Fast Charging on Li-ion Batteries with ANFIS Control

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ABSTRACT — Most electrical energy used today comes from fossil fuels, which can deplete and contribute to air pollution. In Indonesia, the sun can be used as an alternative energy source and converted into electrical energy utilizing solar panel technology. The voltage generated by the solar panel is relatively high, so it needs to be lowered using a DC-DC converter type buck converter. This electrical energy can be stored using a battery which can be charged in a fast-charging mode to shorten the charging time. The most suitable battery type for fast charging is the lithium-ion (Li-ion) type for its capability to receive large current as big as 1C or equal to the battery capacity. Due to the temperature and solar irradiance effects, the output generated by the solar panel source is not constant. Moreover, to prevent overcharging, a constant current (CC) method with a constant current of 10 A and a constant voltage of 14.4 V was used which the PWM duty cycle driver was controlled using the adaptive neuro-fuzzy inference system (ANFIS) algorithm to obtain a faster response to reach the specified set point. ANFIS is a combination of two algorithms, i.e., artificial neural network (ANN) and fuzzy inference system (FIS). This research was conducted in simulation, the charging current results at the CC method of 10.01A were obtained and would move from the CC method to constant voltage (CV) when the state of charge (SoC) was 85% and the voltage reached 14.4 V. Then, the charging method would change to CV with a constant charging voltage of 14.4 V. When compared to the previous research using fuzzy control, the time required for ANFIS controls to reach set points was 3.2 ms, which is 2.3 ms faster than fuzzy controls, and ANFIS controls can reach set points with fewer errors.

KEYWORDS — ANFIS, Buck Converter, CC-CV, Fast Charging Li-ion Battery.

I. INTRODUCTION

Along with rapidly growing technology, the use of electrical energy is also increasing. Therefore, to minimize the scarcity due to the use of fossil fuels, an alternative energy source is required. Given that Indonesia is a country with a tropical climate, renewable and environmentally friendly energy can be utilized throughout the day as an alternative energy source [1]. Energy sourced from the sun is later converted into electrical energy utilizing solar cells using solar panels. However, there is a drawback of this solar energy, i.e., it can only be used in the daytime [2]. Therefore, the electrical energy can be stored in a battery to address this issue. The DC voltage generated on the solar panel is high enough to charge a 12 V battery. So, a DC-DC converter in a form of a buck converter is required to decrease the voltage from the solar panel to the battery [3].

The battery charging process typically takes a considerable amount of time, whereas, in this modern era, people generally want everything to be completed quickly. Therefore, this study discusses the fast battery charging technique. A fast-charging battery requires a bigger current compared to the standard charging process. The rechargeable battery type is known as a secondary battery, while the battery type that can be charged with a 1C charging level for 60 minutes is the lithium-ion (Li-ion) type battery. Li-ion batteries are advantageous due to their high efficiency, light battery mass, slow discharge when not in use, and versatility. Li-ion batteries can be used in electrical equipment, military industries, electric vehicles, and aerospace [4], [5].

In addition, the charging method in the fast-charging battery using the Li-ion battery also needs to be considered. Generally, people do not pay much attention to when the battery is fully charged, resulting in overcharging. As a result, it can shorten the battery lifespan as the temperature exceeds the permitted limit [6]. A method suitable for Li-ion battery charging using constant current-constant voltage (CC-CV) is needed to avoid such things. The CC-CV charging method is better than only using either the CC or CV because the CC and CV phases can complete each other. Its working principle is that the fast-charging battery constantly uses a charging current of 1C in the early phase of charging so that the voltage reaches the set point. After the voltage reaches the set point, the battery charging voltage will be constant and the current will lower until reaches 0.02C up to 0.07C causing the battery charging to stop [7].

Based on the explanation of the previously mentioned issues, this research aims to propose the development of a fast mode Li-ion battery charging without damaging the battery and can provide protection from the risk of overcharging using a solar panel source whose voltage is stepped down with a buck converter with the CC-CV charging method and controlled with the adaptive neuro-fuzzy inference system (ANFIS) algorithm. ANFIS algorithm is an adaptive neural network based on a fuzzy inference system (FIS), so this algorithm has advantages in making predictions and can make decisions based on rules that have been made more accurately [8], [9].

II. METHODS

The methods used in this study starting from block diagrams, and flowcharts, to system planning, will be explained below.

A. SYSTEM DESIGN

In this study, a fast battery charging system using a 12 V/10 Ah Li-ion battery was made which was carried out in a simulation using MATLAB software with a block diagram as shown in Figure 1. This study aims to demonstrate that ANFIS control is superior to fuzzy control used in previous studies

This system uses three 100 WP solar panel sources assembled in series. The 53.4 V voltage from the solar panel

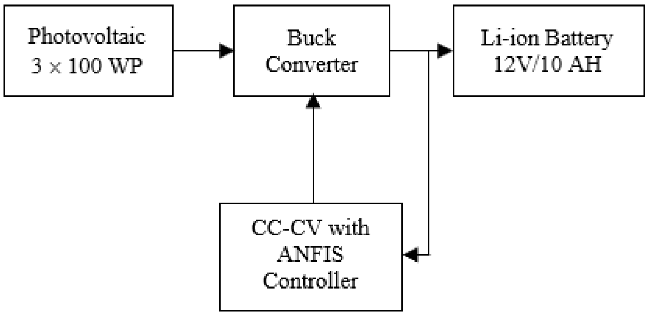

Figure 1. Block diagram of the system.

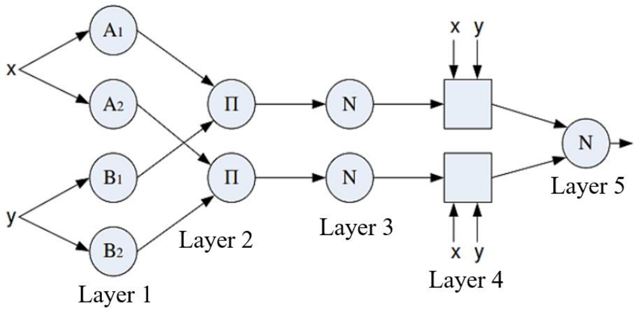

Figure 2. ANFIS architecture.

was lowered up to 14.4 V using a buck converter. Then, the voltage and output current of the buck converter were controlled using the ANFIS algorithm CC-CV method with a constant current of 10 A and a constant voltage of 14.4 V. In ANFIS control, there are five layers as shown in Figure 2, namely the fuzzification layer (output in the form of membership degrees), the product layer (multiplication results of all inputs), the normalization layer (the reweighting process to obtain the total value), the defuzzification layer (neurons that are adaptive to the output), and the total output layer (a single neuron from the sum of all outputs from the fourth layer). Then, the electrical power would be stored in a battery designed for charging with a large current, i.e., a Li-ion 12 V/10 Ah.

B. SOLAR PANELS

A solar panel is a device made of semiconductor materials capable of converting solar energy into electrical energy. Polycrystalline solar panels were used in this study. Despite their lower efficiency, polycrystalline solar panels are slightly less expensive and can still produce electricity when it is cloudy. This system uses three 100 WP solar panels assembled in series where the positive pole of the solar panel must be connected to the negative pole of other solar panels aiming at increasing the voltage. Therefore, it is expected that the buck converter can produce a high current proportional to the voltage drop; the greater the voltage drops, the higher the produced current [10]. The specifications of solar panels used are presented in Table I. assuming that the solar panel is in ideal conditions with a temperature of 25°C and irradiation of 1000 W/m2.

Current-voltage (I-V curve) and power-voltage (P-V curve) curves are typically used to describe PV characteristics, with the output voltage of the solar panel being affected by changes in irradiance and temperature. Irradiance or solar radiation on the Earth varies, depending on the state of the sun-to-earth spectrum [11].

C. BUCK CONVERTER

A buck converter is an electronic circuit that steps down the voltage from DC to DC by the switching method. It is referred to as a buck converter because the output voltage is smaller than the input voltage (step-down converter). Figure 3 presents the buck converter circuit [12], [13]. Buck converter supplied using DC current is composed of several components, namely MOSFET for current counter according to duty cycle, drive circuit to control MOSFET to work on or off, inductor (L) to store energy in the form of current stored when MOSFET is on and released when MOSFET off, diode (x) to flow current generated by inductor when MOSFET off, capacitor (C) for voltage filters so that the ripples produced are not too large, and the load (R) used in this study used a load in the form of a Li-ion battery.

TABLE I
SOLAR PANEL SPECIFICATIONS

Polycrystalline SP 100 WP Silicon Solar PV Module		
Specification	***Value***	***Unit***
Pm	100	W
Voc	21.8	V
Isc	6.05	A
Vmp	17	V
Imp	52	A
Max System V	1000	V
Dimension	1125 × 670 × 30	mm
Test Condition	AM 1.5 1000 W/m² 25°C	

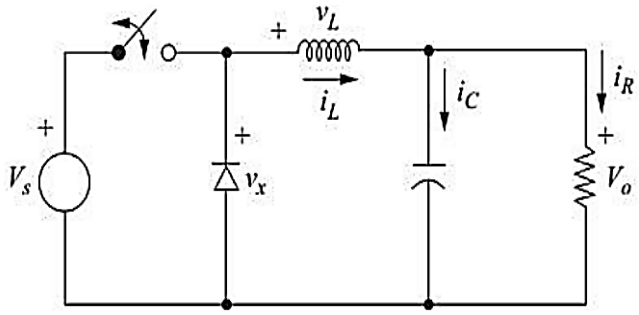

Figure 3. Buck converter series.

The operation of this converter was determined at a period when the switch was on and off. The diode was biased backward when the switch was on, causing the inductor current to flow in the direction of the load and producing a positive inductor voltage [14]. Inductor voltage equation when the switch is on:

$$V_L = V_s - V_o = L\frac{di_L}{dt} \quad \text{or} \quad \frac{di_L}{dt} = \frac{V_s - V_o}{L}. \tag{1}$$

Changes in inductor current when the switch is on:

$$\frac{\Delta i_L}{\Delta t} = \frac{\Delta i_L}{DT} = \frac{V_s - V_o}{L} \tag{2}$$

Settlement for Δ_{iL} when the switch is on:

$$(\Delta_{iL})_{closed} = \left[\frac{V_s - V_o}{L}\right] \text{DT}. \tag{3}$$

The diode became forward-biased when the switch was off, which caused the inductor currents to flow to the load side [15]. Inductor voltage when the switch is off:

$$V_L = -V_o = L\frac{di_L}{dt} \quad \text{or} \quad \frac{di_L}{dt} = \frac{-V_o}{L}. \tag{4}$$

Changes in inductor current when the switch is off:

$$\frac{di_L}{dt} = \frac{\Delta i_L}{\Delta t} = \frac{\Delta i_L}{(1-D)T} = \frac{-V_o}{L}. \tag{5}$$

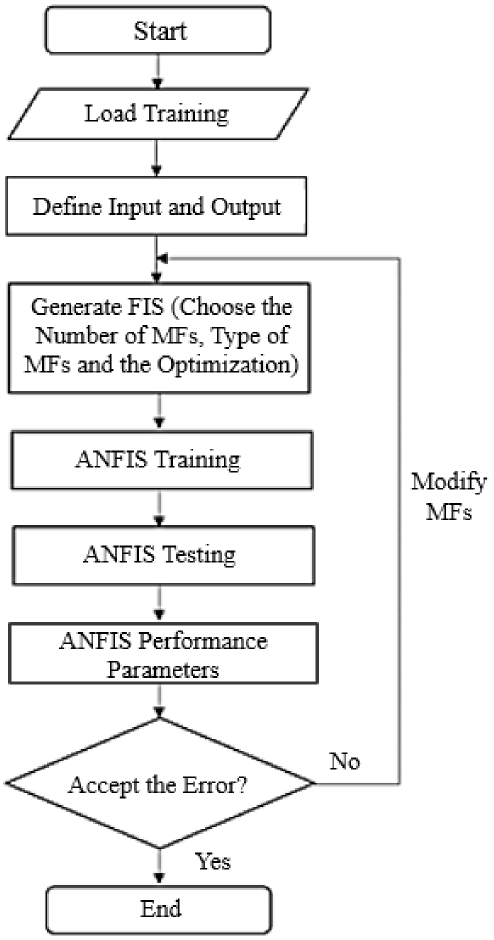

Figure 4. ANFIS flowchart.

Settlement for Δ_{iL} when the switch is off is:

$$(\Delta_{iL})_{opened} = -\left[\frac{V_o}{L}\right](1 - D)T. \qquad (6)$$

At the steady state, the inductor current (i_{-L}) at the end of the switching cycle is equal to the beginning of the next switching cycle. That is the change in current i_{-L} in one period equal to zero:

$$(\Delta_{iL})_{closed} + (\Delta_{iL})_{opened} = 0 \qquad (7)$$

$$\left[\frac{V_s - V_o}{L}\right] DT - \left[\frac{V_o}{L}\right](1 - D)\,T = 0$$

$$V_o = V_s \times D.$$

Information:

V_L = Inductor voltage (V)
V_s = Source voltage (V)
V_o = Output voltage (V)
i_L = Inductor current (A)
L = Inductor (μH)
$D \times 100$= Duty cycle (%)
T = Period (s)

So that the specifications used in the system in this study are as follows.

V_s = $V_{MP} \times 3 = 17.8 \times 3 = 53.4$ V
I_s = 5.62 A (Imp of the Solar Panel)
V_{out} = 14.4 V (120% of the battery voltage
I_{out} = 10 A (Charging current of the fast-charging battery)
f_s = 40 kHz
rVo = 0.1%

TABLE II
SOC BATTERY SIMULATION DATA DURING A CLOSED-LOOP (WITH ANFIS CONTROL)

SoC (%)	Vin (V)	Vout (V)	Iout (A)
70	59.22	14.31	10.01
75	59.22	14.34	10.01
80	59.21	14.37	10.01
85	59.20	14.40	10.01
90	59.27	14.40	9.44
95	59.21	14.40	8.09
97	60.01	14.41	7.07

rI_L = 20%

$D = \frac{V_{out}}{V_s} = \frac{14.4}{53.4} = 0.27 \times 100\% = 27\%$

$R = \frac{V_{out}}{I_{out}} = \frac{14.4}{10} = 1.44\ \Omega$

$L = \frac{V_{out} \times (1-D)}{\Delta I_L \times f} = \frac{14.4 \times (1-0.27)}{2 \times 40000} = 131.4\ \mu\text{H}$

$C = \frac{1 - D}{8 \times L \times rVo \times f^2} = \frac{1 - 0.27}{8 \times 131.4 \times 10^{-6} \times 0.001 \times 40\text{k}^2}$
$= 434.03\ \mu$F.

D. FAST-CHARGING BATTERY

Fast mode battery charging involves charging the battery with a high converter output power to charge the battery quickly. Fast mode battery charging differs from conventional battery charging in several ways, including the method and duration of battery charging, as well as the amount of power needed. The are five conditions required for fast-charging batteries [16].

First, the converter is designed with a large output power that follows the buck converter's plan at point E. Second, Li-ion batteries designed to receive a large current are used. The main parts making up a Li-ion battery are the negative electrode (anode), a positive electrode (cathode), an electrolyte, and a separator. When compared to other battery types, Li-ion batteries have the following advantages: Li-ion batteries can be used for fast mode battery charging with the CC-CV charging method [17]. Compared to other battery types with the same capacity, Li-ion batteries are lighter in weight. In addition, it has a high energy density, allowing it to store a large amount of energy. The Li-ion battery discharge is 5%/month.

Third, the employed method is CC-CV. The CC-CV charging method is a combination of two methods, namely CC and CV. The initial process of charging the battery uses the CC method, in which the battery is charged with a predetermined CC and the voltage will gradually increase linearly with time until it reaches the maximum value limit. Then it is continued with the battery charging process using the CV method when the state of charge (SoC) reaches 85%, that is, the battery is charged with a predetermined CV and causing the continuous charging current to decrease. It aims to prevent overcharging conditions and overvoltage that can damage Li-ion batteries. This CV method ends when the current has decreased to touch a predetermined point and the battery capacity has been fully charged [18], [19].

Fourth, the average current used for fast charging is 0.5C - 1C or 1 A.s with the battery temperature when charging between 10°C - 45°C (25°C is recommended). The first characteristic of the fast-charging battery is the slow charger. In the slow charger charging type, the commonly used battery types are NiCd and lead acid with a C-rate of 0.1C for 14 hours

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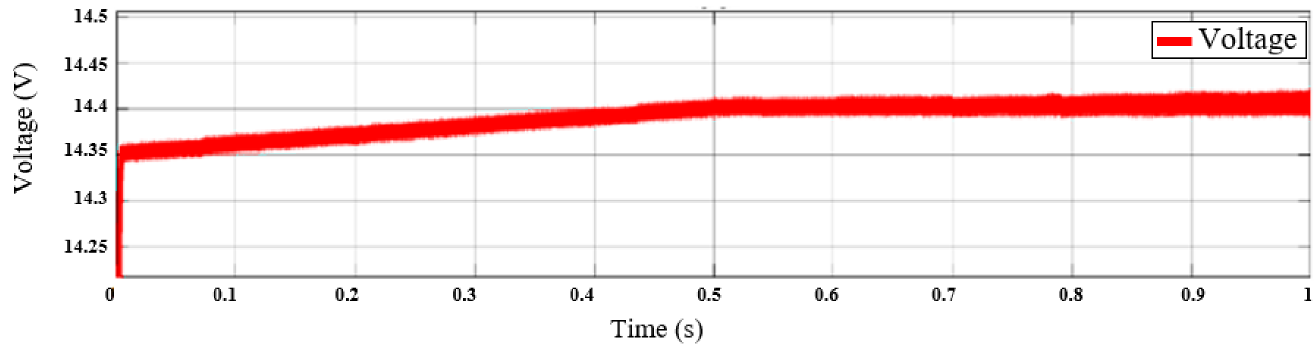

Figure 5. Constant voltage waveforms.

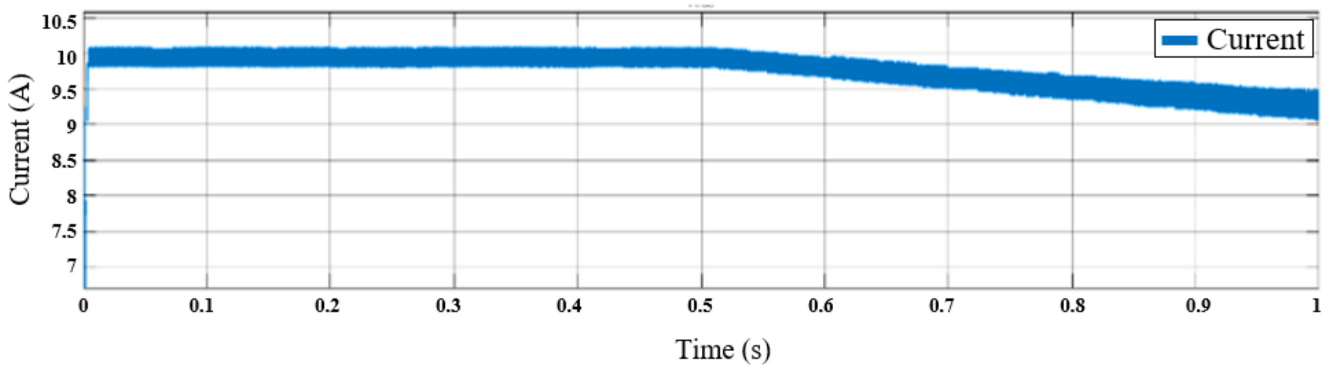

Figure 6. Constant current waveforms.

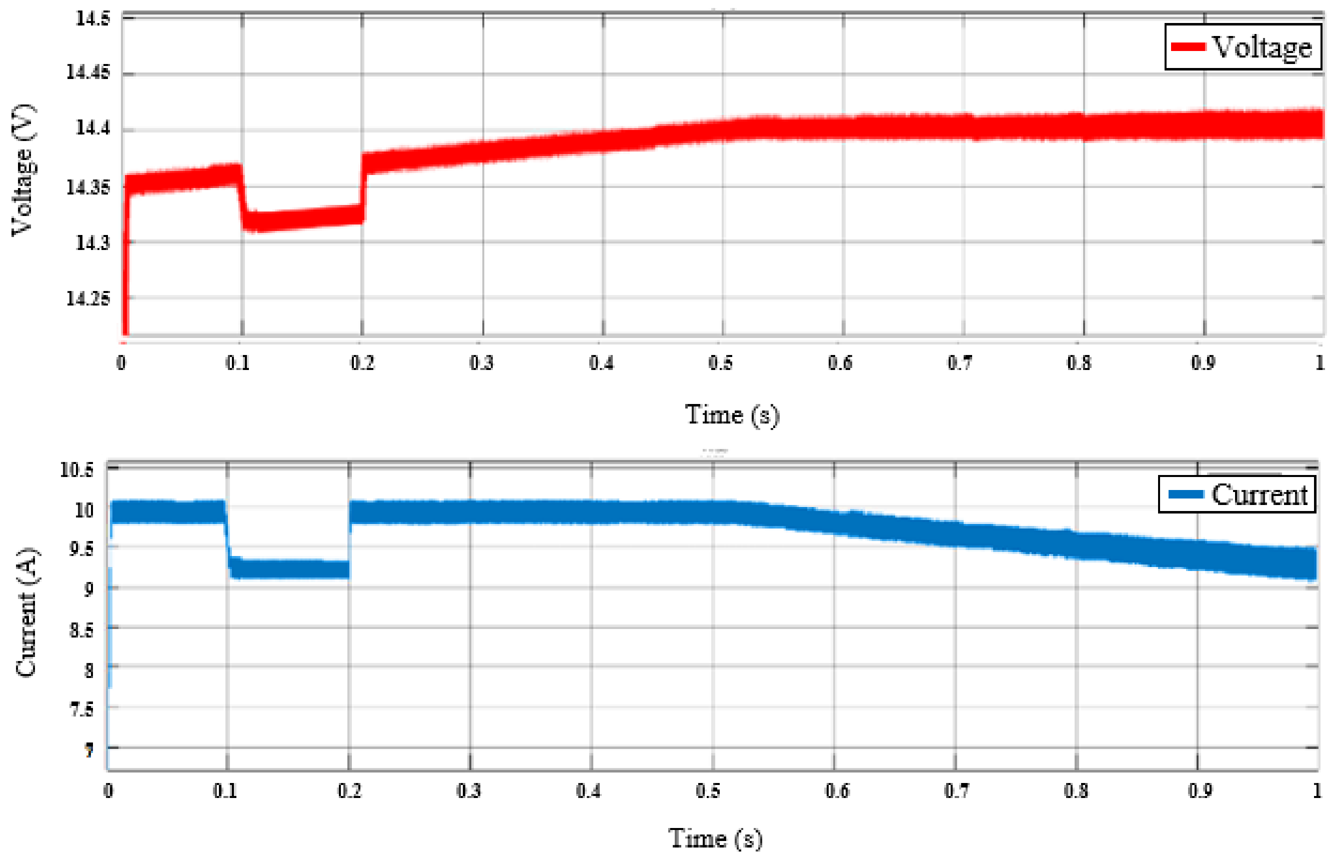

Figure 7. Constant current waveforms with disturbances.

of charging and temperatures between 0°C - 45°C (32°F - 113°F). Under the condition that charging is done continuously on a slow basis or a fixed timer and remove the battery while charging. The second is a rapid charger. The commonly used battery types for the rapid charger charging type are NiCd, NiMH, and Li-ion with a C-rate of 0.3C - 0.5C for 3 - 6 hours of charging and temperatures between 10°C - 45°C (50°F - 113°F). Under the condition that the battery capability is based on voltage, current, temperature, and timer. The third is the Fast charger. The commonly used battery type in this fast charger

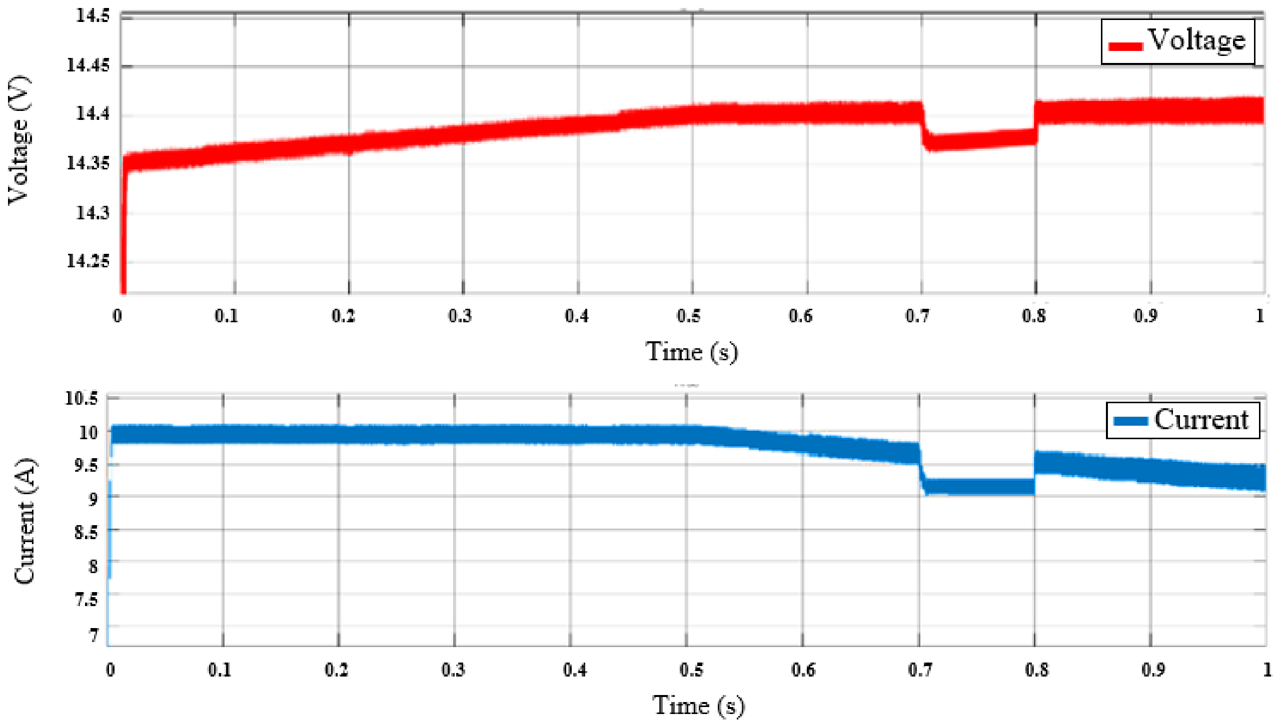

Figure 8. Constant voltage waveforms with disturbances.

charging type is similar to those used in the rapid charger, namely NiCd, NiMH, and Li-ion with a C-rate of 1C for 1 hour + charging and temperatures between 10°C - 45°C (50°F - 113°F). Under the same condition as the fast charging with a faster service. The fourth is the ultra-fast charger. The battery type used in this ultra-fast charger is similar to those used in the rapid and fast charger charging namely NiCd, NiMH, and Li-ion with a C-rate of 1C - 10C for 10 - 60 minutes of charging and temperatures between 10°C - 45°C (50°F - 113°F). Under the condition that it applies a very fast charging up to 70% SoC, limited with a special battery [20].

E. ANFIS

ANFIS is a combination of two methods, namely fuzzy logic methods and artificial neural networks, where fuzzy inference is trained using algorithms derived from artificial neural network systems. ANFIS control is used to control and stabilize the current and voltage according to a predetermined setting point [21]–[24]. Figure 4 presents the ANFIS flowchart.

Based on the flowchart in Figure 4, the first step is to determine the input and output. The ANFIS has two inputs and one output. The input of ANFIS control is the error and delta error obtained from the output voltage and current of the buck converter. While the output of ANFIS is the duty cycle used to regulate the magnitude of the output voltage of the buck converter. The error, delta error, and duty cycle data were obtained from the learning process using the fuzzy method. The data generated by the FIS was used as ANFIS control training data. This fuzzy control generated 7.5 million data. Then the data were reduced to 434 data in ANFIS for CV and 595 data in ANFIS for CC. The data were reduced by simplifying the obtained data by deleting some data of the same value. The simplified data should be representative of all existing data. The amount of data reduction depends on the need. It is necessary to do trial and error in order to obtain the maximum final results.

Second, a generate FIS was used to determine the number and type of membership degrees. In this control, the number of membership functions used was 7 × 7 membership functions for ANFIS constant voltage and constant current because the more the number of membership functions used, the smaller the resulting error will be, and it greatly affects the resulting output. The selected data type was constant trimf (triangular) because it is the simplest type. The selection of the data type does not really affect the generated output.

Third, the ANFIS trains FIS using a hybrid method that connects the least squares estimator (LSE) method and the error back propagation (EBP) method with 1000 iterations. This iteration is used to get a training value that is close to the actual value. The more iterations performed, the smaller the error value and the better the training data. With 1000 iterations, the error was 0.0019675 for ANFIS CV and 0.024117 for ANFIS CC.

Fourth, the FIS testing is performed on the result of tested training data. The results of plotting the duty cycle training data in the form of a red dot which is the result of ANFIS training compared to the blue dot which is the center point of the ANFIS training data input.

Fifth, a new membership function is obtained from the ANFIS design that has been done. ANFIS is a trained fuzzy method, so new membership functions are generated for the process of changing inputs from crisp to fuzzy sets with their respective membership functions. This new membership function is used to control the output current and voltage values of the converter. ANFIS input membership function in the form of ANFIS error and delta error consists of 7 MFs. Then, there is an ANFIS output membership function in the form of a duty cycle consisting of 49 MFs.

III. RESULTS AND DISCUSSIONS

After planning according to the existing parameter data, then the results of the 12 V/10 Ah Li-ion battery fast charging simulation can be known.

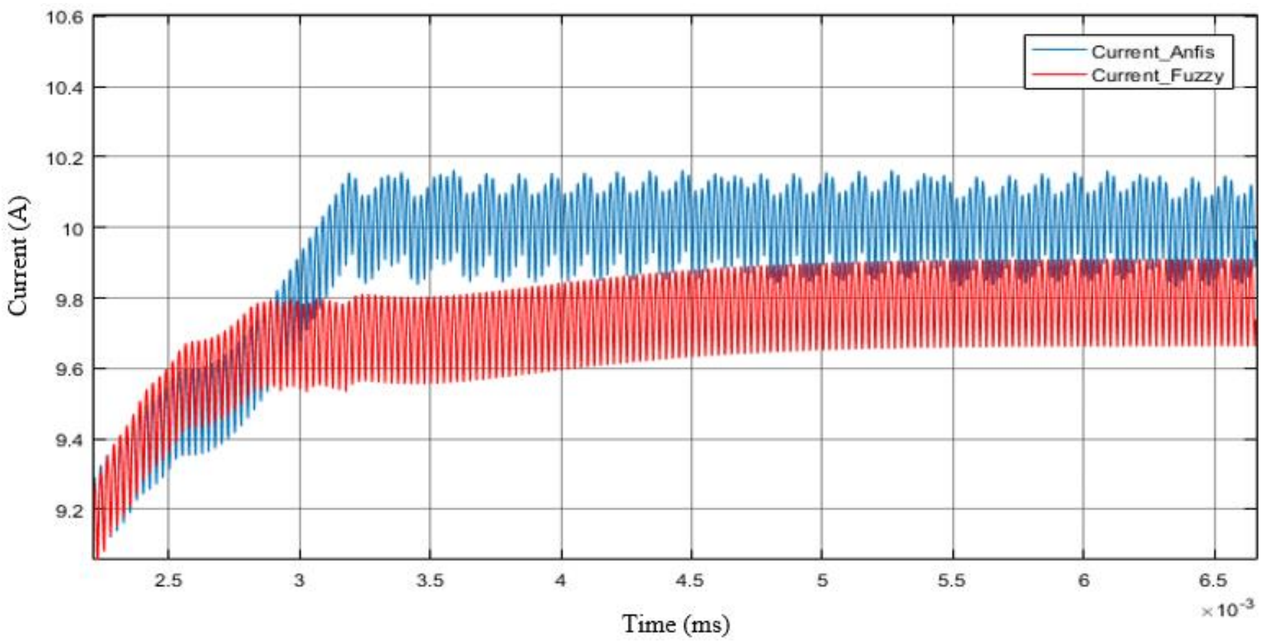

Figure 9. Current comparison of CC method between fuzzy control and ANFIS.

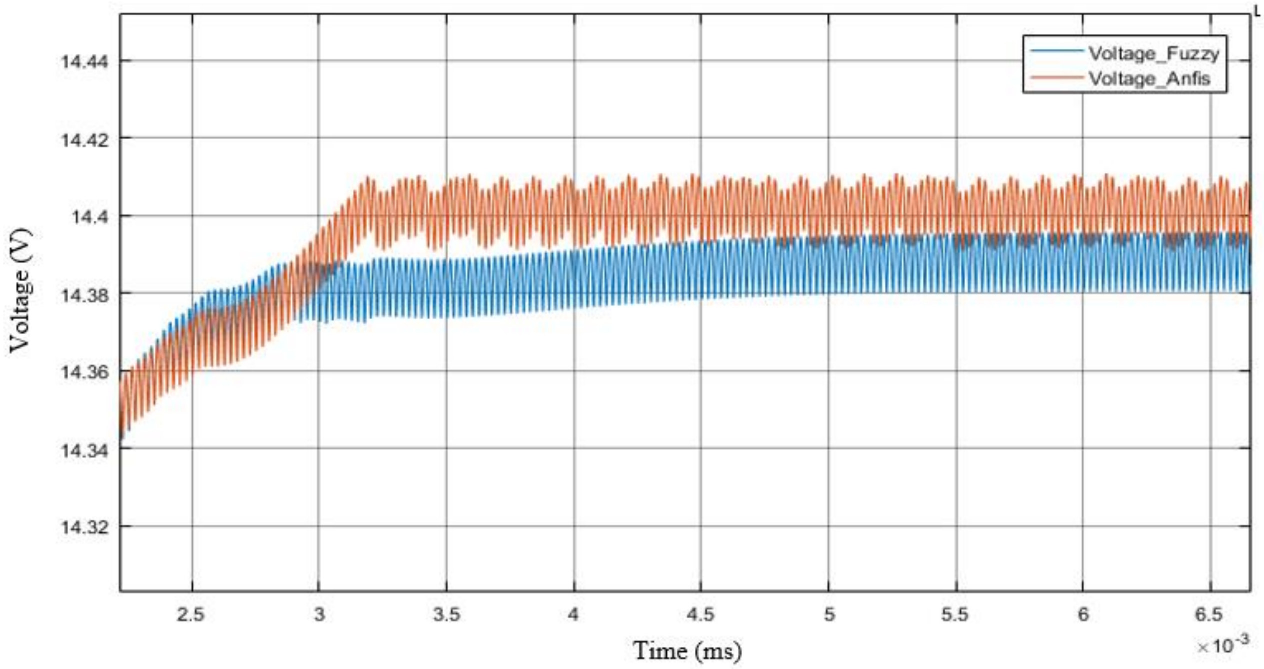

Figure 10. Voltage comparison of CC method between fuzzy control and ANFIS.

A. CLOSED-LOOP SIMULATION RESULTS (WITH ANFIS CONTROL)

In this research, the charging methods used for fast-charging 12 V/10 Ah Li-ion batteries were CC (10 A) and CV (14.4 V). Then, simulated system testing was carried out using ANFIS control to maintain the duty cycle on the converter to remain stable following the predetermined set point.

The output waveform from the voltage when using the constant voltage method is presented in Figure 5. Using ANFIS control for the voltage to reach the set point of 14.4 V requires a MATLAB simulation time of 0.5 s and the voltage will be constant. The output waveform of the converter current during constant current mode is illustrated in Figure 6. By using ANFIS control, the initially constant current will drop from the 0.5 s of MATLAB simulation time. ANFIS control can speed up the voltage time to reach a steady state compared to using fuzzy control, the details of which are presented in point C (comparison of ANFIS and Fuzzy control).

The battery SoC change data with close loop simulation (using ANFIS control) are illustrated in Table II. Table II demonstrates that the charging method from a CC of 10.01 A moves to the CV charging method on the 85% SoC with a decreasing charging current to keep the voltage constant at 14.4 V.

B. CLOSED-LOOP SIMULATION RESULTS (WITH ANFIS CONTROL) WHEN GIVEN A DISTURBANCE

To test whether the ANFIS control can function, when the system is in the constant current or constant voltage method, it

TABLE III
COMPARISON OF FUZZY AND ANFIS CONTROL OUTPUTS

Time (ms)	Output Current (A)		Output Voltage (V)	
	Fuzzy	*ANFIS*	*Fuzzy*	*ANFIS*
3.2	9.7	10	14.38	1.4
5.5	9.8	10	14.39	14.4

was given a disturbance in the form of nonconstant irradiation. Figure 7 and Figure 8 demonstrate the CC-CV test waves with interference.

The waves in Figure 7 and Figure 8 indicate that if there is a change in irradiation in the CC method at 0.1 s to 0.2 s, the current and voltage drop and the current returns to constant. Similarly, if there is a change in irradiation in the CV method at 0.7 s to 0.8 s, the current and voltage decrease and the voltage returns to constant. Therefore, it can be concluded that the control can run well as planned.

C. COMPARISON OF ANFIS AND FUZZY CONTROL

Furthermore, the difference in advantages of using ANFIS control versus fuzzy control must be proven by simulating with MATLAB software. Figure 9 and Figure 10 illustrate a comparison graph of CC-CV using fuzzy logic controller and ANFIS. A more detailed difference is presented in Table III.

The results of the graphs and tables illustrate the difference between the two methods used. Although ANFIS had a slower rise time than fuzzy, it took less time to reach a steady state or set point when using ANFIS control. At time 3.2 ms the output voltage using ANFIS control was able to reach the set point at 14.4 V while using fuzzy control the voltage was still at 14.38 V. At time 5.5 ms the output voltage using fuzzy control reached a steady state at a voltage of 14.38 V but did not reach the set point. For the output current using ANFIS control, the current could reach the set point at 10 A, while using fuzzy control the current was unable to reach the set point, which was a steady state at a current of 9.8 A. ANFIS control had a 0% error, which was superior to the fuzzy logic controller, which had a current error of 2% and a voltage error of 0.07%. This research concludes that ANFIS control is superior to fuzzy control because ANFIS is a combination of two ANN and fuzzy controls, combining the advantages of the two controls to produce better output results.

IV. CONCLUSION

In this research, based on the simulation results, the designed charging could reach 85% SoC in 0.5 s. Before reaching 85% SoC, the system performed charging with the CV method. After reaching 0.5 s the system performs charging with the CC method. ANFIS control on this system was able to run proven when given a disturbance, the current and voltage remained constant. ANFIS control results is better output than the fuzzy logic controller because ANFIS control could reach the set point faster (3.2 ms) than the fuzzy logic controller (5.5 ms).

CONFLICT OF INTEREST

The authors of the research titled “Fast Charging on Li-ion Batteries with ANFIS Control” declare that there is no conflict of interest in this research.

AUTHOR CONTRIBUTION

Conceptualization, Renny Rakhmawati, Zhafira Rana Khalisa Permana, Rachma Prilian Eviningsih; research methodology, Renny Rakhmawati, Suhariningsih; software, Renny Rakhmawati, and Zhafira Rana Khalisa Permana; validation, Renny Rakhmawati, Zhafira Rana Khalisa Permana, Rachma Prilian Eviningsih, Suhariningsih; formal analysis, Renny Rakhmawati; sources, Renny Rakhmawati; writing-preparation of original drafts, Renny Rakhmawati and Zhafira Rana Khalisa Permana; writing-review and editing, Renny Rakhmawati and Rachma Prilian Eviningsih.

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