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Design and simulation of battery charging system with constant temperature – constant voltage method

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Abstract

Batteries are essential to many contemporary applications, including electric cars and portable electronics. Overheating and charging time efficiency are the two biggest issues with battery charging. Overheating presents safety hazards and hastens battery deterioration. Due to their inability to regulate temperature, conventional charging techniques like Constant Current - Constant Voltage (CC-CV) result in excessive temperature rises during battery charging, which shortens battery life. A novel approach that helps lessen excessive temperature rises is the Constant Temperature - Constant Voltage (CT-CV) method, according to researchers. In order to avoid excessive temperature increases during the initial charging, the CT technique initially regulates the applied temperature. Second, to guarantee full capacity without causing damage to the battery, the CV technique is used to maintain a steady voltage. A fuzzy logic controller (FLC) control system is used to regulate the temperature and current at the DC-DC converter's output. The FLC control system's goal is to control the duty cycle such that the buck converter's output is 65V 11.5A. The simulation results show that the CT-CV method can reduce the increase in temperature in the battery with an average temperature during the battery charging process of 23.57° C with fuzzy control and 23.71° C with PI control. In addition, by comparing two control systems with the CT-CV method, namely PI and fuzzy, it was found that the fuzzy method was able to accelerate battery charging by 4.16% compared to the PI control.

1. Introduction

Recent years have seen tremendous growth in the electric vehicle (EV) and hybrid electric vehicle (HEV) industry, largely driven by advances in battery technology. The environmental advantages, longer lifetime, and low self-discharge of $LiFePO_4$ batteries have made them highly desirable for use in electric cars, energy storage grids, and renewable energy systems, among other uses [1]. $LiFePO_4$ batteries are popular for their performance and long life, but their efficiency and lifespan depend on several factors, including their chemical composition, operating temperature, and depth of discharge [6]. Higher currents are required to speed up charging, but this can lead to overheating. Excessive heat during charging can shorten battery life by accelerating the aging process and reducing power output and charging efficiency [7][8][9]. During operation, batteries can become self-heating due to the direct correlation between temperature and internal resistance. In addition, the internal resistance has an impact on battery life; a gradual rise in temperature can have a dramatic impact on performance and life [21].

To overcome the limitations of conventional charging methods, a new approach called CT-CV (Constant Temperature-Constant Voltage) charging was designed. Using this method, the charger can control the charging current based on the battery temperature, ensuring the battery remains cool during the charging process. This improves battery performance and life. When the battery reaches the correct voltage, the charger enters a safe and efficient charging mode called constant voltage [10][11][12].

Specialized equipment is required to safely and efficiently charge lithium batteries due to the unique resistance that occurs during this operation, especially when considering the battery capacity. BUCK converters are excellent DC-DC converters for charging batteries, among other uses. The improved performance and battery life are a result of the BUCK converter's efforts to reduce input current and output voltage ripple. In addition, these converters are quite efficient, minimizing power loss during charging [13].

To precisely control the battery temperature during charging, a fuzzy temperature controller (FTC) can be used. The FTC generates a small, adjustable current that is added to the main charging current, thus allowing more accurate control over the temperature rise. Once the battery reaches a certain state of charge, the charger switches to the voltage controller, which further reduces the charging current to ensure safe and efficient charging [14]. The regulation control mechanism is a Fuzzy Logic Controller (FLC), which helps keep the temperature under control and ensures a stable charging voltage [15].

2. Research Method

This system will use a Fuzzy Logic Controller to create and simulate the Tool's usage as a charging system.

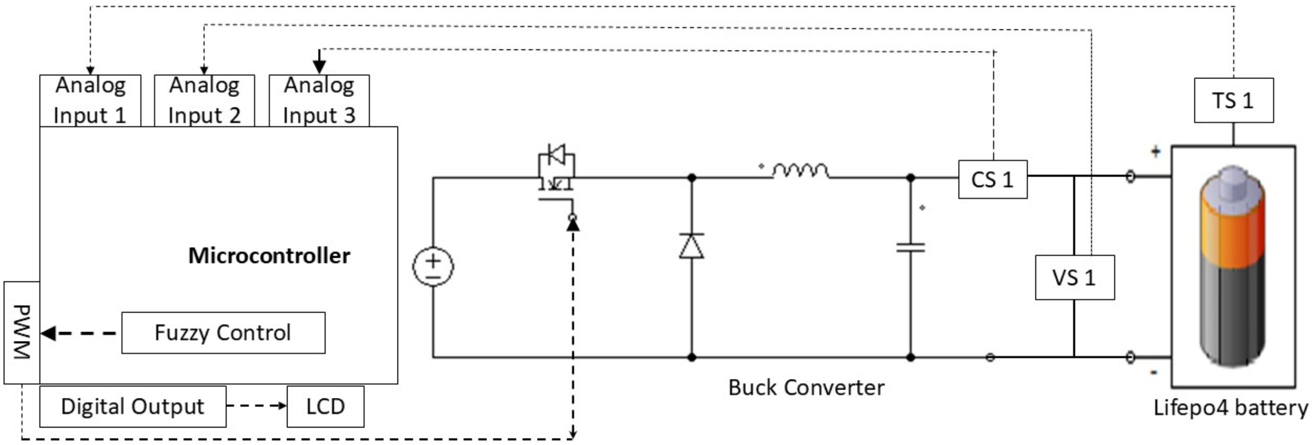

Figure 1. Block Diagram of the Battery Charging system

The LiFePO4 battery control hardware is shown in Figure 1. This system employs the constant temperature-constant voltage (CT-CV) method, which ensures that the charging temperature remains within the permitted range. This study makes use of a 60V 23Ah LiFePO4 battery. To keep the charging voltage steady, we use a buck converter that is managed by fuzzy logic controller to keep the output voltage at 65V and the current at 11.5A. An STM32F407VGTX microcontroller analyzes the data and displays it on an LCD screen. A series of current and voltage sensors maintain tabs on these variables. The charging system's job is to keep the battery from becoming too hot and damaging itself, so it keeps an eye on its temperature. As a result, the battery life will be extended.

2.1 Buck Converter Planning

When converting between DC and AC power, a buck converter reduces the output voltage (Vo) to a level below the input voltage (Vs). An electrical current is stored by an inductor to power it. When using a Buck converter, both the input and output voltages have the same polarity [16]. The input voltage parameters determine the duty cycle required to configure the Buck Converter and achieve the desired output. Both the input and output of the converter are fitted with capacitors to minimize voltage ripple. In this setup, the output current is half of the battery's total capacity. The specific values of each component that affect the output parameters of the buck converter are provided in Table 1 below [17].

Table 1. Buck Converter

Parameter	Value
Input Voltage (V_{in})	110 V
Output Voltage (V_{out})	65 V
Input Current (I_{in})	3,67 A
Output Current (I_{out})	11,5 A
Frequency	40 Khz
Resistance (R)	5,65 Ω
Inductance (L)	289,03 μH
Capacitance (C)	11,05 μF

When the switch is turned ON, the input voltage is directly applied across the inductor, causing the inductor current to rise. The voltage across the inductor is expressed as Equation 1.

$$V_L = V_{in} - V_{out} = L\frac{dI_L}{dt_{on}} \tag{1}$$

This equation is derived from Faraday's Law, which states that the voltage across an inductor is proportional to the rate of change of current through it. So, it is expressed as Equation 2.

$$L \times dI_L = (V_{in} - V_{out}) = dt_{on} \tag{2}$$

Equation 2 describes the change in inductor current during the ON period, which is proportional to the difference between input and output voltage. When the switch is turned OFF, the energy stored in the inductor is released to the load through the diode. In this state, current flows from the inductor to the load and returns to the inductor via the diode. As the current direction remains the same but the voltage direction is reversed, the inductor voltage becomes negative [18]. Therefore, it is expressed as Equation 3.

$$V_L = -V_{out} = L\frac{dI_L}{dt_{on}} \tag{3}$$

Since the inductor current decreases during the OFF time, the derivative diLL is negative. However, for magnitude analysis, it can be expressed as Equation 4.

$$V_L = L\frac{dI_L}{dt_{off}} \tag{4}$$

In steady-state operation, the total change in inductor current over one complete switching cycle must be zero. After substituting Equations 2 and 4, we obtain Equation 5.

$$V_{out} = \frac{(V_{in} - V_{out})dt_{on}}{dt_{off}} \tag{5}$$

To simplify converter control, the duty cycle is introduced. It is defined as the ratio of the ON time to the total switching period, so it is expressed as Equation 6.

$$D = \frac{dt_{on}}{dt_{on} + dt_{off}} \tag{6}$$

Using this definition, the output voltage can be expressed in its standard buck converter form. It can be expressed as Equation 7.

$$\mathrm{Vo} = \mathrm{VS} \times \mathrm{D} \tag{7}$$

Description:
V_L = Voltage across the inductor (V)
V_{in} = Input voltage from the source (V)
V_{out} = Output Voltage (V)
I_L = Current through the inductor (A)
$\frac{dIl}{dton}$ = rate of change of inductor current during the on period
$\frac{dIl}{dtoff}$ = rate of change of inductor current during the off period
dt_{on} = duration of time when the switch is ON
dt_{off} = duration of time when the switch is ON
L = Inductor
D = Duty Cycle

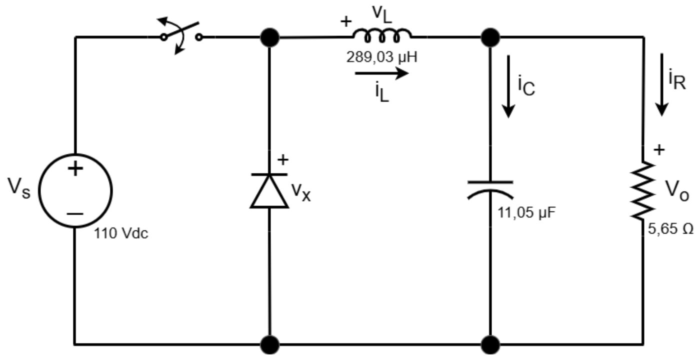

Figure 2. Buck Converter

The buck converter is shown in Figure 2. There is no current flowing through the diode when the mode 1 switch is closed (ON) since it is in a reverse bias condition. The current will be flowing from the source via the inductor L and the load R under these conditions.

2.2 Charging Methods

At this time, the CC-CV approach has become the de facto norm for billing procedures. The first step is to charge the battery up to the current recommended by the manufacturer. This is usually somewhere between half a cell's capacity and one cell's capacity. Charging battery packs with many cells linked in series requires proper cell equalization methods. Depending on the current and the battery's internal resistance, the cell temperature during CC-CV charging may rise by 3-7˚C [19].

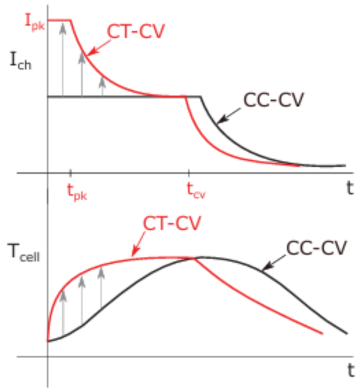

Figure 3. Conceptual Depiction of CT-CV Charging in Comparison with CC-CV Charging at the same Temperature

As seen in Figure 3, the temperature profile during CC-CV charging is typically under for much of the CC phase and then increases when CC ends and CV begins. As a result, there may be an opportunity to increase the charging current while in the CC phase, and decrease it while switching to CV mode. This means that the final temperature may be reached much faster than with the standard CC-CV charging method [20]. The main distinction between the conventional CC-CV charger and the proposed CT-CV charger is the approach to controlling the current. Charging the CT-CV without modifying the power converter circuit is possible if the CC-CV system's power devices can handle double the rated current [21]. Charging LiFePO4 batteries with CT-CV is more efficient. It detects the battery's temperature and condition and adjusts the charging current accordingly, enabling faster charging without harming the battery. This technique also aids in reducing the rate of battery deterioration. To ensure the safety of its users, many newer battery management systems (BMS) include temperature sensors as standard equipment [22].

2.3 Close Loop Integration Simulation Modeling (MATLAB)

Modeling the whole system with control mechanisms in place, the closed-loop integration simulation (closed circuit) represents the system as a whole. Using a regulated rectifier, the PLN source is first stepped down to 110V in this configuration. Fuzzy logic controls the BUCK converter, which takes the rectifier's output and changes the voltage to 65V, so it matches the battery's demands. Figure 4 shows the results of the simulation that was run in order to verify the closed-loop integration process using the MATLAB R2021a program.

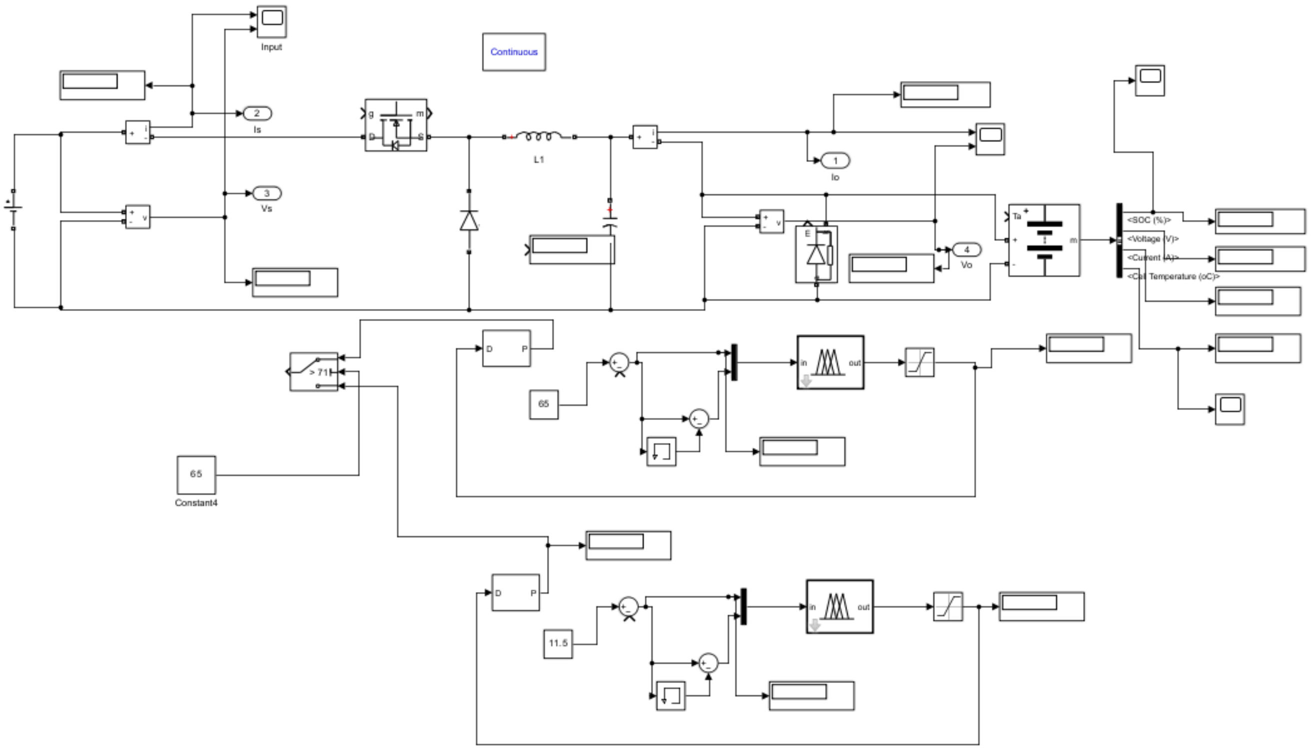

Figure 4. Close-loop Integration Simulation Circuit

2.4 Fuzzy Logic Controller Design

The followings are examples of algorithms and mathematical calculations that are a part of fuzzy logic. This approach uses range-to-point control with each input. Linguistic variables are used to classify each input/output parameter [23]. The Sugeno method is used as the Fuzzy Logic Control technique in this system. Easy tweaking, suitability for complicated systems, and interpretability are all hallmarks of the Sugeno method's results. This article details a system that uses Fuzzy Logic Control to handle pulse width modulation (PWM), which is used to maintain a steady voltage output from the Buck Converter [24].

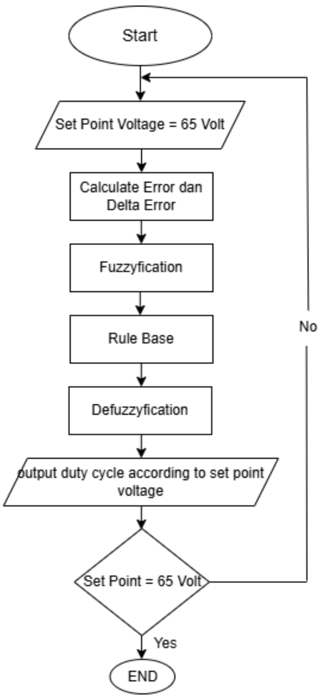

Figure 5. Fuzzy Logic Control Flowchart

The flowchart of Fuzzy Logic Control system is shown in Figure 5. Based on this voltage parameter, two fuzzy variables will be generated and used as inputs into the system: error (e) and delta error (de). A duty ratio for PWM production from the Buck Converter will be the outcome of the further processing of these two variables via Fuzzification, Fuzzy Inference System, and Defuzzification. As said, fuzzy data is created by converting crisp data to fuzzy [25].

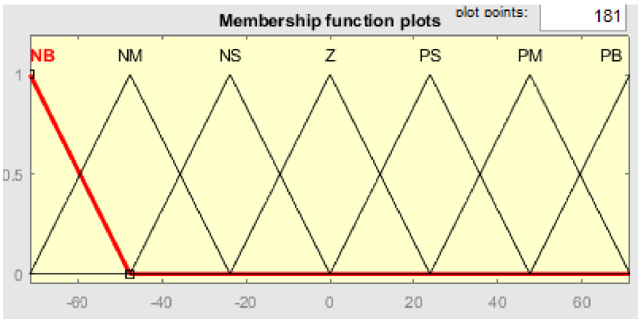

Figure 6. Membership Function for the Error Variable

Figure 6 illustrates the membership function for the error variable, with values ranging from -65 to 65.65.

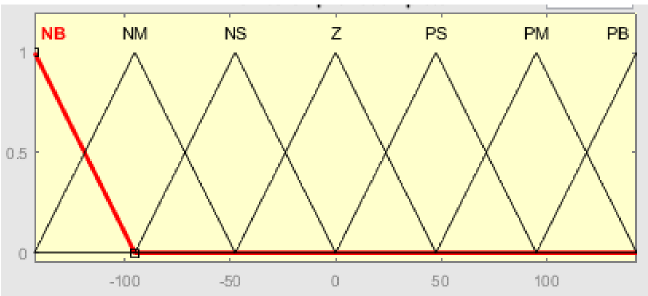

Figure 7. Membership Function Variable Delta Error

Figure 7 illustrates the membership function for the fuzzy output, with duty cycle values ranging from 0 to 1. This function is used to determine the correct duty cycle based on the system's input values. The fuzzy inference system will handle the fuzzy output according to the rules that have been previously set in Table 2.

Table 2. Rule Base of Fuzzy Logic Control

dE \ E	NB	NM	NS	ZO	PS	PM	PB
dNB	NB	NB	NB	NB	NM	NS	ZO
dNM	NB	NB	NB	NM	NS	ZO	PS
dNS	NB	NB	NM	NS	ZO	PS	PM
dZO	NB	NM	NS	ZO	PS	PM	PB
dPS	NM	NS	ZO	PS	PM	PB	PB
dPM	NS	ZO	PS	PM	PB	PB	PB
dPB	ZO	PS	PM	PB	PB	PB	PB

In Table 2, the rows represent the values of error change (dE), while the columns represent the values of error (E). Both variables are categorized into seven fuzzy sets: Negative Big (NB), Negative Medium (NM), Negative Small (NS), Zero (ZO), Positive Small (PS), Positive Medium (PM), and Positive Big (PB). Each cell in the table represents the fuzzy output based on the combination of these two input variables.

For example, if the error value is NM (Negative Medium) and the error change is dNS (Negative Small), then the output is NB (Negative Big). This indicates that if the error is still significantly negative and the error change is small, the system will apply a strong negative correction to improve the situation. These rules follow the fundamental principle of fuzzy control where the combination of error and error change determines the magnitude and direction of the corrective action. The values in this table are designed so that the control system can respond smoothly and adaptively to changing conditions, avoiding excessive oscillations or instability.

The control activities that influence the duty cycle output are guided by the basic principles outlined in Table 2. After the fuzzy inference system produces its output, it undergoes defuzzification processing, which turns the fuzzy set into a real number. When controlling a system that uses fuzzy output values, defuzzification is the act of converting them back into a precise classical output [24]. When defuzzification is performed using the Centroid approach, precise results are obtained by finding the distribution's center. The outcome is a duty cycle value between zero and one, which keeps the setpoint constant. Two separate controllers are used in this system: one to set the voltage at 65V and another to set the current at 11.5A. The schematic of the fuzzy logic Control circuit is shown in Figure 8.

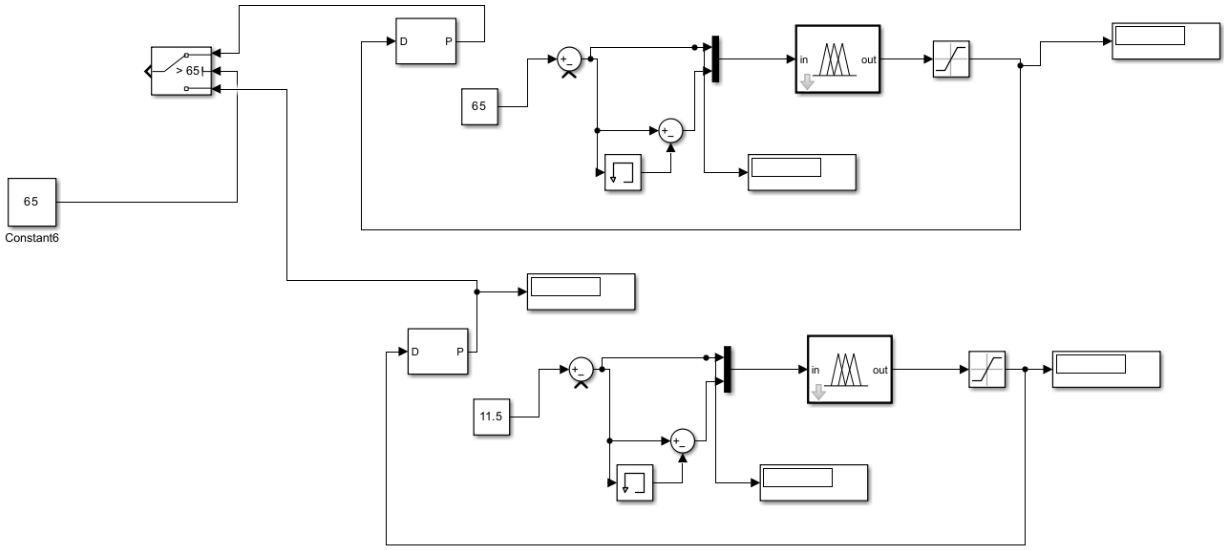

Figure 8. Fuzzy Logic Control Circuit Design

The control circuit is designed independently, taking input voltage and current setpoint values, as shown in Figure 8. The system calculates duty cycle values by converting the input voltage and current into two fuzzy variables: error and delta error, which are then processed using fuzzy logic. This allows the system to adjust the duty cycle dynamically. The circuit incorporates two fuzzy logic controllers, each responsible for different charging modes. A switch is used to alternate between the constant temperature (CT) and constant voltage (CV) charging modes, ensuring optimal performance during the charging process.

3. Results and Discussion

A steady output current and voltage may be achieved with the use of BUCK converters, which are designed using simulations. As a simulation tool, MATLAB 2021a is used for both open-loop and closed-loop models.

3.1 Open Loop integration Testing Simulation

In the integration simulations, closed-loop systems using fuzzy logic control are combined with open-loop (open-circuit) systems. The process begins with simulating an open-loop integration test, where the system operates without control to observe its behavior. Power is supplied by a PLN source connected to a regulated rectifier. The rectifier then provides power to the buck converter, which supplies energy to the battery load. To gather data, the battery's State of Charge (SoC) is adjusted from 40% to 95%. Throughout the simulation, the input voltage (Vin) from the rectifier and the output voltage (Vout) from the buck converter are recorded. The results of this simulation are presented in Table 3.

Table 3. Open Loop Charging

No	Voltage (V)	Current (A)	SOC (%)
1	60.22	11,5	40
2	60.92	11,4	50
3	61.42	11,5	60
4	62.42	11,5	70
5	63.41	11,4	80
6	64.71	11,5	85
7	65	9,8	88
8	65	5,3	90
15	65	2.1	95

Table 3 above presents data on battery charging, showing the relationship between voltage, current, and state of charge (SOC). As the SOC increases, the voltage gradually rises from 60.22V at 40% SOC to 65V at 95% SOC. The current remains relatively stable at around 11.4-11.5A until the SOC reaches 85%. After this point, the charging current starts to decrease, dropping to 9.8A at 88% SOC, 5.3A at 90% SOC, and 2.1A at 95% SOC. This pattern indicates an initial constant current (CC) phase, followed by a constant voltage (CV) phase where the current decreases as the battery approaches full charge. This charging strategy is commonly used in lifepo4 batteries to ensure efficient charging while maintaining battery safety and lifespan.

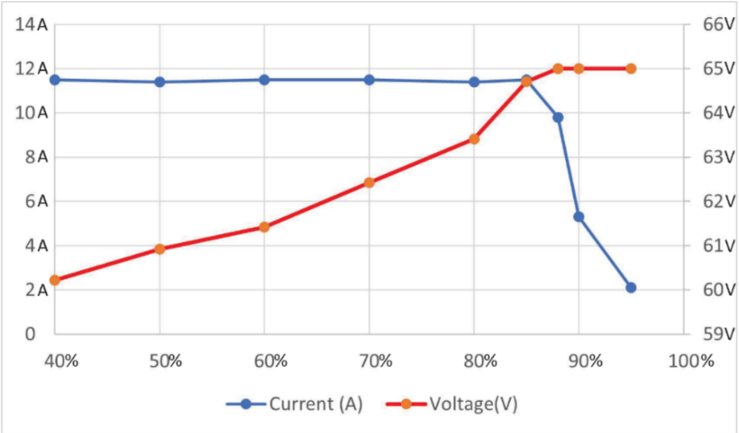

Figure 9. Open Loop Graphics

To monitor the battery's health in both constant current and constant voltage modes, a graph was generated using the data from Table 3 above. Charges are applied at a constant current of 11.5A as seen in Figure 9 for State of Charge (SOC) ranging from 40% to 88%. The 65V constant voltage charging procedure is initiated when the level of charge reaches 85-100%. Finding the duty cycle value for use in future closed-loop system tests was the goal of this test.

3.2 Closed-loop integration testing simulation

The findings obtained from the closed-loop simulation with fuzzy logic control in the current fuzzy logic design's constant temperature-constant voltage approach of closed-loop testing are as follows. Until the temperature hits 25˚C, the system initially maintains a steady current of 11.5A. After reaching this temperature, the current is progressively decreasing to 5A in order to maintain a steady temperature of 25˚C. The charging voltage of the batteries is progressively raised until it reaches the preset value of 65V simultaneously. The current drops and the voltage remains constant until it hits the set point. This closed-loop test compared two control strategies to find out which one might enhance the charging efficiency of LiFePO4 batteries.

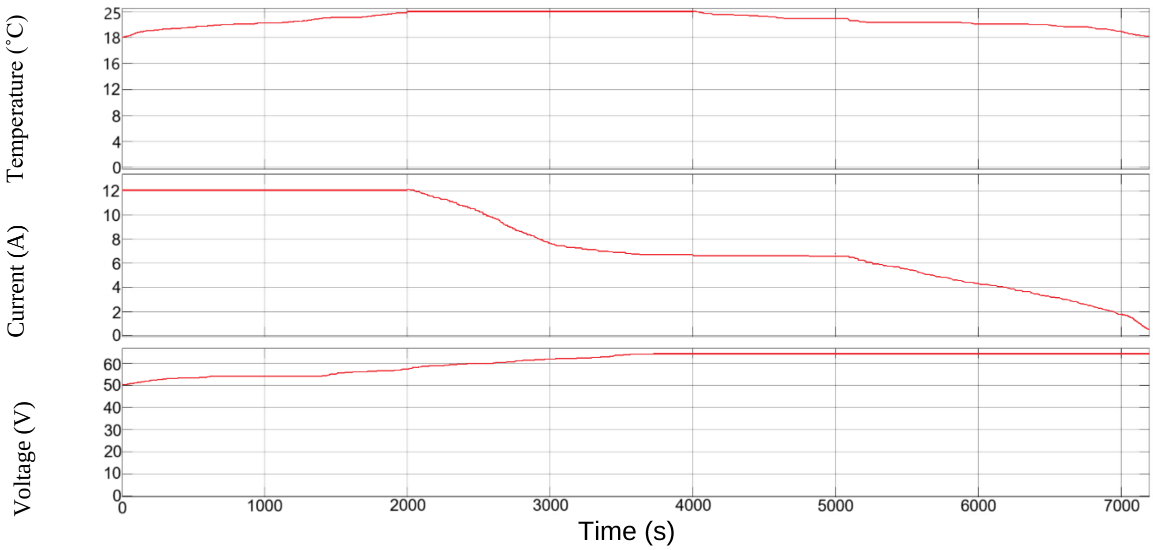

Figure 10. Simulation Result of Battery Charging Integration with CT-CV Method Using Fuzzy Logic Controller

Figure 10 illustrates the simulation results using fuzzy control, featuring a 2-hour charging period, a 5˚C temperature variation (ΔT), and a temperature set point of 25˚C. In this setup, fuzzy control, based on the Sugeno method, gradually reduces the initial high current until the set temperature is reached. Unlike conventional charging methods, which take longer to stabilize the temperature, fuzzy control plays a vital role in accelerating the process by limiting the current.

The system utilizes a buck converter that outputs 60V and 23Ah when connected to a LiFePO4 battery. The output voltage of the buck converter is regulated through fuzzy logic. The fuzzy control system receives voltage and current as inputs and continuously adjusts the duty cycle during the charging process using the Constant Temperature-Constant Voltage (CT-CV) approach to optimize charging efficiency, which employs 25˚C temperature reference. To optimize the duty cycle using the fuzzy technique, the voltage set point is set at 65V.

Initially, the charging process begins with a high current of 11.5A, but within 2000 seconds, the fuzzy control has stabilized the current. As the current steadily decreases until it stabilizes at around 5A, the charging process transitions to a constant voltage mode. The current will continue to become weaker over the following two hours. At about 3800 seconds, the setpoint is achieved when the voltage stabilizes at 65V.

As the temperature increases in response to the large initial charging current, the system maintains the temperature at 25˚C, which is the set reference for the fuzzy control. The temperature remains stable at 25˚C throughout the process. Once the charging reaches constant voltage at 65V, the temperature begins to drop until it returns to the initial battery temperature of 18˚C.

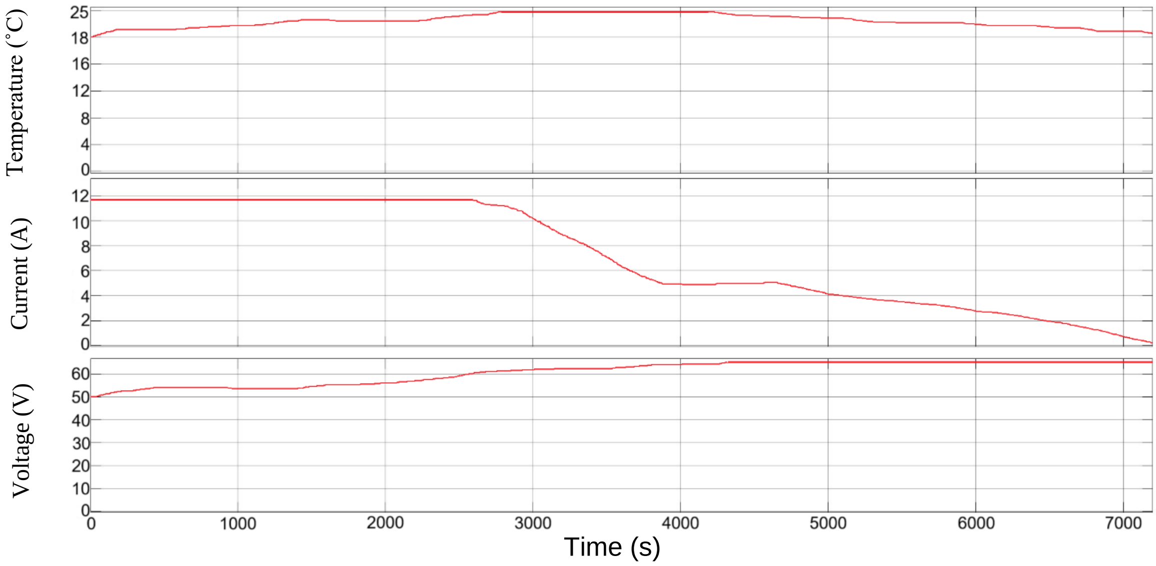

Figure 11. Results of Simulations using the CT-CV Charging Method with PI Control

Meanwhile, Figure 11 illustrates the use of PI control with the same set point tuning method based on analytic calculations, which found that with the same temperature set point with fuzzy logic (25˚C), it can be obtained with a max value of 24.8˚C but with a different time to reach constant temperature, i.e. at 2800 seconds. Initially, the charging process begins with a high current of 11.5A, but within 2300 seconds, the PI control has stabilized the current. As the current steadily decreases until it stabilizes at around 5A in 4800 seconds, the charging process transitions to a constant voltage mode. A new CV condition can be reached at 4200 seconds with setpoint of 65V.

Table 4. Comparison of Charging Time

Condition	Charging Time (s)	
	Fuzzy control	PI control
CT	2000	2800
CV	3700	4200
Overall Charging Time	7200	7500

Table 4 shows the comparison of charging time with the two conditions and the comparison of the two controls being used. The charging time using PI control was 2800 seconds in CT mode and 4200 seconds in CV mode, so the overall charging time was 7500 seconds. On the other hand, the charging time using fuzzy control was 2000 seconds in CT mode and 3700 seconds in CV mode. Both were using the same set point temperature of 25˚C and set point voltage of 65 V. The comparison of the two methods can be seen in Equation 8.

$$comparison\ of\ charging\ time: \frac{t2 - t1}{|t1|} \times 100\%$$
$$\frac{7500 - 7200}{7500} \times 100\% = 4{,}16\% \quad (8)$$

Description:
t1 : Overall charging time of PI method
t2 : overall charging time of fuzzy method

The calculation result using Equation 5 where t1 is the charging time of the PI method and t2 is the charging time of the fuzzy method using the charging time comparison formula shows that fuzzy logic is 4.16% faster compared to the PI control method.

4. Conclusion

Based on simulation studies, which show a strong connection between a battery's internal resistance and its surface temperature, monitoring the cell's surface temperature can provide valuable insights into the battery self-heating behavior during operation. Internal resistance plays a critical role in determining the overall lifespan of a battery and is closely linked to how well its temperature is regulated. The main goal of studying the CT-CV charging method is to manage temperature fluctuations and extend the battery lifespan with an average charging temperature of 25.37°C with fuzzy logic control and 23.71°C with PI control. At an ambient temperature of 25˚C, this method proved to be more efficient in achieving faster charging. Moreover, it effectively controlled the temperature, even in the nonlinear state of charge (SoC) region, where internal resistance tends to rise.

On the other hand, a comparison between PI control and fuzzy control showed a 4.16% reduction in charging time. The fuzzy controller parameters are proven to have a very important impact at 25˚C temperature and 65V set points and can reduce the charging time, making it more efficient. Meanwhile, the PI control can run well, but it requires a slightly longer charging time with an achieved set point of 24.8˚C.

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