Balancing Charging System Using Adaptive Neuro-Fuzzy Inference System Based On CUK Converter

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Abstract—In a battery set, there is always a voltage difference caused by charging and discharging. Therefore, it is necessary to pay attention to the battery or State of Charge (SOC) condition to balance the batteries in a balanced state. Unbalanced battery conditions result in decreased performance of the battery. For that, we need a balancing circuit that works actively with the help of a DC-DC converter. DC-DC converters generally have the same principle as buck-boost converters to increase and decrease the output voltage. However, the output still has a reasonably large ripple in the waveform. Therefore, the CUK converter is used, which is a development of the buck-boost converter topology. The output of this CUK converter has smaller ripples because it uses two capacitors and two inductors. Among the various methods used to adjust the duty cycle of the CUK converter, a precise and accurate algorithm is needed to overcome the instability of the converter output. The method used to adjust the duty cycle uses the Adaptive Neuro-Fuzzy Inference System (ANFIS) algorithm to develop the Fuzzy approach. The system is simulated in MATLAB Simulink software. The simulation results show that the output of the CUK converter with the ANFIS method has a faster response speed reaching a set point of 1.95 × 10-4 seconds and the accuracy of the output voltage with ANFIS is 99.94%, while the accuracy of the output converter current using ANFIS is 65.7%.

Keywords—ANFIS, balancing, battery, CUK converter, state of charge (SOC).15

I. Introduction

In this modern era, there are many new innovations in technology that are already in production and development [1]. Technological products are electrical equipment around us, and we are even obliged to use them to support our activities. These electrical tools can directly or indirectly have tremendous positive influence in maximizing and realizing the goals of all our activities [2]. Efficiency is the main reason why the electrical appliance is continually under development [1]-[2].

The use and utilization of batteries will not be separated from human activities in this modern era, such as cellphones, laptops, electric cars, even the industrial sector. However, the use of batteries is often not matched with adequate care due to ignorance in taking care of the battery. Batteries can quickly experience deterioration or diminishing efficiency with age [3].

There are several solutions for solving this problem. This paper will discuss using a series of "Balancing Charging System using Adaptive Neuro-Fuzzy Inference System based on CUK Converter", which is expected to solve one of the problems in the battery. These namely instability between battery cells results in a decrease in battery performance. The risk of battery damage is reduced due to imbalance between battery cells.

One of the most commonly used electronic devices to provide the required output voltage is a DC-DC converter. DC-DC converters consist of several types, such as buck, boost, and buck-boost converters. The CUK converter topology works like a buck-boost converter which can provide an output voltage greater or less than the input voltage. With the addition of components on the input side in inductors and capacitors, this CUK converter's output has a smaller ripple than buck-boost [4]. CUK converters work depends on the inductance speed, load resistance, and switching frequency. In the operation of this converter, the output can be adjusted to be bigger or smaller by changing the PWM value through the duty cycle setting.

The CUK will be used for this system because it is proportional enough to be used as a converter that has the same input voltage rating value as the output and its manufacturing costs are relatively cheap. MATLAB software will be used to run the simulation process. So that in this study the voltage and current regulation of the to charge the battery using a CUK converter by applying the principle of constant voltage and constant current which is controlled by ANFIS control.

II. Methods

Fig. 1 shows the research system design and system modelling, which will be explained in the points below:

A. System Design

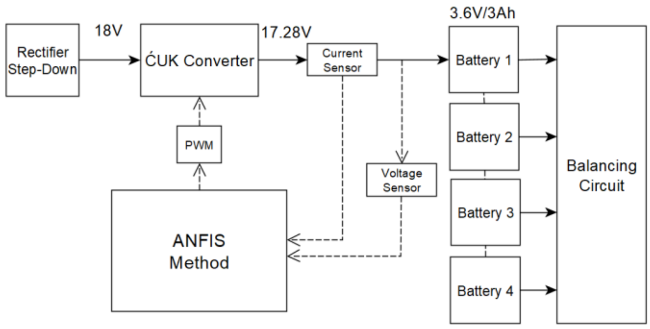

Fig. 1. Block diagram system.

The system designed is a system that can charge the battery and balance each battery cell. ANFIS is used as an algorithm for stabilizing the output voltage and current of the converter to create a more stable output wave [5]. The balancing circuit design is used to stabilize the SOC of each battery that has a different SOC value.

The system is designed in a simulation using MATLAB Simulink software. The simulated parts consist of ANFIS, CUK converter, battery balancing circuit, and the sensor for each parameter, as shown in Fig. 1**.**

B. *Modelling of CUK Converter*

The CUK converter is a DC-DC converter that is derived from the buck-boost converter. The CUK converter is composed of two inductors (L and Lo), two capacitors (C and Co), a diode (D), and a switch (IGBT or MOSFET) as shown in Fig. 2. With the inductor on the input side and the capacitor on the input side, this converter gives a smaller output current ripple than the buck-boost converter.

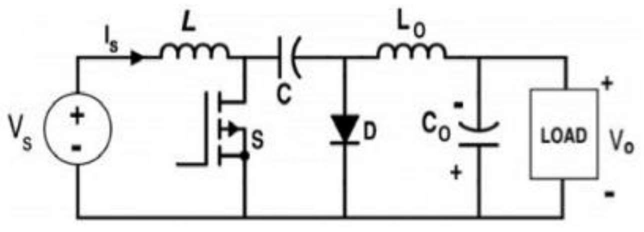

Fig. 2. Topology CUK converter.

There are two modes for running the CUK converter. When the switch is closed (ON), the current in C (Capacitor1) flows from the input to L (Inductor1) then returns to the negative side of the input circuit [6]. Then Co (Capacitor2) discharges, the current flows from Co (Capacitor2) to Lo (Inductor2) and flows to the load as can be seen in Fig. 4. So that when the switch is closed, the current of the inductor Lo (Inductor2) is the same as capacitor C (Capacitor1).

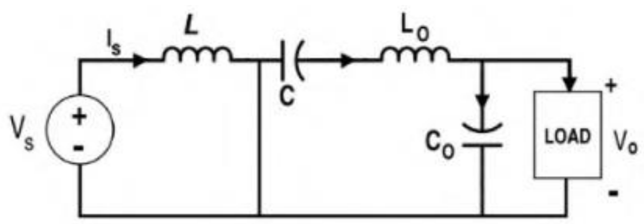

Fig. 3. CUK converter when switching open.

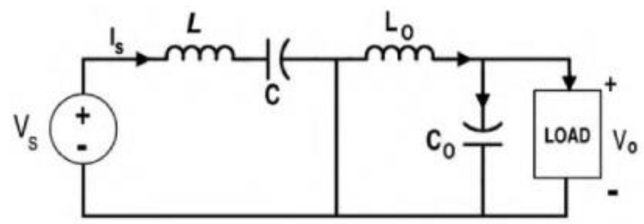

Fig. 4. CUK converter when switch closed.

The following condition is when the circuit is open (OFF), as in Fig. 3. The input current will flow towards L (Inductor1) and then forwarded to C (Capacitor1). It is found that current L (Inductor1) is equal to current C (Capacitor1) [6].

From the above, the duty cycle value is obtained as in equation (1).

$$D = \frac{V_{out}}{V_{out}+V_{in}} \tag{1}$$

From the equation that has been obtained, it takes the value of the input voltage, output voltage, and switching frequency. Table I below is the design of the CUK converter used.

TABLE I. CUK CONVERTER DESIGN

Parameter		**Values**	**Unit**
Input Voltage (Vs)		18	Volt
Input Current (Is)		3	Ampere
Output Voltage (Vo)		17.28	Volt
Output Current (Io)		1.5	Ampere
Switching Frequency		100	kHz
Capacitor1 (C)		22	uF
Capacitor2 (Co)		10	uF
Inductor1 (L)		79.347	uH
Inductor2 (Lo)		76.173	uH
Resistor		3	Ohm

C. *ANFIS Modelling*

Neuro-fuzzy is a first-order Sugeno model that integrates fuzzy logic systems and artificial neural networks. The neuro-fuzzy system is an artificial neural network system based on a fuzzy interface that is trained using a learning algorithm [7]. Simple steps for designing ANFIS is shown in Fig. 5.

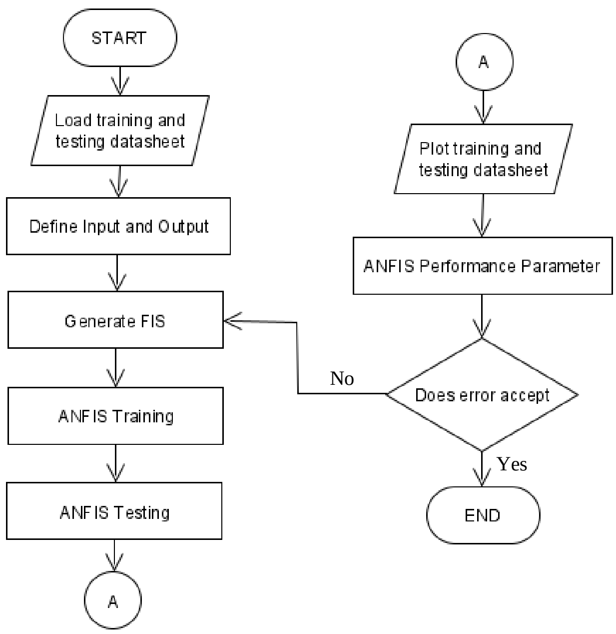

Fig. 5. ANFIS design flowchart.

1) *Input and Output ANFIS*

ANFIS consists of delta error and error as input parameters and produces one output. The ANFIS input is obtained from the current output and voltage output of the converter [8]. So there are two ANFIS controllers with each input and output, control for constant voltage and control for constant current. Data from errors and delta errors amounted to 404 data held, then entered in the ANFIS toolbox to carry out the training process. At the same time, the output is a duty cycle that will be used to adjust the CUK converter.

2) Generator FIS Design

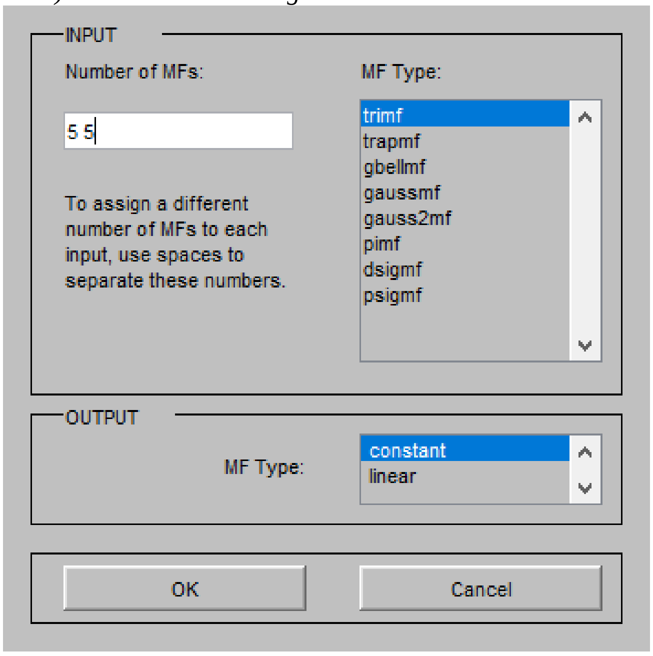

Fig. 6. Generated FIS.

After entering the data to be trained, it is necessary to select the number of membership functions (MF) to be used, as shown in Fig. 6. In the generated fuzzy inference system used to generate this FIS, choose the number of membership functions 5x5, with the selected MF type being constant [8]-[9]. The data used is stored in matrix form to be read by MATLAB during the ANFIS training process.

3) ANFIS Training and Testing

The results of the ANFIS training are in the form of learning from errors using 5 and 10000 iterations. In the learning process, two learning processes use a hybrid method that connects the Least Squares Estimator (LSE) method or the forward path and the Error Backpropagation (EBP) method, with 10,000 iterations selected as the ANFIS train parameter. This determines the iteration value used to get the error value closest to the actual value. More iterations will produce a better training value because the error value obtained will be smaller.

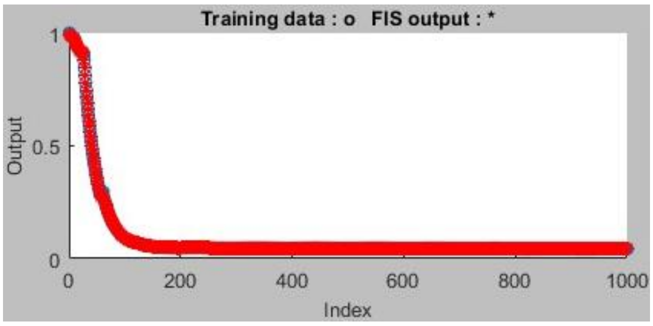

Fig. 7. ANFIS testing for voltage.

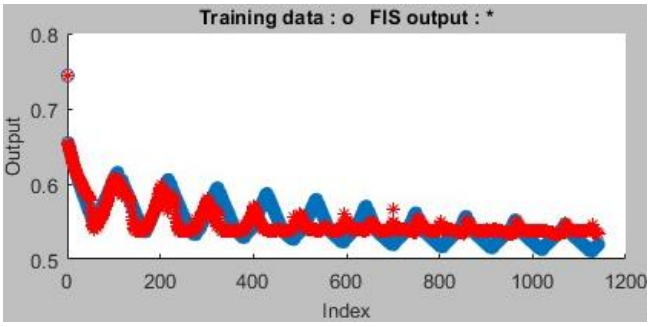

Fig. 8. ANFIS testing for current.

The results of plotting training data are shown in Fig. 7 and Fig. 8. This data is the value of the duty cycle of the ANFIS training results that have been tested, and it can be seen that the red dot (ANFIS training results) has entered precisely at the blue dot, which is the data center point (ANFIS training data).

4) ANFIS Performance Parameter

Fig. 9 to Fig. 12 are the new membership functions generated from the ANFIS training data. Because ANFIS is a derivative of Fuzzy, it is necessary to determine the membership function parameters, which are almost similar to fuzzification in Fuzzy., The membership function consists of 5 triangles [10].

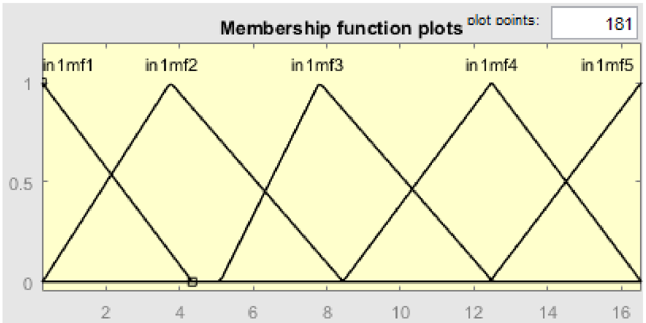

Fig. 9. ANFIS error membership function for voltage control.

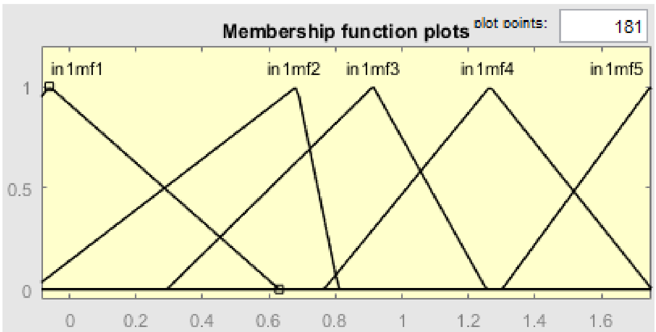

Fig. 10. ANFIS error membership function for current control.

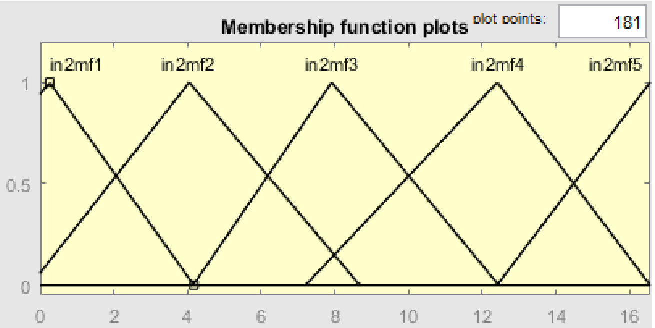

Fig. 11. ANFIS delta error membership function for voltage control.

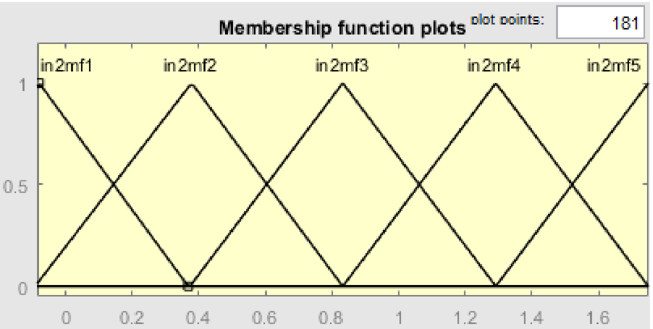

Fig. 12. ANFIS delta error membership function for current control.

Fig. 9 and Fig. 11 are ANFIS inputs for voltage control from the converter. Fig. 10 and Fig. 12 are inputs for current control from the converter. The output of ANFIS will produce 25 membership functions for each control, as shown in Fig. 13 and Fig. 14.

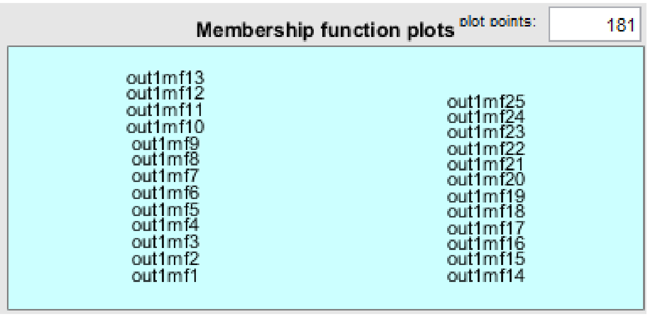

Fig. 13. Output ANFIS membership function for voltage control.

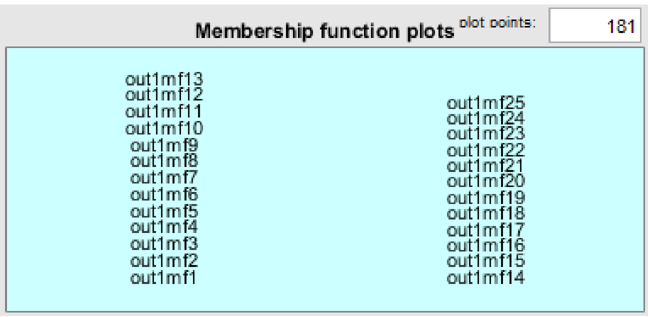

Fig. 14. Output ANFIS membership function for current control.

The results of the output membership function parameters for voltage control and current control can be explained in Table II.

TABLE II. MEMBERSHIP FUNCTION PARAMETERS

Membership Function	Parameters for Voltage Control	Parameters for Current Control
out1mf1	-0.0314	0.5859
out1mf2	0.6642	0.06333
out1mf3	0.9512	0
out1mf4	0	0
out1mf5	0	0
out1mf6	0.01572	0.4972
out1mf7	0.6284	0.9397
out1mf8	1.221	0
out1mf9	1.788	0
out1mf10	0	0
out1mf11	0	0.5983
out1mf12	0.9724	0.007612
out1mf13	0.7865	0
out1mf14	1.306	0
out1mf15	0.2282	0
out1mf16	0	0.6126
out1mf17	0	0.551
out1mf18	0.5246	0
out1mf19	0.9348	0
out1mf20	1.271	0.001431
out1mf21	1.059	0.6596
out1mf22	0.06692	0.4671
out1mf23	0	0
out1mf24	0.5949	0
out1mf25	0.9358	0.7455

D. *Balancing Circuit Design*

The designed system uses a balancing circuit that refers to previous research [11] - [14]. By making a few modifications to the way it works.

Its working principle can be explained in simple terms. When there is a difference in the value of each battery cell, the battery with the highest value will dispose of its charge to equalize its value with the battery that has the value in the middle. The battery with the lowest value will be charged first to reach the value of the battery in the middle. After getting the same battery value, the system will move from the battery balancing process to the battery charging process.

In Fig. 15, it can be explained that each battery is arranged in parallel with two switches, namely switches that are placed in parallel with a battery and switches parallel to two batteries are used to accelerate the energy dissipation process. If the highest value in a battery pack is on the switch, it includes. The inductor installed is used as an intermediary for the battery to make the process of dissipating energy faster.

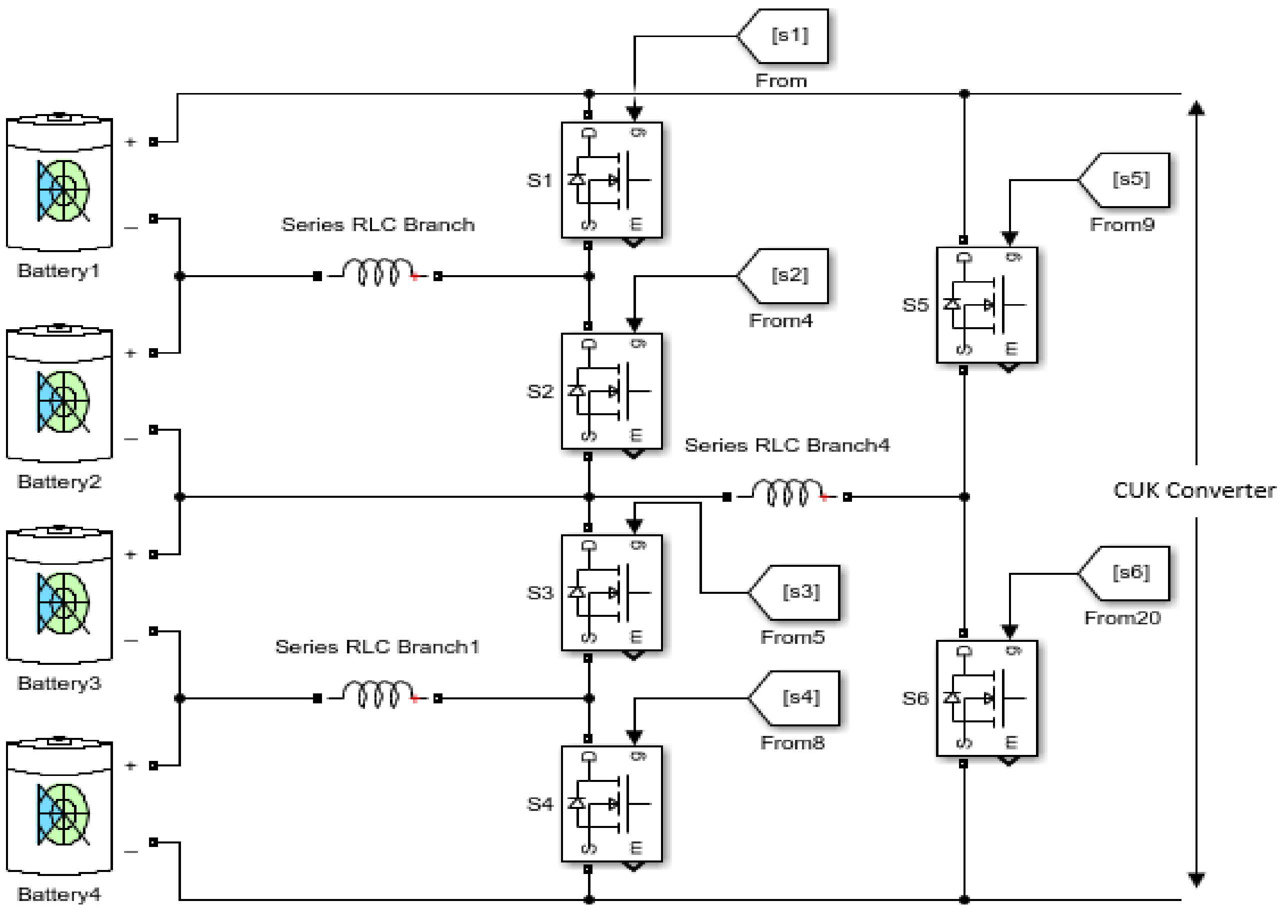

Fig. 15. Battery balancing circuit.

III. Results and Discussion

This section describes system testing and analysis of the simulation test results. The test aims to determine how the system works and see the system's success rate according to predetermined specifications.

A. *CUK Converter Result*

The charging process on the battery is implemented in the CUK converter circuit. Using four batteries with lithium-ion, strung in series at a voltage value of 3.6 volts per cell and the full condition, the voltage is 4.2 volts.

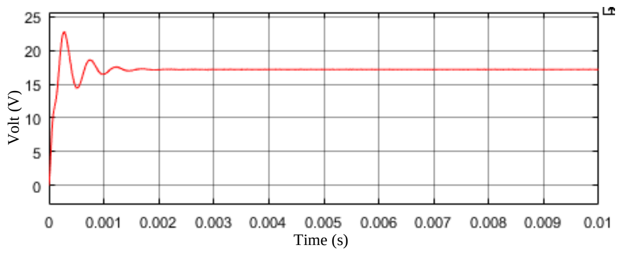

Fig. 16. System response when open-loop with 49% duty.

Fig. 16 is the output of the CUK converter that has been designed according to predetermined parameters, and the simulation will be running with MATLAB Simulink software during open-loop conditions. The required battery charging voltage is 17.28 volts. Fig. 16 shows that the output voltage generated by the converter at 49% duty cycle is 17.28 volts which is the voltage required for the battery charging process. Then the results obtained have met the predetermined set point for the charging process of 4 3.6 volt lithium-ion batteries arranged in series [15].

B. Optimal Charging Results for Lithium-Ion Batteries

Fig. 17 and Fig. 18 show the voltage response by comparing the Fuzzy and ANFIS methods as control methods used. As shown in Fig. 21, the voltage response can be seen that the response using the ANFIS method is more stable than the response using the Fuzzy method, which looks less stable.

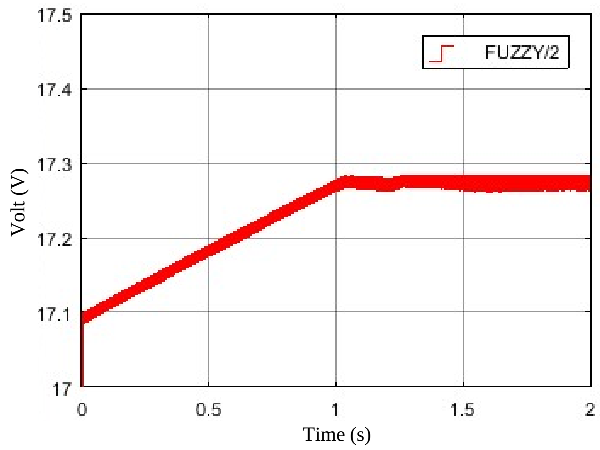

Fig. 17. Voltage response with fuzzy.

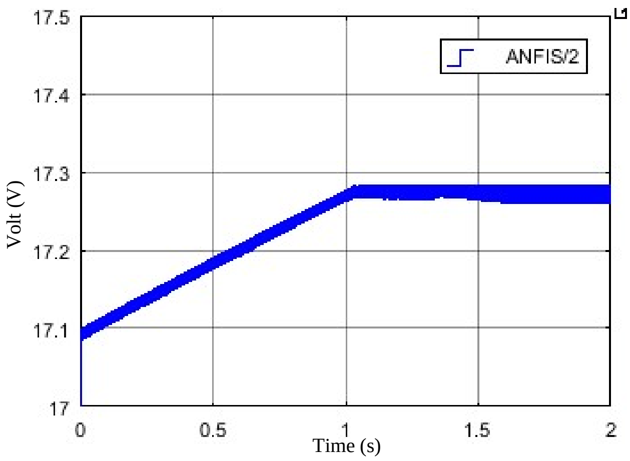

Fig. 18. Voltage response with ANFIS.

The comparison of the current response can be seen in Fig. 19 and Fig. 20, which shows the difference in converter output using the fuzzy method and the ANFIS method. Similar to the voltage response, the output current using the ANFIS method looks more stable than the Fuzzy method as shown in Fig. 22.

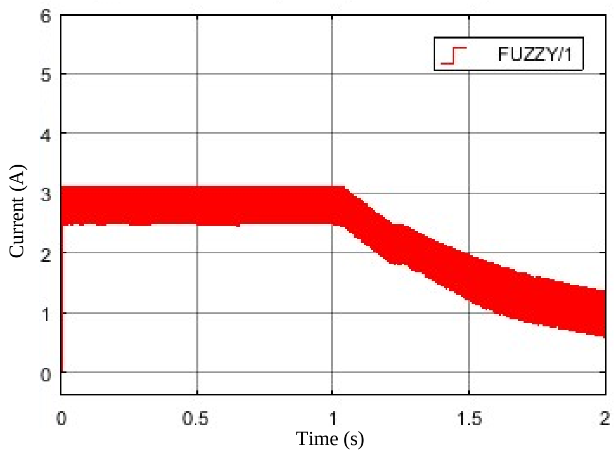

Fig. 19. Current response with fuzzy.

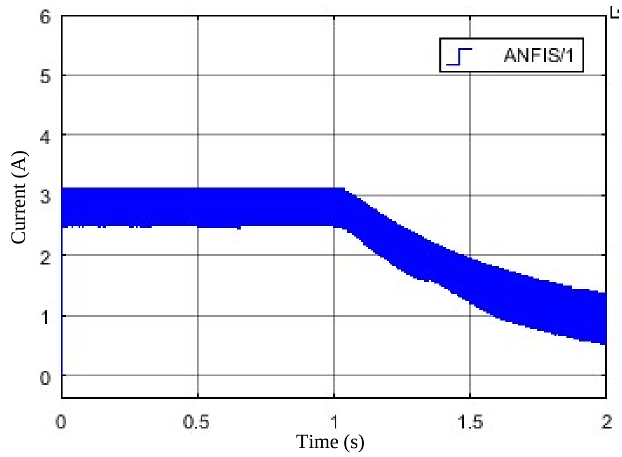

Fig. 20. Current response with ANFIS.

When examined in more detail, it will be seen that the response using the ANFIS method reaches the set point faster than using the Fuzzy method, as can be seen in Fig. 21 and Fig. 22.

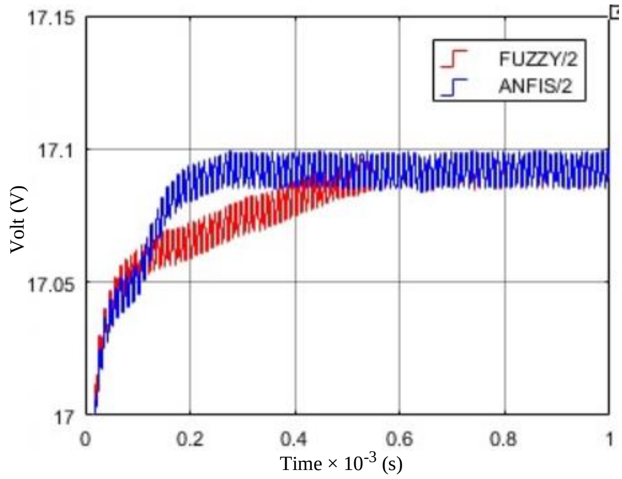

Fig. 21. Converter output voltage.

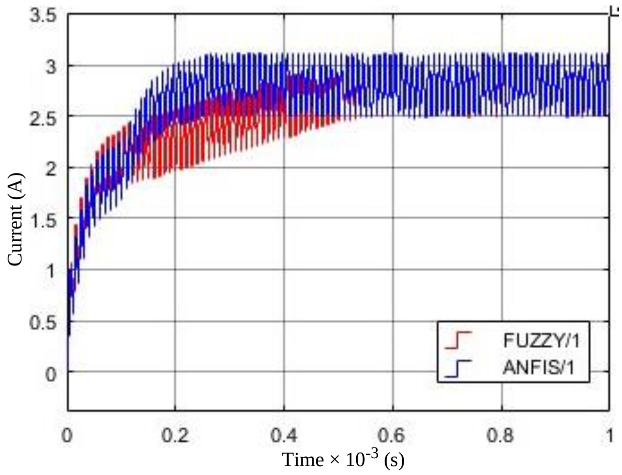

Fig. 22. Converter output current.

TABLE III. SYSTEM RESPONSE

Time (10^{-4})	**Output Current**	
	Fuzzy	**ANFIS**
1.95	2.54 A	3 A
4.75	3 A	3.09 A

Table III explains that the ANFIS method can accelerate the system response to reach the set point of 1.95×10^{-4} seconds. In comparation to the Fuzzy method, which takes 4.75×10^{-4} seconds to get the set point. Meanwhile, to reach a stable value, it takes 2.65×10^{-4} seconds using the ANFIS method, and takes 6.65×10^{-4} seconds using the Fuzzy method.

TABLE IV. SYSTEM ACCURACY

Method*/*Accuracy	**Fuzzy**	**ANFIS**
Voltage	99.92%	99.94%
Current	61.6%	65.7%

After the two systems are running stably, the accuracy of the output voltage and output current can be determined using both methods. These methods compare to the setpoint values that have been determined, as shown in Table IV. When the average value of the accuracy of the two methods is taken, the value for ANFIS voltage accuracy is 99.94% and for Fuzzy is 99.92%. Meanwhile, the current output accuracy with the

ANFIS method is 65.7% compared to the Fuzzy method, which is only 61.6%.

C. Results of System Integration

The results of this system integration are carried out after obtaining good results for testing the converter and the ANFIS method, which will be used for duty cycle regulation, which affects the converter's output, which is also used as the input voltage and current for the battery. After the converter planning and control method have been designed, then it can combine the converter circuit with the planned load and battery balancing circuit, as shown in Fig. 15. The results of system integration by giving a difference of 5% battery SOC value is shown in Fig. 23.

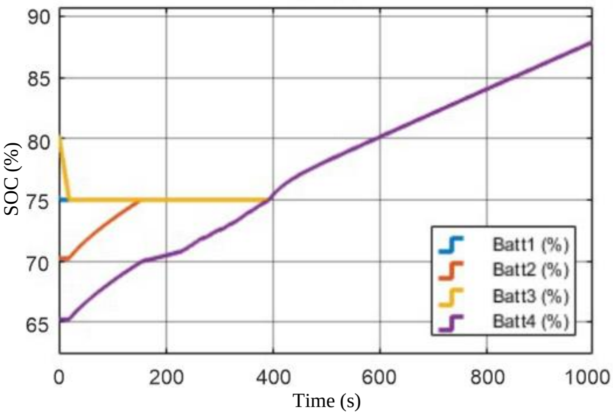

Fig. 23. The result of integration with the battery balancing system.

Fig. 23 shows the results of the overall system integration simulation. When it has a difference in SOC, the battery will be processed by a balancing circuit until the same SOC value is obtained for each battery cell. In Fig. 23, it is shown that the battery balanced value is at 75% SOC, and it takes 393 seconds for all batteries to reach a balanced SOC value. It takes 19.71 seconds for the three batteries to discharge to get the proportional value. While battery two and battery 4 carry out the charging process first to reach a stable value, it takes 152 seconds for battery 2 and 393 seconds for battery 4. After getting a balanced value for all batteries, namely at 75% SOC, the system will continue the process from the balancing process be the charging process for all battery cells.

IV. Conclusion

By performing simulations using MATLAB Simulink software, a comparison of the output of the CUK converter with the ANFIS method and the Fuzzy method is obtained. From the simulation, it can be seen that ANFIS is superior to Fuzzy in several aspects, namely response time, stability, and accuracy. ANFIS has a faster response to reach the setpoint, which takes 1.95×10^{-4} seconds, compared to Fuzzy that requires 4.75×10^{-4} seconds to reach the set point. ANFIS takes 2.65×10^{-4} seconds after getting the setpoint to become stable then Fuzzy takes 6.65×10^{-4} seconds. In the aspect of converter current output accuracy, ANFIS has an output voltage accuracy of 99.94% compared to Fuzzy at 99.92% and an output current accuracy of 65.7% compared to Fuzzy, which has an accuracy of 61.6%. The battery charging process is successfully simulated by alternating between the balancing mode and changing to the charging mode after the battery condition has reached the same or balanced value.

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