribution indicates that the higher-amplitude temperature variations observed during the fast-charging process are reflected by a broader spread of the trajectories in phase space. The resulting phase-space representation exhibits a dynamic trend consistent with the continuous and pronounced temperature increase observed in the temperature–time curve. Figure 8 presents the phase-space representation generated using the Lorenz model based on the temperature data obtained under the two-stage PID/PWM-controlled cooling scenario.

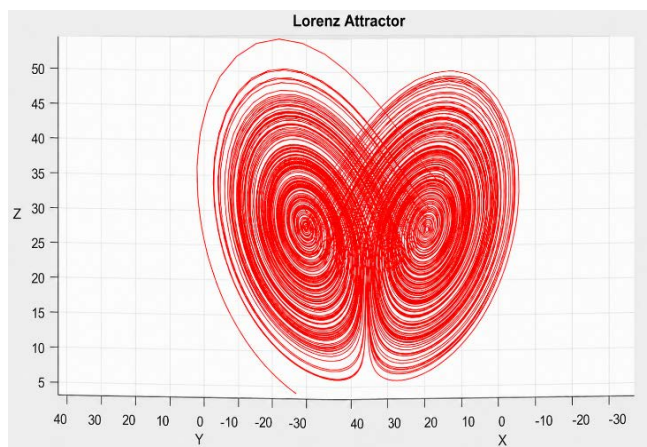


Figure 8. Lorenz attractor representation of the temperature data obtained under two-stage PID/PWM-controlled cooling

Figure 8 shows that, in the Lorenz attractor generated from the temperature data obtained under the two-stage PID/PWM-controlled cooling scenario, the phase trajectories are clustered more densely in specific regions. Although the characteristic two-lobed structure of the attractor is preserved, the trajectories exhibit a more regular and confined distribution. This observation visually supports that the developed control approach can maintain temperature variations within a more stable range around the target value. Figure 9 presents the phase-space representation generated using the Rössler model based on the temperature data obtained with the cooling system disabled.

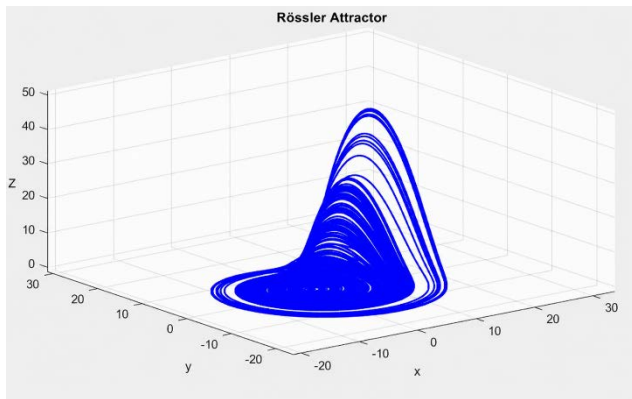


Figure 9. Rössler attractor representation of the temperature data obtained with the cooling system disabled

Figure 9 shows that the phase trajectories of the Rössler attractor generated from the temperature data obtained under the no-cooling scenario are distributed over a broader region. In particular, the outer trajectories form larger loops and exhibit a wider spread in the upper region of the attractor. This behavior indicates that the higher-amplitude temperature variations occurring during the fast-charging process are reflected by a broader distribution of the trajectories in phase space. The resulting phase-space representation exhibits a dynamic trend consistent with the continuous temperature increase observed in the temperature-time curve. Figure 10 presents the phase-space representation generated using the Rössler model based on the temperature data obtained under the two-stage PID/PWM-controlled cooling scenario.

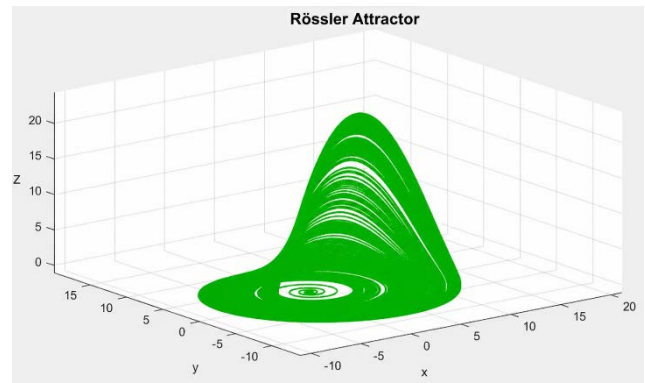


Figure 10. Rössler attractor representation of the temperature data obtained under two-stage PID/PWM-controlled cooling

Figure 10 shows that the phase trajectories of the Rössler attractor generated from the temperature data obtained under the two-stage PID/PWM-controlled cooling scenario are concentrated within a more confined region. Compared with the no-cooling condition, the outer trajectories become narrower, and the attractor exhibits a more regular geometric distribution. This appearance visually supports the ability of the developed control approach to constrain temperature variations within a narrower operating range. Figure 11 presents the phase-space representation generated using the Duffing model based on the temperature data obtained with the cooling system disabled.

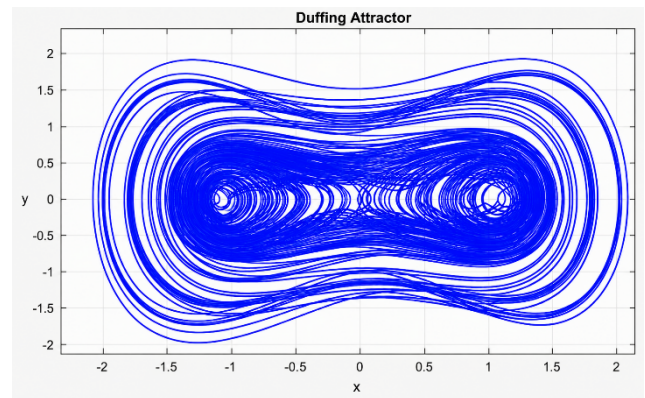


Figure 11. Duffing attractor representation of the temperature data obtained with the cooling system disabled

Figure 11 shows that the phase trajectories of the Duffing attractor generated from the temperature data obtained under the no-cooling scenario are distributed over a broader region.

Although the characteristic double-lobed structure of the attractor is preserved, the outer trajectories form larger loops and the overall distribution in phase space becomes more extensive. This behavior indicates that the higher-amplitude temperature variations observed during the fast-charging process are associated with a broader dynamic operating region in phase space. The resulting phase-space representation exhibits a dynamic trend consistent with the uncontrolled temperature increase observed in the temperature-time curve. Figure 12 presents the phase-space representation generated using the Duffing model based on the temperature data obtained under the two-stage PID/PWM-controlled cooling condition.

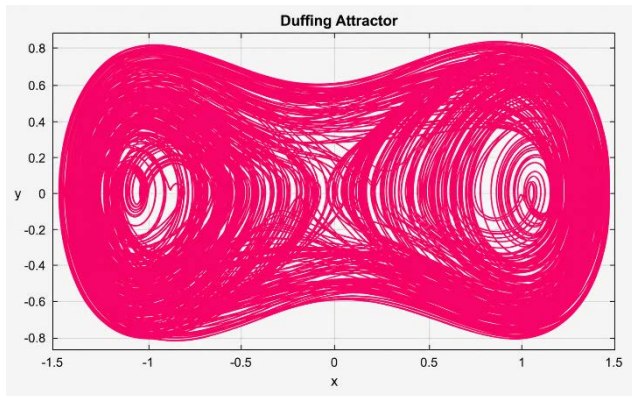


Figure 12. Duffing attractor representation of the temperature data obtained under two-stage PID/PWM-controlled cooling

Figure 12 shows that the phase trajectories of the Duffing attractor generated from the temperature data obtained under the two-stage PID/PWM-controlled cooling scenario are concentrated within a more confined region. Compared with the no-cooling condition, the outer trajectories become narrower, and the attractor exhibits a more regular geometric distribution. This appearance visually supports the ability of the developed control approach to constrain temperature variations within a narrower operating range. Figure 13 presents the phase-space representation generated using the Chua model based on the temperature data obtained with the cooling system disabled.

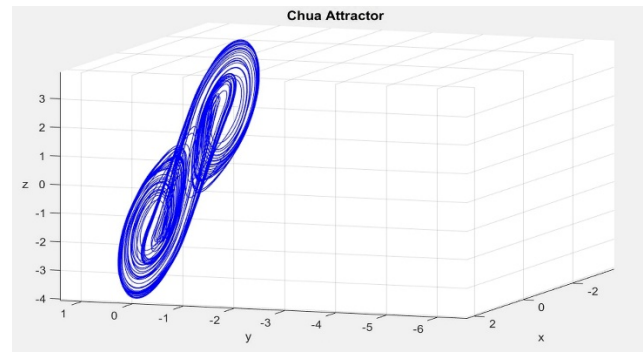


Figure 13. Chua attractor representation of the temperature data obtained with the cooling system disabled

Figure 13 shows that the characteristic two-lobed structure of the Chua attractor generated from the temperature data obtained under the no-cooling scenario is preserved. The phase trajectories form wide loops around both lobes and spread over a relatively broad region of phase space. In particular, the pronounced outer trajectories indicate that the temperature variations occurred over a wider range and that the dynamic behavior of the system extended across a broader phase-space region. This representation exhibits a dynamic trend consistent with the temperature-time curve observed under the no-cooling condition during fast charging.

Figure 14 presents the phase-space representation generated using the Chua model based on the temperature data obtained under the two-stage PID/PWM-controlled cooling condition. Figure 14 shows that the characteristic two-lobed structure of the Chua attractor generated from the temperature data obtained under the two-stage PID/PWM-controlled cooling scenario is preserved, while the phase trajectories become more densely concentrated in specific regions. Compared with the no-cooling condition, the trajectories exhibit a more regular distribution and a more confined spread in phase space. This representation visually supports the ability of the developed control approach to constrain temperature variations within a narrower operating range.

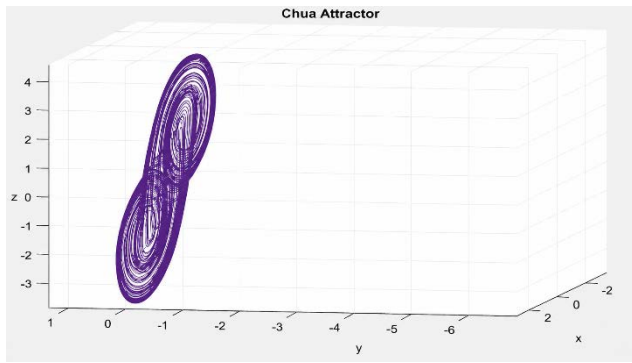


Figure 14. Chua attractor representation of the temperature data obtained under two-stage PID/PWM-controlled cooling

When the phase-space representations obtained from the Lorenz, Rössler, Duffing, and Chua attractors are evaluated together, it can be observed that these four models, despite their different mathematical structures, reflect the variations in the experimental temperature data with similar overall trends. Under the no-cooling scenario, the phase trajectories generally spread over a broader region, whereas under the two-stage PID/PWM-controlled cooling scenario, the trajectories became concentrated within more confined regions and exhibited a more regular distribution.

The emergence of similar trends across all chaotic attractor models, despite their different dynamic structures, indicates that the variations in the experimental temperature data were consistently reflected in the corresponding phase-space representations. However, the chaotic attractor analyses employed in this study were not considered an independent method for quantitatively validating the performance of the control algorithm. Rather, they were used as a complementary analysis approach to qualitatively examine the dynamic characteristics of the experimental temperature data through different mathematical models and to visually support, from a phase-space perspective, the findings obtained from the temperature-time curves.

#### 4. Conclusions and Future Work

In this study, an experimental thermal management system was developed to monitor temperature variations in lithium-ion batteries in real time during fast charging and to manage Peltier-based active cooling through a two-stage control approach. To evaluate the performance of the developed system, three different scenarios were comparatively investigated under identical experimental conditions: operation without cooling, hysteresis-controlled cooling, and two-stage PID-controlled operation. In all experimental scenarios, the same charging infrastructure was used, and the evaluations focused on the effect of the applied thermal control method on battery temperature.

In the absence of active cooling, the battery temperature was observed to increase continuously throughout the charging process. Hysteresis-controlled operation was able to limit the temperature rise within predefined threshold values; however, a certain degree of temperature oscillation occurred due to the on-off nature of the control structure. In the two-stage PID-controlled approach, the Peltier module operated at the maximum PWM duty cycle until the battery temperature approached the target value. Once the temperature came within approximately 1 °C of the target value, the PID algorithm was activated, and the cooling capacity was dynamically adjusted according to instantaneous temperature variations. The experimental results demonstrated that this control approach could limit the temperature rise occurring during fast charging and maintaining the battery temperature in a more balanced and stable manner around the target value.

The experimental temperature data were also evaluated from a phase-space perspective in MATLAB using the Lorenz, Rössler, Duffing, and Chua chaotic attractor models. These chaotic attractors were not incorporated into any stage of the control algorithm; rather, they were employed solely to visually examine the dynamic behavior of the temperature data obtained under different control scenarios through different mathematical models. The resulting phase-space representations revealed distinct visual differences between the uncontrolled condition and the two-stage PID-controlled operating condition in terms of trajectory distribution and regions of concentration. The similar trends observed across the different chaotic attractor models provided a complementary perspective for qualitatively evaluating the dynamic characteristics of the temperature data. Nevertheless, the phase-space analyses based on the chaotic attractors were not considered a standalone quantitative method for validating the performance of the proposed control approach. Instead, they were treated as a complementary visual analysis method that supports the experimental temperature results from a phase-space perspective.

By implementing the developed system in real time on Arduino Mega-based hardware, temperature, current, and voltage data were monitored simultaneously, while the operating level of the Peltier module was dynamically controlled according to the battery temperature. The experimental findings demonstrated that, under the present experimental conditions, the two-stage PID-controlled Peltier cooling approach provides a practical and effective method for managing the temperature rise occurring during fast charging. However, no separate experimental analysis was conducted in this study to investigate reductions in charging time or to compare the effects of different charging current levels.

The developed two-stage control approach enabled real-time monitoring of battery temperature during fast charging and the experimental implementation of active cooling in response to temperature variations. When the findings obtained from the uncontrolled, hysteresis-controlled, and two-stage PID-controlled scenarios were evaluated together, the two-stage control approach was found to effectively limit temperature rise and enable the battery temperature to exhibit a more balanced and stable thermal behavior around the target value. Future studies are planned to investigate the developed system under different charging currents, battery capacities, and environmental conditions. In addition to thermal performance, the effects of the proposed approach on charging time, energy consumption, and cooling efficiency will also be quantitatively evaluated.

## References:

- [1]. J. Xie and Y.-C. Lu, "A retrospective on lithium-ion batteries," *Nat. Commun.*, vol. 11, no. 1, Art. no. 2499, 2020. doi: 10.1038/s41467-020-16259-9.
- [2]. A. Tomaszewska, Z. Chu, X. Feng, S. O'Kane, X. Liu, J. Chen, C. Ji, E. Endler, R. Li, L. Liu, Y. Li, S. Zheng, S. Vetterlein, M. Gao, J. Du, M. Parkes, M. Ouyang, M. Marinescu, G. Offer, and B. Wu, "Lithium-ion battery fast charging: A review," *eTransportation*, vol. 1, Art. no. 100011, 2019. doi: 10.1016/j.etrans.2019.100011.
- [3]. S. Lei, Z. Zeng, S. Cheng, and J. Xie, "Fast-charging of lithium-ion batteries: A review of electrolyte design aspects," *Battery Energy*, vol. 2, no. 5, Art. no. e20230018, 2023. doi: 10.1002/bte2.20230018.
- [4]. Y. Zeng, D. Chalise, S. D. Lubner, S. Kaur, and R. S. Prasher, "A review of thermal physics and management inside lithium-ion batteries for high energy density and fast charging," *Energy Storage Mater.*, vol. 41, pp. 264-288, 2021. doi: 10.1016/j.ensm.2021.06.008.
- [5]. A. K. Thakur, R. Sathyamurthy, R. Velraj, R. Saidur, A. K. Pandey, Z. Ma, P. Singh, S. K. Hazra, S. W. Sharshir, R. Prabakaran, S. C. Kim, S. Panchal, and H. M. Ali, "A state-of-the-art review on advancing battery thermal management systems for fast-charging," *Appl. Therm. Eng.*, vol. 226, Art. no. 120303, 2023. doi: 10.1016/j.applthermaleng.2023.120303.
- [6]. S. Gungor, S. Gocmen, and E. Cetkin, "A review on battery thermal management strategies in lithium-ion and post-lithium batteries for electric vehicles," *J. Therm. Eng.*, vol. 9, no. 4, pp. 1078-1099, 2023. doi: 10.18186/thermal.1334238.
- [7]. Y. Dai and A. Panahi, "Thermal runaway process in lithium-ion batteries: A review," *Next Energy*, vol. 6, Art. no. 100186, 2025. doi: 10.1016/j.nxener.2024.100186.
- [8]. K. Wang, D. Ouyang, X. Qian, S. Yuan, C. Chang, J. Zhang, and Y. Liu, "Early warning method and fire extinguishing technology of lithium-ion battery thermal runaway: A review," *Energies*, vol. 16, no. 7, Art. no. 2960, 2023. doi: 10.3390/en16072960.
- [9]. X. Zhang, S. Chen, J. Zhu, and Y. Gao, "A critical review of thermal runaway prediction and early-warning methods for lithium-ion batteries," *Energy Mater. Adv.*, vol. 4, Art. no. 0008, 2023. doi: 10.34133/energymatadv.0008.
- [10]. D. Hu, S. Huang, Z. Wen, X. Gu, and J. Lu, "A review on thermal runaway warning technology for lithium-ion batteries," *Renew. Sustain. Energy Rev.*, vol. 206, Art. no. 114882, 2024. doi: 10.1016/j.rser.2024.114882.
- [11]. N. Pamuk, "Determination of chaotic time series in dynamic systems," *J. Balikesir Univ. Inst. Sci. Technol.*, vol. 15, no. 1, pp. 78-92, 2013.
- [12]. E. A. Gospodinova, "Research on the stability model in discrete dynamical systems with the Lorenz attractor and the Kropotov-Pakhomov neural network," *Entropy*, vol. 28, no. 1, Art. no. 12, 2026. doi: 10.3390/e28010012.
- [13]. O. E. Rössler, "An equation for continuous chaos," *Phys. Lett. A*, vol. 57, no. 5, pp. 397-398, 1976. doi: 10.1016/0375-9601(76)90101-8.
- [14]. I. Kovacic and M. J. Brennan, *The Duffing Equation: Nonlinear Oscillators and Their Behaviour*. Chichester, U.K.: John Wiley & Sons, 2011. doi: 10.1002/9780470977859.
- [15]. L. O. Chua, M. Komuro, and T. Matsumoto, "The double scroll family," *IEEE Trans. Circuits Syst.*, vol. 33, no. 11, pp. 1072-1118, 1986. doi: 10.1109/TCS.1986.1085869.
- [16]. Y. Ortiz, P. Arévalo, D. Peña, and F. Jurado, "Recent advances in thermal management strategies for lithium-ion batteries: A comprehensive review," *Batteries*, vol. 10, no. 3, Art. no. 83, 2024. doi: 10.3390/batteries10030083.
- [17]. D. C. Wynn and A. M. Maier, "Feedback systems in the design and development process," *Res. Eng. Des.*, vol. 33, no. 3, pp. 273-306, 2022. doi: 10.1007/s00163-022-00386-z.
- [18]. M. K. Mahek, M. Ramadan, S. S. bin Dol, M. Ghazal, and M. Alkhedher, "A comprehensive review of thermoelectric cooling technologies for enhanced thermal management in lithium-ion battery systems," *Heliyon*, vol. 10, no. 24, Art. no. e40649, 2024. doi: 10.1016/j.heliyon.2024.e40649.
- [19]. K. Chang, Y.-Z. Li, X. Hou, and X. Li, "Numerical study of fuzzy-PID dual-layer coordinated control strategy for high temperature uniformity of space lithium-ion battery pack based on thermoelectric coolers," *Journal of Energy Storage*, vol. 56, p. 105952, 2022. doi: 10.1016/j.est.2022.105952.
- [20]. K. H. Ang, G. Chong, and Y. Li, "PID control system analysis, design, and technology," *IEEE Transactions on Control Systems Technology*, vol. 13, no. 4, pp. 559-576, Jul. 2005. doi: 10.1109/TCST.2005.847331.