SEPIC Converter for Lead Acid Battery Charger Using Fuzzy Logic type-2 Controller

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***Abstract*—Over time, the earth where we live is getting warmer every year, this is due to the greenhouse and excessive use of fossils can make a bad influence on the environment. Of course, this is not very good for the sustainability of our environment, as a result the ozone layer decrease with the depletion on our earth, particularly in a tropical country like Indonesia, with the resulting impact, our country will be increasingly affected by the impact. This battery charging using a vrla battery and the system has a working system by utilizing a source of lighting from the sun which will be processed into a source of electricity with a solar panel, the system is designed with an output voltage of 14 Volt with an input voltage of 36 Volt from the solar panel, the voltage will be lowered by the SEPIC converter according to the value from The duty cycle value is set on the MOSFET and used to charge the battery according to the calculation of load requirements. This system focuses on how to maximize a vrla battery charger with the CC-CV (constant current constant voltage) charger method with an interval type-2 fuzzy logic system (IT2FLS) algorithm and condition switch on cc to cv on 14 volt on SoC on soc 99.60%. and has 0% error's setpoint on constant voltage. The fuzzy type-2 algorithm can be used to charge the vrla battery.**

***Keywords*—battery charger, constant current constant voltage, fuzzy logic type-2, sepic converter.**

I. Introduction

Global warming is a form of imbalance ecosystems on earth due to the process of increasing the average temperature of the atmosphere, oceans, and land on earth. Over the last hundred years or so, the temperature on Earth's surface has risen an average of 0.74 ± 0.18 °C [1]. The temperature increase on the earth's surface occurs one of them being caused by increased greenhouse gas emissions, such as: methane, nitrous oxide, carbon dioxide, hydrofluorocarbons, sulfur hexafluoride, and perfluorocarbons in the atmosphere. These emissions are mainly generated from the process of burning fossil fuels (petroleum and coal) and the consequences of deforestation and forest burning [2].

Solar panels, of course, require batteries in terms of storing the power generated, therefore This system uses a Sepic converter to adjust the input power for the vrla battery charger with the CC-CV (Constant Current-Constant Voltage) method applied with fuzzy logic type 2 algorithm. A microcontroller is used with the Fuzzy Type-2 algorithm given to keep the voltage and current constant. A fuzzy Type-2 system (IT2FLS) algorithm is a form of development of the Fuzzy Logic system (T1FLS) algorithm. The FLC method is a control system scheme that uses the concept of fuzzy set theory in its design with three main processes which are fuzzifier, inference, and defuzzifier, meanwhile fuzzy type-2 has four main processes which are fuzzifier, inference, type-reduction, fuzzified. T1FLS has a problem, it hasn't handled uncertainly linguistic, numerical, and an unstructured environment. However, it became the basis for the creation of an interval type-2 fuzzy logic system (IT2FLS). Recently, IT2FLS has caught the attention of researchers and is very useful when experiencing obstacles in determining the proper membership function, or in modeling the diverse opinions of individuals differently. Because it has a more formation complex, IT2FLS is considered potentially better to model uncertainty [3]. The Fuzzy Type-2 algorithm is used to control the PWM generation, which controls the converter output voltage so that it is constant, with a standard charging for a voltage of 110%-130% and a current of 10%-30% of the lead-acid battery capacity [4]. Fig.1 is the main system of design. On system use, a sepic converter, which has advantages which are the same polarity with input, low ripple voltage and current depends on capacitor's value [5].

II. Method

A. System design

This system has a source from photovoltaic 200 Wp from 100 Wp series circuit, with CC-CV charging method, figure 1 shows the system design.

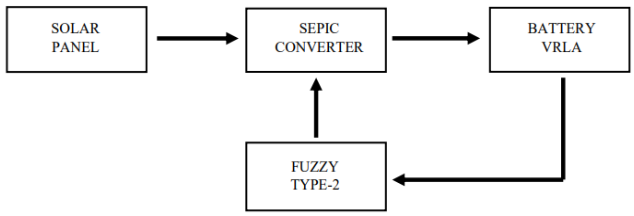


Fig. 1. System design

B. System modeling

1) Lead Acid Battery

The lead-acid battery applied to charge, it advise to not give heavy-duty discharge because it can make the battery doesn't have a long lifetime. But vrla battery is not suitable for a starter battery in an electric vehicle. The lead-acid has potential full capacity after 50 to 100 cycles [6].

2) Modelling of Sepic Converter

SEPIC Converter has a full name Single-Ended Primary Inductance Converter one of DC/DC converter that allows the output voltage (Vo) to be lower, equal, and greater than the input voltage (Vs). The SEPIC output is controlled by the MOSFET which will then be set pulse width by PWM (Pulse width modulation) [5].

The SEPIC converter has a topology from the buck-boost converter, these three converters can produce Vo which can be greater or less than Vs according to the duty cycle but the buck-boost converter has an opposite polarity on the output voltage, on the contrary on the SEPIC converter without changing the polarity this is possible and suitable for the more versatile SEPIC converter. In addition, the selection of contractors and inductors on the SEPIC converter can also reduce the output ripple value of voltage and current. Fig. 2 SEPIC converter has 2 inductors and 2 capacitors [7].

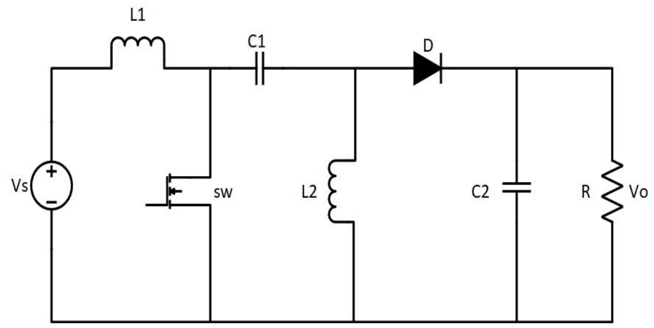


Fig. 2. Equivalent circuit of the sepic converter

where:

V_s = converter's input (V)
L_1 = inductor 1 (μH)
L_2 = inductor 2 (μH)
C_1 = capacitor 1 (μF)
C_2 = capacitor 2 (μF)
sw = switch
D = Diode
R = resistance (Ω)
V_o = converter's output(V)

When the switch of the SEPIC converter is closed, Vs will charge L_1 and C_1, while for C_2 it will power L_2 [5][6]. The output is controlled by C2 and the diode is reverse biased. Fig. 3 will show the SEPIC converter in the on and off conditions of the diode. When the switch (SW) is closed, the voltage will pass through L_1 and the diode will be off [7].

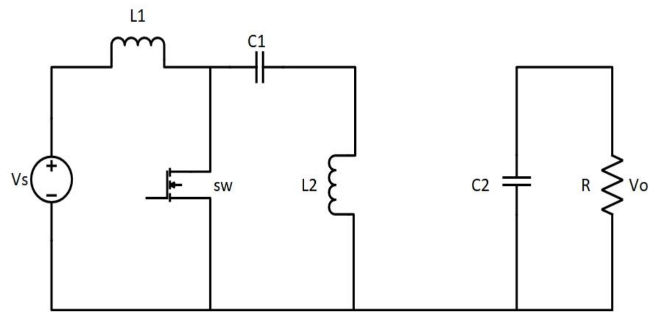


Fig. 3. SEPIC converter circuit on a switch condition

The diode will be on, and the diode will be forward biased, when the SEPIC converter switch is off. The power on L_1 will run out and temporarily L_2 will send power to the load [7]. Fig. 4 will show the SEPIC converter with the switch off and the diode forward biased [8].

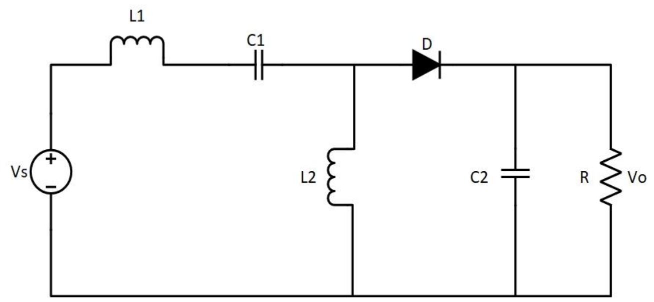


Fig. 4. SEPIC Converter circuit off switch conditions

From basic operations, we can find out the value of the system duty cycle [8]. It assumed that the efficiency of the circuit is 80% [9]. So the duty cycle (D) value can be calculated using the equation:

$$D = \frac{V_o}{V_s + V_o} \tag{1}$$

The value of the selected component can be calculated using the equation. The equation describes to find first inductor ripple output value to calculate the maximum current for a sepic converter using the equation :

$$\Delta I_{L1} = \frac{V_s \times D}{L_1 \times f} \tag{2}$$

The equation describes to find second inductor ripple output value to calculate the maximum current for a sepic converter using the equation :

$$\Delta I_{L2} = \frac{V_s \times D}{L_2 \times f} \tag{3}$$

The equation describes to find Inductor RMS Current value using the equation for the sepic converter:

$$IL_{rms} = \sqrt{{I_o}^2 + \left(\frac{\Delta i_L/2}{\sqrt{3}}\right)} \tag{4}$$

The equation describes to find maximum current value to find maximum current inductor on sepic converter using the equation:

$$I_{max} = I_o + \frac{\Delta i_L}{2} \tag{5}$$

The equation describes to find first inductor ripple output value to calculate the first capacitor value for a sepic converter using the equation:

$$\Delta V_o = 0.1\% \times V_o \tag{6}$$

The equation describes to find first inductor ripple output value to calculate the first capacitor value for the sepic converter using the equation:

$$\Delta V_{C1} = 0{,}1\% \times V_{C1} \tag{7}$$

The calculation describes to find capacitor's value to the selected component first capacitor of sepic converter:

$$C_1 = \frac{V_s \times D}{R \times \Delta V_{c1} \times \text{f}} \tag{8}$$

The calculation describes to find capacitor's value to the selected component second capacitor of sepic converter:

$$C_2 = \frac{V_o \times D}{R \times \Delta V_o \times f} \quad (9)$$

Where:

V_s = Input Voltage (V)
V_o = Output Voltage (V)
I_{max} = Maximal Current (A)
R = Resistance (ohm)
f = Switching Frequency (Hz)
L = Inductor (H)
ΔI_L = Inductor Ripple Current (A)
$IL_{(rms)}$ = Inductor RMS Current (A)
C = Capacitor (F)
ΔV_o = Ripple Output Voltage (V)
D = Duty Cycle

TABLE I. RESULTS OF SEPIC CONVERTER COMPONENT CALCULATIONS

Parameters	Symbol	Value	Units
Input voltage	V_s	36	Volt
Output voltage	V_o	14	Volt
Output Current	I_o	4	A
Inductor Ripple Current	ΔIL	1	A
Inductor RMS Current	IL_{rms}	4.03	A
Voltage ripple	ΔV_o	0,014	Volt
Switching Frequency	F_{sw}	40	KHz
Inductor Max Current	I_{max}	4.5	A
Inductor 1	L_1	252	µH
Capacitor1	C	2500	µF
Inductor 2	L_2	252	µH
Capacitor 2	C_2	2500	µF
Resistor	R	3.5	Ω

C. CC-CV Methods

In the battery charging process there are several methods including the constant voltage method (CV), constant current (CC), and also keeping the voltage and current values constant, known as the (CC-CV) method. The charging battery will discuss the charging method constant current-constant voltage because this method is safe. After all, it does not cause overcharging. After all, when charging moves from CC to CV, the charging current in the battery will decrease [10].

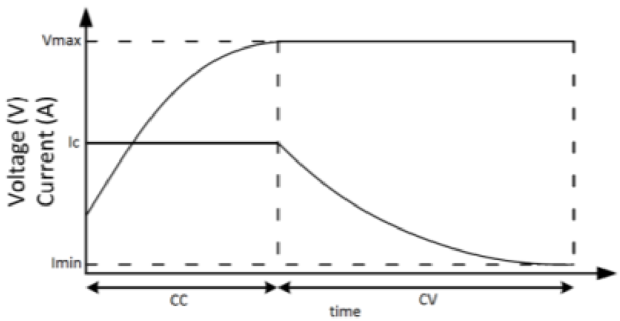


Fig. 5. Charging curve of the CC-CV method

Fig. 5 is a graph of the cc-cv charging, the constant current condition follows the constant voltage with the voltage increases because the SoC of the battery increases too, when the lead-acid battery is almost full, the voltage will be constant and the current decrease [10].

Fuzzy Logic Control Fuzzy Type-2 is a form of development of the method of Fuzzy Logic Control (FLC). The FLC method is a control system scheme that uses the concept of fuzzy set theory in its design. FLC have three stages in the FLC method such as fuzzification, inference mechanism, and defuzzification. The Type-2 Fuzzy Method has advantages over the FLC method in determining the right membership function, and modeling a variety of different data [10]. Fig. 6 is a block diagram of a type-2 fuzzy logic system:

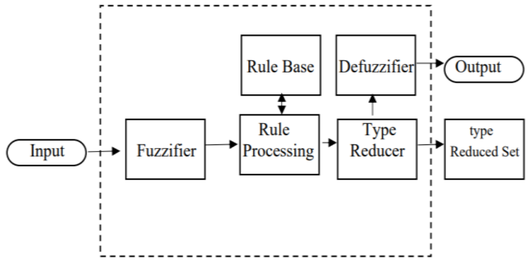


Fig. 6. The Basic Structure of the Fuzzy System.

The fuzzifier are mapped by the crisp input values $x = [x1, \ldots \ldots, xn]$ into the range of the IT2FLS. Fig. 7 shows the area on the input value of the membership function interval type-2 fuzzy logic, the result of the interval represents the cross of the upper and lower limits membership function. The rule base is the knowledge base on fuzzy logic into "if … then". The conditional "if … then" has a general form on the equation (10) with the concern on the IT2 system contains N rules [11].

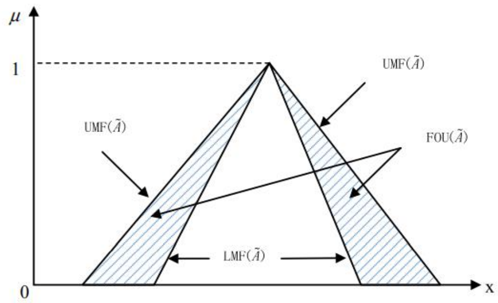


Fig. 7. upper and lower membership function

$$\underline{f}^N = \mu_{\underline{f_1^N}}(x_1) \times \mu_{\underline{f_2^N}}(x_2) \times \ldots \times \mu_{\underline{f_n^N}}(x_n) \quad (10)$$

$$f^N = \mu_{f_1^N}(x_1) \times \mu_{f_2^N}(x_2) \times \ldots \times \mu_{f_n^N}(x_n) \quad (11)$$

The big difference between traditional type-1 fuzzy logic and type-2 systems, the type-2 fuzzy logic systems have more stages with a type reduction process, which converted type-2 fuzzy sets to type-1 and then the final process on defuzzification result is the same. Karnik-Mendel (KM) type reduction [12]. The Karnik Mendel (KM) type reduction was time-consuming in real-time controlling processes and this was an iterative search process. The range of uncertainty and the secondary membership function are decided by the third dimension of footprint-of-uncertainty (FOU) and Type-2 fuzzy sets, respectively. And then the design of Type-2 FLC can offer additional degree-of-freedom to handle many uncertainties of the systems for these features [13].

(Mendel and John 2002) µA(x, u) is represented type-2 membership function in the universe of discourse X in a T2FS. If all $\mu_A(x, u) = 1$, this is called IT2FS (interval type-2 fuzzy set) [12]. The special things of the type-2 fuzzy set, it has an interval type-2 fuzzy set, which is defined as follows:

1) Fuzzification

Fuzzifier In Fuzzy Type-2, fuzzification is the process of constructing firm quantities into membership values in the IT2FLS set and generating the boundaries of LMF and UMF. UMF and LMF are fuzzy sets that have the highest and lowest values of FOU (Footprint of Uncertainties) [13], this is can describe in Fig. 7.

2) Rule Base

Rule base inference/ inference is the system of fuzzy has a function to do decision-making on the fuzzy logic's concept. The degree of membership obtained in the previous process, is then combined based on certain predetermined rules. Consequently, the interval set of the second grade belongs to the interval [0,1]. The ability to decrease the uncertainty of the system is the main feature of the type-2 fuzzy set. This is possible through a bounded region (Fig. 7) FOU (Footprint of Uncertainty) is the part of the membership function. The membership function then called FOU divided into two parts in terms of lower (LMF) and Upper (UMF) membership function type-2 fuzzy set. In the real study case, the measurement noise is the main source of uncertainty and by use of the FOU, the negative effect on the control system is possible to reduce the uncertainty [13].

3) Type reduction

Type Reduction In the main process of the logic system, this process is a special process that only Fuzzy Type-2 has and does not have Fuzzy Type-1. Karnik and Mendel were the ones who introduced type reduction. This process is called reduction because, in this process, we are taken from 10 fuzzy type-2 output sets that have been obtained into type-1 fuzzy sets. symmetric output membership functions. On fuzzy type-2 has one more step on the system is called reduction because the inference system is generated by the type-1 fuzzy set. The reduction set type is then defuzzified to get the results will be sent to the battery charging [14].

4) *Defuzzification*

Defuzzification In fuzzy type-1 defuzzification can be interpreted as a process that changes the value of the conclusion set to a firm value which then becomes the output of Fuzzy Type-1. In Fuzzy Type-2, from the previous reduction stage, the output of the reduction set is produced by the point located on the far left (yl) and the point on the far right (yr) [15].

$$y_l = \frac{\sum_{n=1}^{L} f^n y^n + \sum_{n=L+1}^{N} f^n y^n}{\sum_{n=1}^{L} f^n + \sum_{n=L+1}^{L} f^n} \qquad (12)$$

$$\bar{y}_r = y_r = \frac{\sum_{n=1}^{R} \bar{f}^n y^n + \sum_{n=R+1}^{N} f^n y^n}{\sum_{n=1}^{R} f^n + \sum_{n=R+1}^{L} f^n} \qquad (13)$$

To find the value between the right and left functions using the KM iteration algorithm (Karnik Mendel). The output value needs the defuzzification process with an equation (14) [15][16].

$$y_{(x)} = \frac{y_l + y_r}{2} \qquad (14)$$

III. Results and Discussion

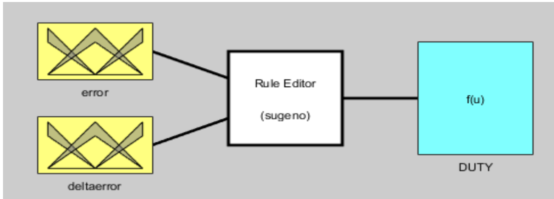
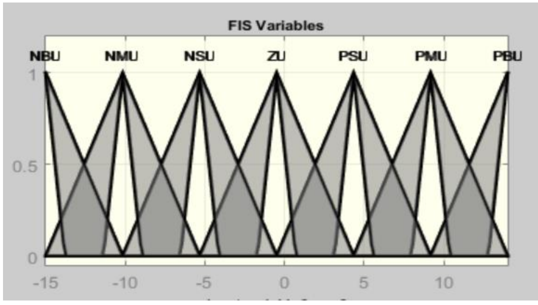
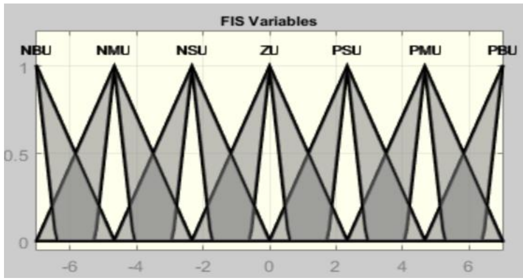


Fig. 8. The structure fuzzy logic-2

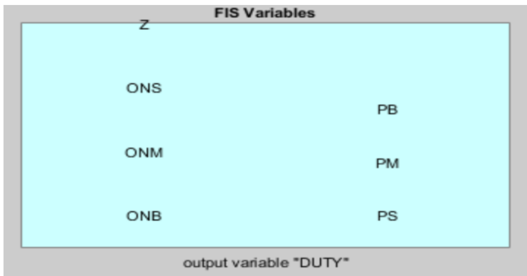
Fig. 8 is an illustration of designing a battery charging control system with input errors and delta errors. Error and delta error input will process in the rule editor of fuzzy logic type-2 with seven membership functions and 49 rule base, after the rule editor process is finished, the output is made a form duty cycle for the sepic converter to set width pulse width modulation (PWM) on MOSFET's switching.



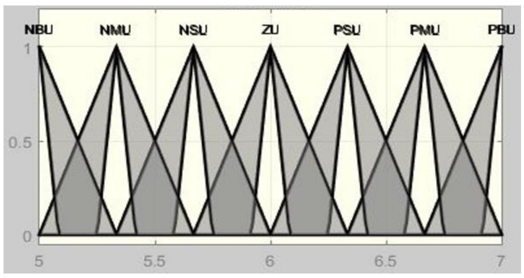
(a)



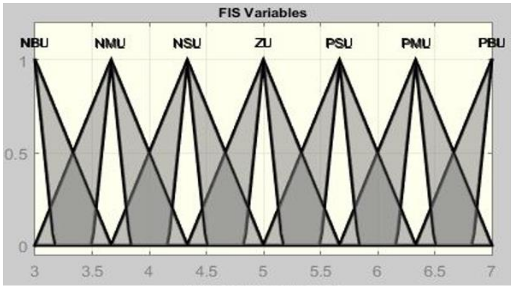
(b)



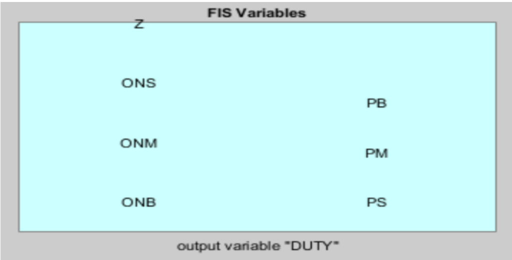
(c)



(d)



(e)



(f)

Fig. 9. Membership Error CV (a), Membership Delta Error (b), Output Variable CV (c), Membership Error CC (d), Membership Delta Error (e), Output variable CC (f).

From Fig. 9, the fuzzification inputs use a 7-membership triangular function. The membership function included negative big (NB), negative medium (NM), negative small (NS), zero (Z), positive small (PS), positive medium (PM), positive big (PB). Fuzzy type-2 has a modification from fuzzy type-1 with an upper and lower limit on membership function and has once more steps for type reduction of the system. The system has 7×7 membership functions and have 49 rules from error input and delta error input. The rules base membership functions of the system in Table II.

TABLE II. RULE BASE OF TYPE-2 FUZZY LOGIC CONTROL

E/dE	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

The simulation charging battery's current is 4 A in the constant current mode with a fuzzy type-2 algorithm. After the charging process, the full charge voltage of this system is 14 V with lead-acid battery charging. At first when the charging starts, the battery charging is in mode constant current to supply the battery with 4 A and slowly the battery's voltage will increase to 14 volts to charge, and the charging mode change to constant voltage.

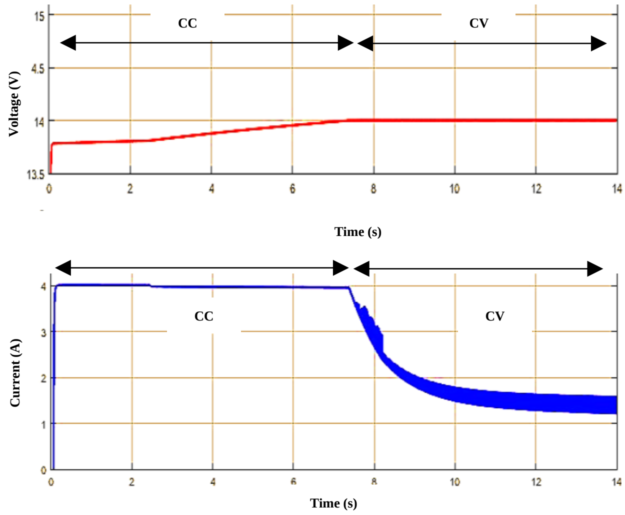


Fig. 10. Graph of cccv charging on SOC 99.60%

Fig. 10 is a CCCV charging line with a constant voltage of 14 v and a constant current of 4 amperes on SoC 99.60% at a vrla battery. On the graph constant voltage represents the red graph with constant voltage, while the constant current represents the blue graph with the current decreasing which indicates the battery is almost full with the lowest current of 1.2 A with a constant of 4.128 amperes.

TABLE III. RESULTS OF BATTERY CHARGING DATA WITH SOC AND STC CONDITION

SoC (%)	Current (A)	Voltage (V)
85	4.128	12.88
87	4.106	12.91
89	4.099	12.92
91	4.072	12.93
93	4.042	12.95
94	4.009	13.00
95	4.001	13.01
96	3.948	13.06
97	3.820	13.17
98	3.711	13.27
99	3.408	13.53
99.5	3.118	13.80
99.6	1.200	14.00
99.7	1.052	14.00
99.8	0.824	14.00

Table III shows the data from charging the CCCV battery using the fuzzy-2 algorithm with STC conditions on the solar panel with SOC starts on 85-99.8 when voltage charge at 12.88 Volt until 14.00 Volt with a current decreasing to 0.824 A and indicates the battery is fully charged.

TABLE IV. CHARGING CONDITION

SoC (%)	Current (A)	Charging Condition
85	4.128	Constant Current
91	4.072	
95	4.001	
SoC (%)	**Voltage (V)**	**Charging Condition**
99.60	14.00	Constant Voltage
99.70	14.00	
99.80	14.00	

Table IV shows CCCV charging process, the charging process starts at a constant current condition with a constant current of around 4 A, after the constant current charging process, the voltage from charging the battery will increase to a voltage value of 14 volts, so that in this process it will fulfil the constant voltage charging process. under constant voltage conditions, the current from the battery charging will slowly decrease. On voltage 14 Volt the charging method change from constant current (CC) to constant voltage (CV) mode are can be described in Fig 15 and Fig. 16.

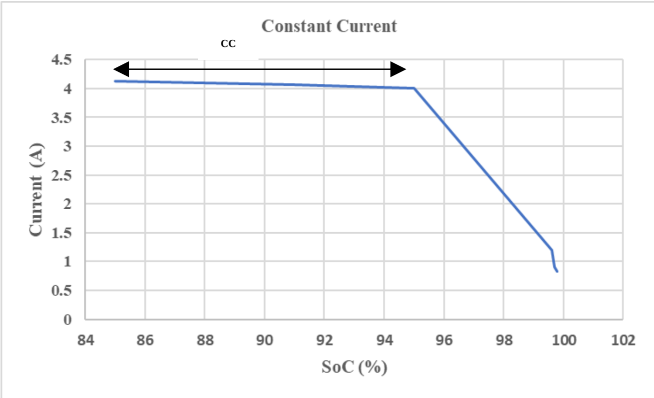


Fig. 11. Graph of constant current

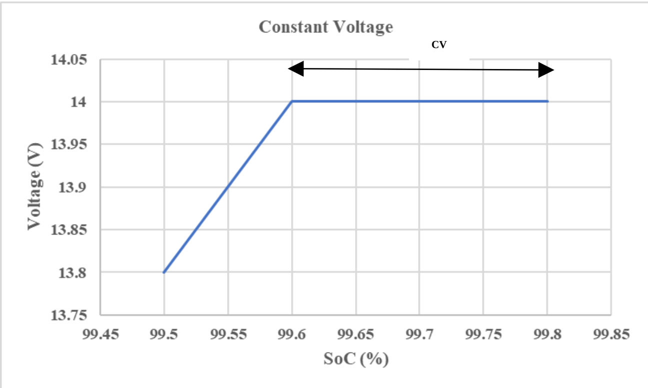


Fig. 12. Graph of constant voltage

Fig. 11 and Fig. 12 are the graph of the CCCV method constant current and constant voltage, the first step to charging using the constant current, after the voltage charge of 14 Volt so the charging process changes from constant current to constant voltage mode until the current's charging slowly decrease. Charging battery begins with constant current 4 A and switches on the constant voltage when output voltage 14 V at SoC 99.60% until battery capacity fully charged.

IV. Conclusion

In this paper it can be concluded that in charging lead-acid batteries using the CCCV charging method using fuzzy type-2 with a constant voltage of 14 volts and also a constant current of around 4 amperes with a charging shift from CC to CV methods at 99.6% SoC, this indicates that the battery is almost fully charged, so the current will drop from 4 to 0.824 ampere under constant voltage methods, The application of Sepic converter running well according to the parameter current and voltage parameters to battery charging using fuzzy type-2 and produce a tiny error for constant current 1.71% 4.128 Ampere which should 4.2 Ampere and 0% error with constant voltage 14 Volt .

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