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Design of SEPIC converter for battery charging system using ANFIS

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Abstract

Rechargeable batteries are the most widely used medium for storing energy today. One type of rechargeable battery that is widely used is lithium-ion batteries. The large use of lithium-ion batteries in society requires companies to research so that the lifetime of these batteries can last a long time and charging can take place quickly. The charging system at this time is less efficient in charging lithium batteries where the time needed is still quite long whereas when lithium batteries are charged with a long time can cause the battery to heat up quickly and can reduce the lifetime of the battery. To overcome this, a system is needed that can control the battery charger process so that the output voltage and current are constant and battery charging is faster. It is hoped that the SEPIC converter system can help many people who forget to unplug the power supply during the charging process to maintain the lifetime of the battery. Setting the output voltage and current in the DC-DC converter can be done using an Adaptive Neuro Fuzzy Inference System which aims to keep the output of SEPIC stable according to the setting point. In this system, the DC-DC converter used is a SEPIC converter which can increase and decrease the output voltage for battery charging. The battery charging process uses the CC-CV method. In the test, the average error is 0.025% whereas when the SOC is 60% to 80% the average error is 0.04%, and when the SOC is 80% to 95% the average error is 0.0005%.

1. Introduction

Energy is one of the basic human needs. Almost all human activities require energy. One of the energies that is often used by humans is electrical energy. Electrical energy is a form of energy that has long been discovered and used for everyday life [1]. The use of electrical energy in the world is increasing over time with the increase in electronic devices. So many humans innovate to make a technology that can store electrical energy, one of which is a rechargeable battery. Rechargeable batteries are the media for storing energy that is most widely used today. One type of rechargeable battery that is widely used is lithium-ion batteries.

Li-ion batteries have many advantages, namely very high efficiency, light battery mass, fairly slow discharge if not used, and can be used in all situations. Li-ion batteries are also widely used in electronic equipment, military industry, electric vehicles, and aerospace [1]. These batteries have high energy density properties, a wide operating temperature range, and a low self-discharge rate, but they are very sensitive to overcharging. The large use of lithium-ion batteries in the community requires companies to research so that the lifetime of the battery can last long and the charging can be completed faster. The charging system at this time is less efficient in charging lithium batteries where the time required is still quite long. When the lithium battery is charged for a long time, it can cause the battery to heat up quickly and reduce the lifetime of the battery. To prevent this condition, a suitable method is needed for charging Li-ion batteries, one method that can be used is the constant current-constant voltage (CC-CV) charging method [2]. The CC-CV charging method is better than CC alone or CV alone because the CC and CV phases can complement each other [3]. The working principle of the CC-CV method in the battery charging process uses a charging current of 0.3C-1C constantly in the initial phase of charging until it reaches the set point voltage. After the voltage reaches the set point, the charging voltage on the battery will be constant according to the set point voltage and the current will drop to a value of 0.02C to 0.07C, so that the battery charging will stop [4].

To overcome the problems that occur in the battery charging process by the capacity of the battery, a tool is needed to charge the lithium battery appropriately. There is a converter that is suitable for charging batteries, namely a DC-DC converter. One of the suitable DC-DC converters is the SEPIC converter. The SEPIC converter can reduce input current ripple, reduce load voltage ripple, and increase converter efficiency [5]. The duty cycle settings on the

SEPIC converter will be controlled using an adaptive neuro-fuzzy inference system (ANFIS) algorithm. The ANFIS algorithm is an adaptive neural network based on the conclusion system of the fuzzy inference system, so this algorithm has an advantage in making a prediction and can make decisions based on rules that have been made more accurately [6][7].

2. Research Method

In this system, the design and simulation of the use of the Tool as a charging system using ANFIS will be carried out.

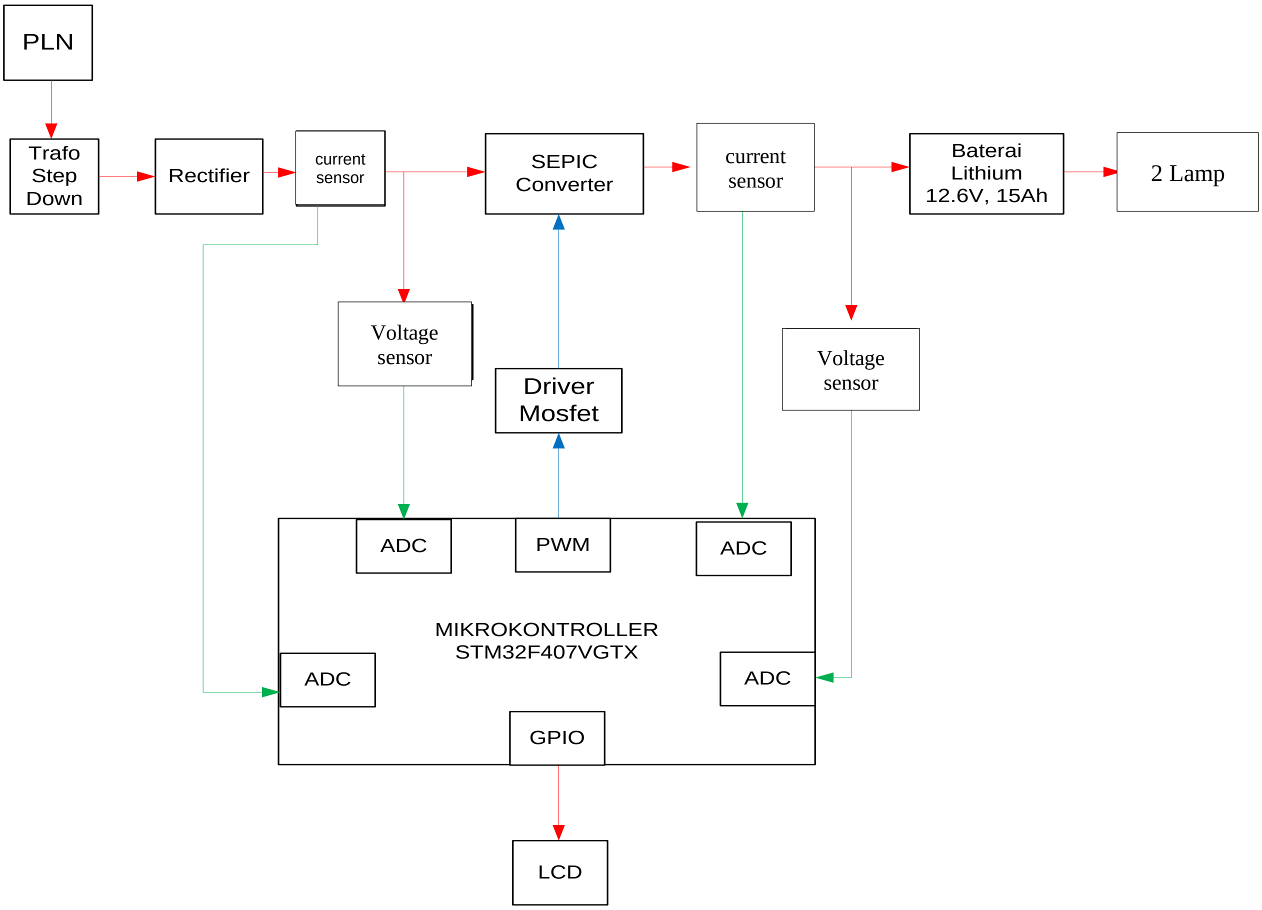

Figure 1. System Blog Diagram

Figure 1 explains that the planning of this system uses a PLN source which is later reduced using a step-down transformer to 20 V after which it is directed using a full wave uncontrolled rectifier, the output of the rectifier is used as a source of SEPIC converters to reduce or increase the voltage according to the battery capacity which is 12.6V, the SEPIC converter’s output is utilized to charge 12.6 V 15 Ah batteries. The battery is then used as a source for 2 lights. Then, there are current sensors and voltage sensors that function to read the value of voltage and current parameters which are later processed in the STM32F407VGTX Microcontroller and displayed on the LCD.

2.1 Rectifier Planning

Rectifier or wave rectifier is one of the media that converts AC (Alternating Current) voltage into DC (Direct Current) voltage [8]. The rectifier used is a single-phase uncontrolled full-wave rectifier. The Uncontrolled Fullwave Rectifier circuit in this project system the given subject has a voltage function supplier for the SEPIC Converter for the battery charging process. The calculation of the output voltage after passing through the rectifier uses Equation 1 and Equation 2 as follows:

$$\mathrm{C} = \frac{1}{2\mathrm{xFxRx}(\frac{\Delta \mathrm{Vo}}{\mathrm{Vm}})} \qquad (1)$$

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$$\mathrm{Vo} = \mathrm{Vm} - \frac{\mathrm{Vm}}{\mathrm{4xFxRxC}} \quad (2)$$

Description:
Vo = Output Voltage (V)
Vm = Maximum Voltage (V)
F = Frequency (Hz)
R = Resistance (Ω)
C = Capacitor (F)
Δvo = Voltage Ripple

Determining the value of output voltage, and capacitance are carried out using Equation 1 and Equation 2. From the calculation using Equation 1 and Equation 2. The value of each component used to determine the Rectifier output parameters can be seen in Table 1 below.

Table 1. Rectifier Specifications

Parameter	Value	Unit
Vs	20	V
Vo	26	V
Io	3.84	A
F	50	Hz
C	0.04	F

2.2 SEPIC Converter Planning

Single Ended Primary Inductor Converter (SEPIC) is a type of converter that is derived from the buck-boost converter topology. Both types of converters can produce output voltages that can be set higher or lower than the input [9]. However, the main difference between the two converters is that the polarity of the buck-boost output voltage is reversed, whereas the SEPIC converter maintains its polarity. Additionally, the addition of capacitors and inductors to the SEPIC converter can reduce current ripple [10]. In this case, the value of the SEPIC input voltage parameter is 26V which is the output value of the rectifier and the SEPIC output voltage parameter is 12.6V which is the battery charging voltage so that the duty cycle calculation can be obtained by using Equation 3 as follows:

$$\mathrm{Vo} = \frac{\mathrm{Vs\ x\ D}}{1 - D} \quad (3)$$

Description:
Vo = Output Voltage (V)
Vs = Source Voltage (V)
D = Duty Cycle

SEPIC Converter can adjust the output voltage larger or smaller than the input depending on the duty cycle that has been planned, this converter is suitable for many applications [11]. The value of the duty cycle can be used to adjust the converter to increase and decrease the desired output. This converter generally also uses inductors, capacitors, diodes, and switching transistors, the calculation of inductors and capacitors can be seen in Equation 4, Equation 5, and Equation 6 as follows [12]:

$$\mathrm{C} = \frac{\mathrm{Vo\ x\ D}}{R\ x\ \Delta C1\ x\ Fs} \quad (4)$$

where

$$\mathrm{R} = \frac{\mathrm{Vo}}{\mathrm{Io}} \quad (5)$$

$$\mathrm{L} = \frac{\mathrm{Vin\ x\ D}}{\Delta IL\ x\ Fs} \quad (6)$$

Description:
R = Resistance (Ω)
L = Inductor (H)

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C = Capacitor (F)
Vo = Output Voltage (V)
Vin = Input Voltage (V)
Fs = Frequency (Hz)
ΔIL = Ripple current
Io = Output Current (A)

In the planning, the SEPIC Converter includes the amount of duty cycle which is influenced by the desired output voltage using Equation 3. In the SEPIC converter planning to reduce the ripple of the voltage, a filter is added from the capacitor at the input and output of the converter [13]. The output current used in this system is determined by using 50% of the battery capacity. The values of resistance, capacitance, and inductance are determined using Equation 4, Equation 5, and Equation 6. The values of each component used to determine the output parameters of the sepic converter are listed in Table 2 below.

Table 2. SEPIC Converter Specifications

Parameter	Value	Unit
Vs	23	V
Vo	12.6	V
Iin	5.84	A
Io	7.5	A
Fs	50	KHz
L	206	μH
C	0.022	F

2.3 Charging Methods and Battery Characteristics

Batteries that are designed to be able to receive a large enough current, namely Li-ion batteries. When performing optimal charging by accelerating the battery charging, it can cause excessive voltage because it is done quickly without switching to a constant voltage condition [14], so the charging treatment can shorten the life of the battery and can also cause battery damage. In overcoming, the battery charging process involves two methods: constant current (CC) and constant voltage (CV) [15]. Initially, the battery is charged using the CC method, which involves charging the battery with a predetermined constant current. The voltage slowly increases until it reaches the maximum limit. Once the voltage reaches the set point, the battery charging process continues using the CV method. The battery is charged using a constant voltage, which is predetermined, resulting in a decrease in the charging current. This method is used to prevent overcharging and overvoltage, which can damage Li-ion batteries. The CV method ends when the current has decreased to a predetermined point, indicating that the battery is fully charged [16]. Figure 2 shows the CC-CV (Constant Current Constant Voltage) charging method.

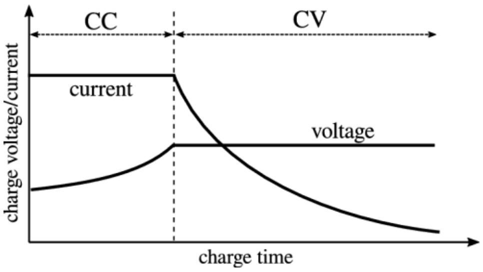

Figure 2. CC-CV (Constant Current Constant Voltage) Charging Method

Lithium-ion batteries are a widely used type of rechargeable battery due to their high energy density and wide operating temperature range. The datasheet for the ICR EVE 18650 lithium battery used can be found in Table 3.

Table 3. Lithium Battery Datasheet

Item	Specification
Min. Discharge Capacity	2500mAh Charge: 0.5A, 4.20V, CCCV 50mA cut-off Discharge: 0.5A, 2.50V DC cut-off
Rapid Charge	CCCV, 1.25A, 4.20±0.05V, 50mA cut-off
CCCV, 1.25A, 4.20±0.05V, 50mA cut-off	4.20~2.50V

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2.4 Closed-Loop Integration Simulation Modelling (MATLAB)

The simulation of the entire system using ANFIS control is achieved through closed-loop integration. This approach involves creating a closed circuit. By using the PLN source which is later lowered using a step-down transformer to 20 V. It is directed using a full wave uncontrolled rectifier. The output of the rectifier is used as the source of the SEPIC converter to reduce or increase the voltage according to the battery capacity, i.e. 12.6V which is regulated using ANFIS logic control. The simulation circuit depicted in Figure 3 was used to carry out a closed-loop integration simulation using MATLAB R2017b software.

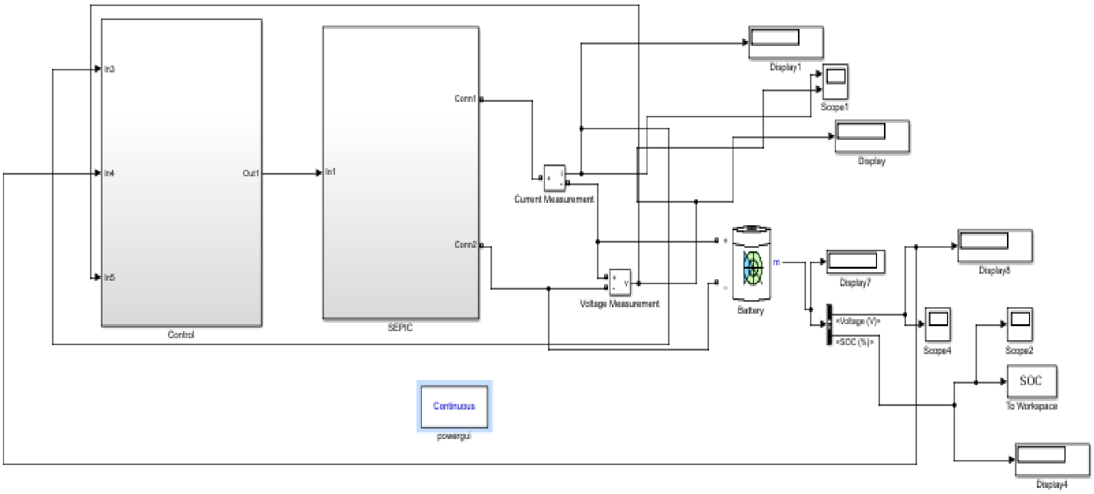

Figure 3. Close Loop Integration Simulation Circuit

2.5 ANFIS Logic Controller

ANFIS control is one of the controls that is widely used in ANFIS control, which integrates two techniques: fuzzy logic methods and artificial neural networks. In this simulation, ANFIS control is employed for the regulation and stabilization of current and voltage based on a predefined setpoint [17][18].

The initial stage in implementing ANFIS control involves determining its input and output as illustrated in the flowchart provided in Figure 3. The ANFIS control system consists of two inputs and one output. The inputs are derived from the error and delta error, obtained from the output voltage and current of the SEPIC converter [19]. The output of ANFIS control is a duty cycle, utilized for regulating the output voltage and current of the SEPIC converter.

In the subsequent step, the generation of FIS is conducted to ascertain the quantity and type of membership degrees. For this control, a total of 7 x 7 membership functions is utilized for ANFIS CV and CC. This selection is based on the rationale that increasing the number of membership functions leads to a reduction in resulting errors [20].

The third step involves ANFIS training, a process utilizing a hybrid method that integrates the least squares estimator (LSE) method and the error backpropagation (EBP) method [21]. The iteration is repeated a hundred times, aiming for a lower error value and improved data quality with an increased number of iterations [21]. Training data is acquired from the running closed-loop SEPIC converter with FLC, consisting of input error and delta error, while the output is the duty cycle.

Table 4 shows the duty cycle determines the amount of output based on the basic rules that govern control action. The fuzzy inference system’s output is then processed into defuzzification input, which is expressed as a fuzzy set of real numbers. Defuzzification is the proses of converting fuzzy output values back into clear output data to control objects [22].

Table 4. Rule Base

ΔE\E	NB	NM	NS	Z	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	Z
NM	NB	NB	NM	NM	NS	Z	PS
NS	NB	NM	NS	NS	Z	PS	PM
Z	NB	NM	NS	Z	PS	PM	PB
PS	NM	NS	Z	PS	PS	PM	PB
PM	NS	Z	PS	PM	PM	PB	PB
PB	Z	PS	PM	PB	PB	PB	PB

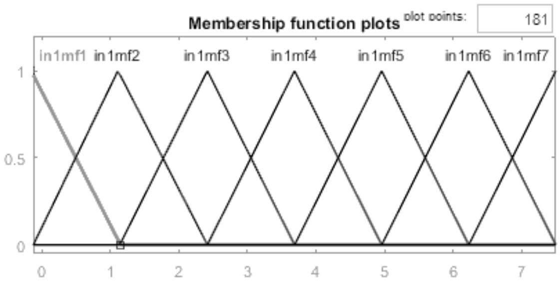

Figure 4. Membership Function Error

Figure 4 shows the Membership Function Design for input 1 of ANFIS fis, namely error. From Figure 4, it can be seen that the number of MFs is as desired, which is 7. Meanwhile, the Membership Function design for delta error can be seen in Figure 5.

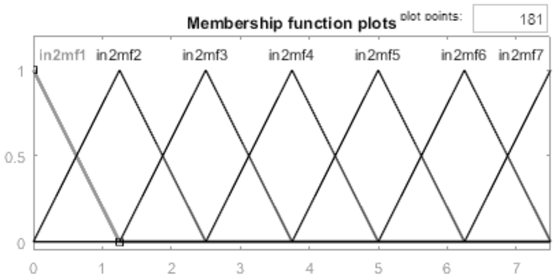

Figure 5. Membership Function Delta Error

Next, ANFIS Testing is carried out on the results of the training data that has been tested. When plotting the duty cycle training data, the red dot represents the result of ANFIS training, while the blue dot represents the input center point of ANFIS training data.

The final stage is the evaluation of ANFIS performance parameters. The ANFIS design process results in a new membership function, which converts crisp input into a fuzzy set with its corresponding membership function [23]. This new membership function is then utilized to regulate the output current and voltage values of the converter. The ANFIS error and delta error, which consist of seven membership functions, serving as inputs for the ANFIS membership function. An ANFIS membership function output is presented as a duty cycle comprising 49 membership functions where the surface anfis can be seen in Figure 6. As for the output parameters, it can be seen in Figure 7. From the training results obtained, the output parameters are 49 outputs.

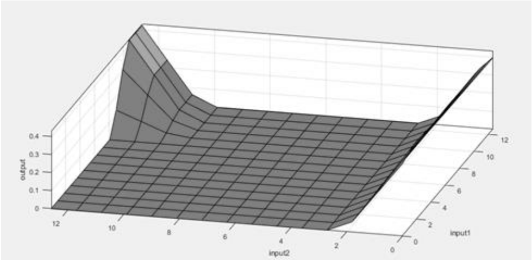

Figure 6. Surface ANFIS

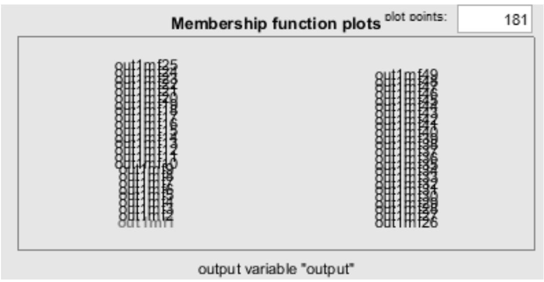

Figure 7. Variabel Output Duty Cycle

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After obtaining the new fis, close loop integration testing is then carried out, which is a test of the entire system using control. With the PLN source, then the PLN source is connected to the transformer to lower the voltage and then rectified using a rectifier. Then the output of the rectifier is used as a source of the SEPIC converter, and the rectifier output voltage will be regulated by the Sepic converter using ANFIS logic control. In the test, ANFIS control is made as shown in Figure 8, where there is control during constant current and constant voltage modes.

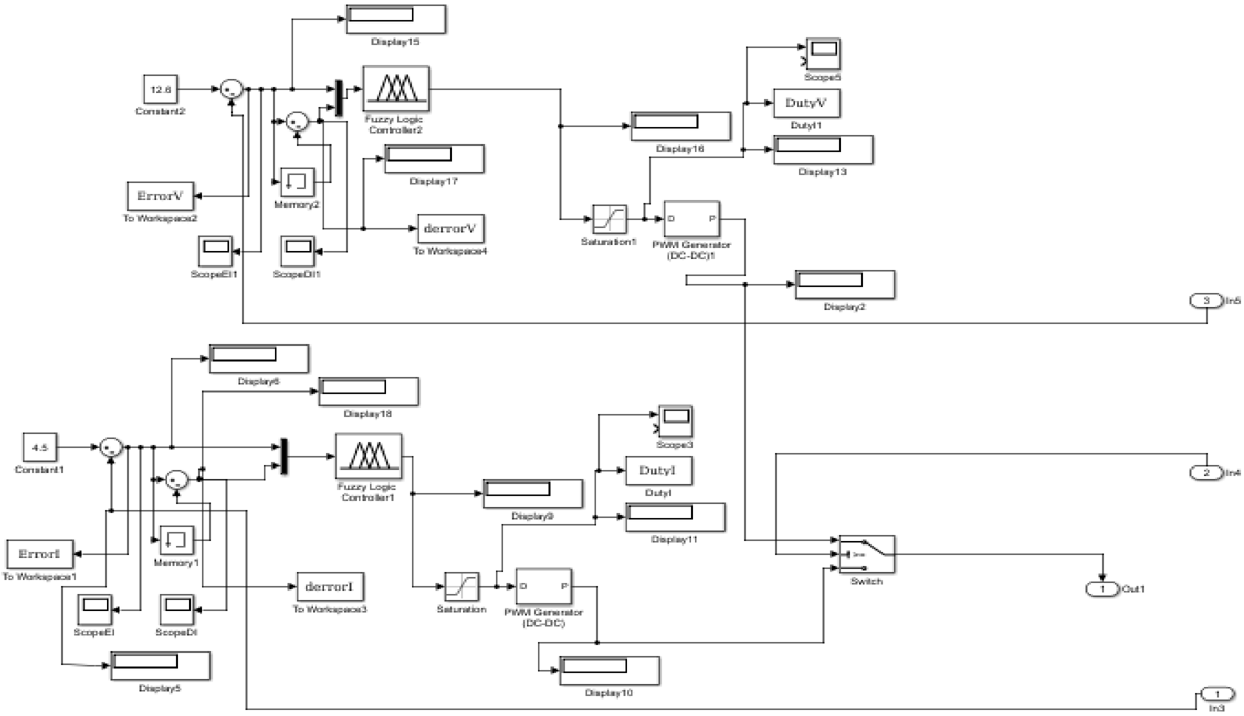

Figure 8. ANFIS Control Circuit

3. Results and Discussion

Simulations are carried out to design the use of SEPIC converters to regulate the output current and voltage to remain constant. Where open loop and close-loop simulations are carried out using the MATLAB 2017 application.

3.1 Open Loop Integration Testing Simulation

Integration simulations are the integration of the open loop (open circuit) and closed circuit using ANFIS. Simulation of the entire system without control, known as the open loop integration test simulation (open circuit), is conducted. The source used is the PLN source, which is connected to a transformer to reduce the voltage and then rectified using a rectifier. The output of the rectifier is used as the SEPIC converter source and then connected to the battery load. Data collection is done by changing the SOC (State of charge) value on the battery from SOC 40% to 100%. The simulation data is taken including the converter input voltage (Vin) which comes from the Rectifier, and the converter output voltage (Vout). The simulation result data table can be seen in Table 5 below.

Table 5. Open Loop Testing

No	INPUT		OUTPUT			
	Voltage (V)	Current (A)	Voltage (V)	Current (A)	PWM	SOC
1	20	5,5	12,38	7,505	39,75	50%
2	20	5,6	12,48	7,502	39,95	60%
3	20	5,7	12,52	7,504	40,05	70%
4	20	5,75	12,57	7,508	41,15	80%
5	20	5,7	12,6	7,42	41,15	85%
6	20	4,9	12,6	7,1	40,75	90%
7	20	3,6	12,6	4,88	39,7	95%
18	20	1,4	12,6	2,1	39,1	97%

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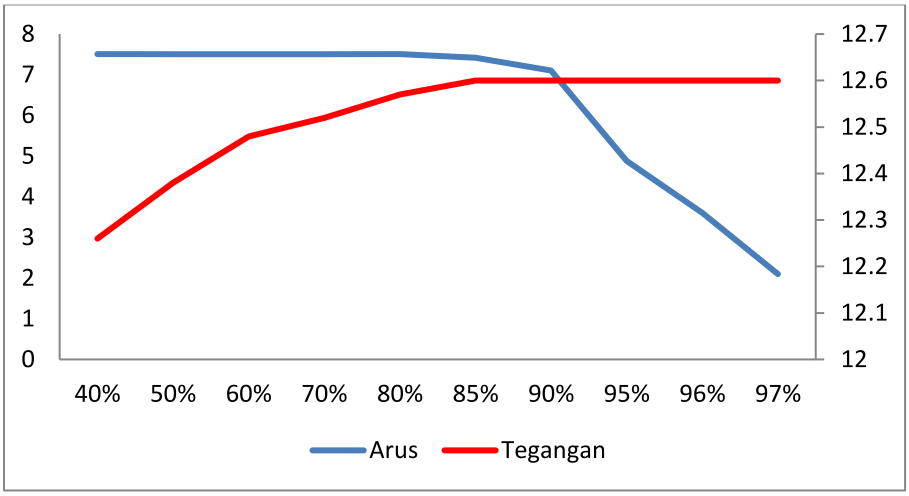

Figure 9. Open Loop Graphics

Based on Table 5 above, a graph is made to see the condition of the battery when the constant current and constant voltage modes. It can be seen in Figure 9 that when SOC 40% to 85% charging is done using constant current with a fixed current of 7.5A and when SOC 85% to 100% charging is done using the constant voltage method with a fixed voltage of 12.6V. This test is carried out to find the value of the duty cycle which will be used for testing in the close loop.

3.2 Simulation of Closed Loop Integration Testing

In closed-loop testing when employing the constant current-constant voltage charging method, the efficiency of the required time is comparatively lower, but the effectiveness is noteworthy as it helps prevent the occurrence of overvoltage. Derived from the established ANFIS design, the following is a closed-loop simulation using ANFIS control. To keep the current constant according to the set point of 7.5A, namely by increasing the battery charging voltage slowly until it reaches a set point of 12.6V. After the voltage reaches the setting point, the voltage will be constant and the current will drop. From the simulation tests that have been carried out, Figure 10 illustrates the output waveform of the current during the constant current battery charging mode, while Figure 11 displays the output waveform of the converter voltage during the constant voltage battery charging mode

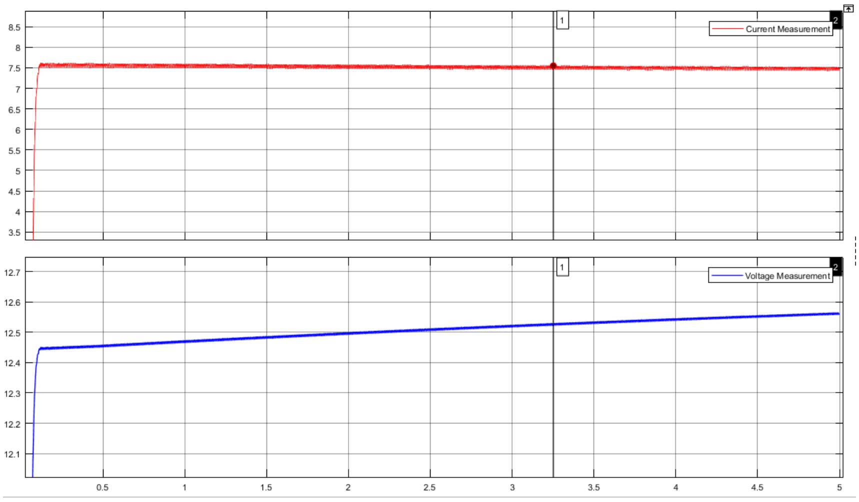

Figure 10. Constant Current Wave

It can be seen that when the battery SOC is 40 - 80%, the current is set to 7.5 A and the voltage will gradually rise over time until it attains the predetermined set point of 12.6 V. When the voltage has reached the specified set point, the method that is run next is constant voltage, where the voltage is kept so that the output is 12.6 V and the current will decrease over time.

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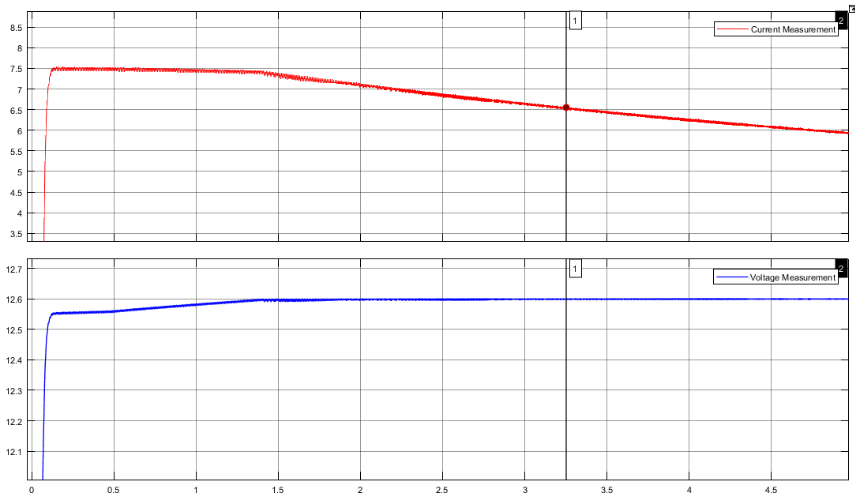

Figure 11. *Constant Voltage Wave*

In Figure 11, the output response is seen under CC-CV charging conditions. The system employs a set point of 7.5 A for constant current and 12.6 V for constant voltage as the battery charging parameters. The transition from constant current to constant voltage takes place when the voltage attains the maximum threshold of 12.6 V where the set point for voltage 12.6 is obtained from the datasheet of the battery. Errors from Close loop testing can be seen in Table 6.

Table 6. Average Close Loop Testing Error

SOC	Error (%)
60	0,012
70	0,073
80	0,042
90	0,0011
95	0,0000624
Total	0,02563248

4. Conclusion

From the simulation tests that have been carried out, the open loop duty cycle conditions produce an average of 41.2% which is to the planning that has been done. For close loop conditions or with ANFIS logic control, the current remains constant until the voltage reaches a predetermined set point. In close loop testing the current remains constant at 7.5 A from soc 30 - 85% then changes to a constant voltage condition at 12.6 V from soc 85% to full. In the test, an average error of 0.025% was obtained where when SOC 60% to 80%, an average error of 0.04% was obtained for the CC state, and when SOC 80% to 95%, an average error of 0.0005% was obtained for the CV state. From the average error generated, it can be proven that the control runs well enough for charging lithium batteries. From these tests, it is found that using 2 charging methods, namely constant current with constant voltage, can speed up battery charging so that it can overcome time efficiency when charging compared to using the CC method alone and the CV method alone, with the change from CC to CV can avoid fast battery heat and avoid overvoltage when charging the battery.

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