Design and Implementation of Buck Converter for Fast Charging with Fuzzy Logic

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***Abstract*—This research presents a battery charger design that can charge faster than using a PWM type solar charge controller (SCC). SCC is often operated when the battery capacity is 80% so that the charging current that can be provided is only 10% to 20% of the battery capacity. The battery charging method applied in this study uses the principle of fast charging by adjusting the value of the current and the output voltage value of the buck converter. Fast charging has its own characteristic, obviously, the charging rate that is greater than the usual charging method, which is up to 1C of the battery capacity. The principle of fast charging in this study uses the constant current / constant voltage method. This converter is designed with the ability to produce current by the charging rate of 1C from a 12Ah battery capacity of 12 A and an output voltage of 16.8 V. To ensure that the output of the converter matches the setpoint, the duty cycle value is adjusted using fuzzy control. Based on the results obtained from the simulation, the control of this study obtained an output current 12 Amperes with error ripple current around 8.3%. The SOC on this battery increased by 75.74% in 45 minutes.**

Keywords—fast charging, fuzzy, buck convreter

I. INTRODUCTION

Electricity is a form of energy that has long been found and used for everyday life. Utilization starts with moving objects to light and many other things. Electrical energy can be generated from power plants that are now of many types such as solar power plants. It can be seen that the country of Indonesia is a country that has a tropical climate so that it has the potential to be able to utilize abundant solar energy. A solar cell (photovoltaic) is a device that can convert sunlight into electrical energy.

Solar is a potential energy source that can be renewed (renewable energy). By using solar cells, solar energy that had not been able to be used as alternative energy can be utilized as electricity that is friendly to the environment. A lot of research has been done to make solar cells as energy providers for battery charging, but not many have applied them using the principle of fast charging.

Research on the principle of fast charging has been carried out by several researchers, such as in research [1] using buck converter with the constant current method to make fast charging controllers used for charging batteries. Research [4] Battery Charging Method of Constant Current Constant Voltage Based on dsPIC30f4012. Research [5] of fast charging systems using fuzzy control. From several studies conducted battery charging with a fast-charging system but not using a source from a solar cell or using a solar cell source using a DC-DC converter without implementing a fast-charging system. So that in this study the voltage and current regulation of the solar cell to charge the battery using a buck converter by applying the principle of fast charging which is controlled by fuzzy logic control.

II. METHODS

A system design in this study will be shown in block diagram Fig.1. And, a system modeling will be explained in the following points.

A. System Design

A fast-charging system was created which can charge batteries faster than PWM type SCC, which is often used for charging batteries with solar cell sources. Fig. 1 shows the design of the fast charging system on the battery.

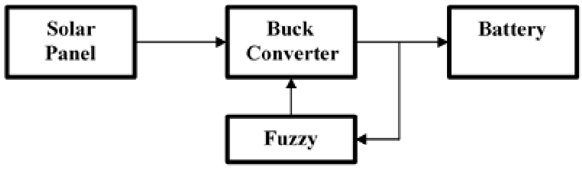

Fig. 1. Overall system

Fig. 1 shows the block diagram of the electrical system that will be examined in this study. In previous studies, the method used to charge batteries was a constant current. Because the constant current method can only maintain a stable current without regard to the converter voltage so it will greatly reduce the lifetime of the battery. Therefore, to maintain the battery life when using the fast charging method, the constant current / constant voltage (CC / CV) method is required. This method allows the battery to be charged quickly while maintaining battery life at the same time. The converter used in this research is a buck converter. The output current in this converter is kept stable first with a constant current condition, then the converter changes the condition to a constant voltage to keep the voltage stable until the battery is fully charged. The control used in this research is the fuzzy logic controller.

B. System Modelling

1) Lithium-Ion Battery

This Lithium-Ion Battery is capable of receiving a charging current greater than other types of batteries. This battery is capable of receiving a charging rate of 1C, which is the Ah capacity of the battery. The charging rate of fast charging is about 1C. Therefore this battery is suitable when fast charging is applied. The battery used in this study is 12 V 12 Ah.

SOC Battery Calculation as the following below, how to measure the State of Charge (SOC) of a battery can be done in 3 ways, that is:

1. Direct measurement, can be done if the battery can be charged at a constant value.
2. SOC from Specific Gravity (SG) measurements, this method depends on changes in measurements of the weight of active chemicals.
3. SOC estimation based on voltage is done by measuring the battery cell voltage as a basis for calculating SOC or remaining capacity.

And, how to find SOC batteries are as follows:

SOC = (Ah_max-(Ah_in+Ah_out))/Ah_max (1)

Where:

SOC = State of Charge

Ah_max = Maximum Current / Hour

Ah_in = Entering Current / Hour

Ah_out = Exiting Current / Hour

Battery modeling includes the charging process based on the battery's State Of Charge (SOC). This battery modeling uses a Thevenin equivalent circuit based on the resistive and capacitive properties of the battery [8].

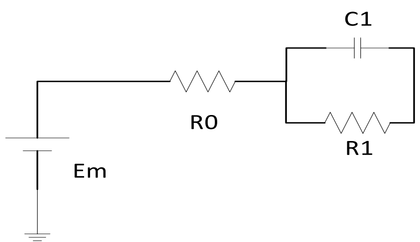

Fig. 2. Lithium-ion battery equivalent circuit

The equation of battery modeling is as follows:

$$E_m = R_0 \cdot I_t + R_1 \cdot I_t \quad (2)$$

$$I_t = I_{ct} + I_{rt} \quad (3)$$

$$\frac{I_{Ct}}{C_1} = R_1 \frac{dI_{rt}}{dt} \quad (4)$$

Where:

Em = Open Circuit Battery Voltage(V)

It = Charging Current (A)

R = Resistor (Ω)

C = Capacitor (F)

2) Photovoltaic Module

Solar cells are energy converters made from semiconductor pieces of different square centimeters in size. Some solar cells are assembled into solar panels that can convert solar energy into dc (direct current) electrical energy with a certain capacity according to the type of material and the area of the solar panel. In terms of price when compared to other renewable energy power plants, solar panels have a relatively expensive price. Therefore, the using of more solar panels in areas that are not properly covered by the electricity flow of PLN or becomes a backup energy when the main electricity source is not available. The equivalent circuit of photovoltaic can be shown in Fig. 3.

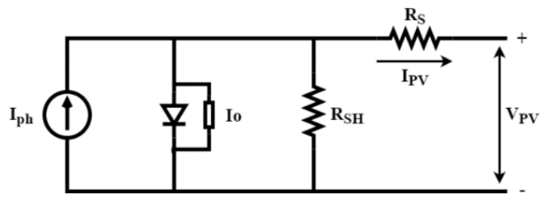

Fig. 3. Equivalent circuit of solar cell PV

The mathematical equation of the PV module can be expressed as:

$$I_{pv} = N_p.I_{pH} - N_p.I_o\left[\exp\left(\frac{q(V_{pv}+R_s.I_{PV})}{A.K.T.N_s}\right)-1\right] - N_p.\left(\frac{V_{PV}+R_S+I_{PV}}{N_S.R_{SH}}\right) \quad (5)$$

where:

I_{pv} = output power pv module (A)

V_{pv} = output voltage PV (V)

I_{PH} = generated current (A)

I_O = current reverse diode (A)

R_s = resistance series solar cell (ohm)

R_{SH} = resistance shunt solar cell (ohm)

N_P = number of paralel solar cell

N_S = number of series solar cell

Q = electront charge (1.6×10^{-19} C)

K = constant boltman (1.38×10^{-23} J/K)

TABLE I. SPECIFICATIONS OF PHOTOVOLTAIC

Parmeters	Value
Maximum Power (Pmax)	100 W
Current at Pmax (Imp)	5.72 A
Voltage at Pmax(Vmp)	17.5 V
Short circuit Current(Isc)	6.35 A
Open circuit Voltage(Voc)	22.0 V

Table I. shows data on solar panels with a maximum power of 100 Watt peak below.

3) Modelling of Buck Converter

Buck converter is a special voltage-lowering converter that applies an SMPS (Switching Mode Power Supply) system. This converter has a higher efficiency when compared to an ordinary voltage-lowering power supply (linear system). The efficiency of this converter can reach more than 90%. The buck converter utilizes the nature of the inductor for high-frequency electric shocks and works in the presence of voltage pulses (as is the case with SMPS). Therefore, in a buck converter circuit, there are always signal generators, MOSFETs, diodes, capacitors, and inductors. The basic concept of the buck converter circuit in Fig. 4 is as follows.

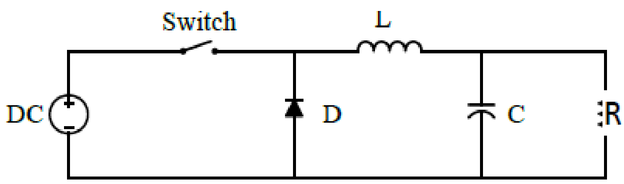

Fig. 4. The topology of buck converter

Fig. 4. is the topology of the buck converter. From this picture can be analyzed how the operation of the converter. When the MOSFET is ON (closed), the electrical energy will pass through the MOSFET and the diode becomes reverse-biased so that the electrical energy is stored in the inductor in the form of current. The diode provides a path for the inductor current when the switch is opened and is reverse-biased when the switch is closed [9].

From basic operations, we can find out the value of the system duty cycle. It is assumed that the efficiency of the circuit is 100%. So the duty cycle value can be calculated using the equation:

$$\text{Duty cycle} = \frac{\text{Vout}}{\text{Vin}} \tag{6}$$

Then what must be considered is the selection of components. The value of the selected component can be calculated using the equation:

$$I_L = \frac{V_o}{R} \tag{7}$$

$$L = \frac{(1-D)Vo}{\Delta IL \, x \, f} \tag{8}$$

$$I_{L\,rms} = \sqrt{I_L^2 + \left(\frac{\Delta I_L/2}{\sqrt{3}}\right)^2} \tag{9}$$

$$C = \frac{(1-D)}{8L\left(\Delta V_o / V_o\right) f^2} \tag{10}$$

Where:

Vin	= Input Voltage (V)
Vout	= Output Voltage (V)
I_L	= Load Current (A)
R	= Resistance (ohm)
F	= Switching Frequency (Hz)
L	= Inductor (H)
ΔIL	= Inductor Ripple Current (A)
$I_{(L\ rms)}$	= Inductor RMS Current (A)
C	= Capacitor (F)
ΔV_o	= Ripple Output Voltage (V)
D	= Duty Cycle

TABLE II. RESULTS OF BUCK CONVERTER COMPPONENT CALCULATIONS

Parameters	**Symbol**	**Value**	**Units**
Input voltage	V_{in}	35	Volt
Output voltage	V_{out}	16.8	Volt
Ouput Current	I_{out}	12	A
Inductor Ripple Current	ΔIL	2.4	A
Parameters	**Symbol**	**Value**	**Units**
Inductor RMS Current	$I_{L\,rms}$	12.02	A
Voltage ripple	ΔV_o	0.084	Volt
Switching Frequency	F_{sw}	40	Khz
Inductor	L	91	uH
Capacitor	C	89.28	uF

4) Modelling Fuzzy

Fuzzy set contains elements that have varying membership values in a set. In contrast to the control system, the resulting value is defined definitively or in other terms, only logic 0 and 1 or work in the on and off regions so that an insignificant change is obtained in the fuzzy logic control system that works between 0 and 1 can be defined so that the controller can work such as the human nervous system that can feel the external environment that is less, somewhat, ordinary, very, or even obscure can be more than that category by adding linguistic factors that are collected in the degree of membership. So by using a fuzzy logic controller, we get conveniences that are not owned by conventional control systems. There are stages called fuzzification, determination of the rule base along with the database then defuzzification. The basic concept of fuzzy shown in Fig. 5.

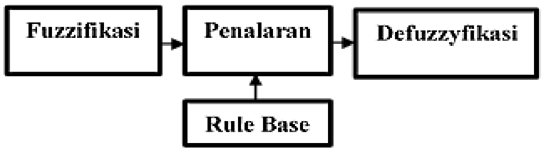

Fig. 5. The basic structure of the fuzzy system

a) Fuzzification

Fuzzification is the process of changing the input from a crisp form into fuzzy (linguistic variable) which is presented in the form of a fuzzy set with each membership function. The membership function used in this system are shown in Fig. 6. and Fig. 7. The membership function consists of 5 triangles and 2 trapezoids.

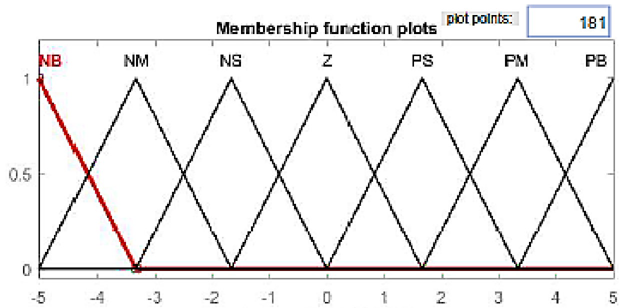

Fig. 6. Variable input error

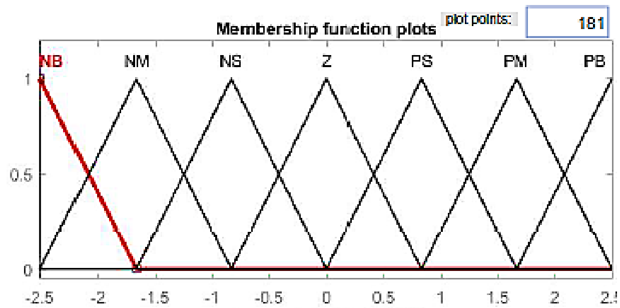

Fig. 7. Variable input delta error

b) Rule Base

Because the output from the fuzzy controller issues a duty cycle value that adjusts to the setpoint, the rule base can be determined by looking at the error and delta error values used as fuzzy input variables. The rule base is used to determine the desired control according to the plant planned by the operator. The decision-making method used in fuzzy is using the Takagi Sugeno Kang (TSK) method or what is commonly called the Sugeno Method where the rules are represented in the form of IF-THEN, and the output or system consequences are not in the form of fuzzy sets, but in the form of constants or linear equation. Table 3 shows the rule base used in this research.

TABLE III. RULE BASE

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

c) Defuzzification

The output from the rule base is still a fuzzy value, so the defuzzification part is needed to change the fuzzy value (linguistic variable) to a firm value which will then be sent to the system/plant. The defuzzification used in this system is the weighted average. In this method, each output membership function above the value indicated by each fuzzy output is truncated. Using the weighted average defuzzification method, the output singleton values are combined using average weights. This method applies to fuzzy sets with symmetric output membership functions. Fig 8 shows the membesrhip function output.

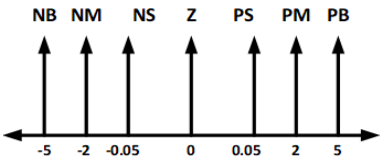

Fig. 8. Membership function output

III. RESULTS AND DISCUSSION

The purpose of this simulation is to test the performance of the system produced by fuzzy control. Fig. 9 shows the simulation of a buck converter. In this simulation, PVs are used as the power supply of the converter. The PV used in this simulation has a power of 200 WP each. This system uses 3 PVs and is arranged in parallel. So the result of the current PV output is around 17.16 Amperes and the output voltage of the PV is around 35 Volts.

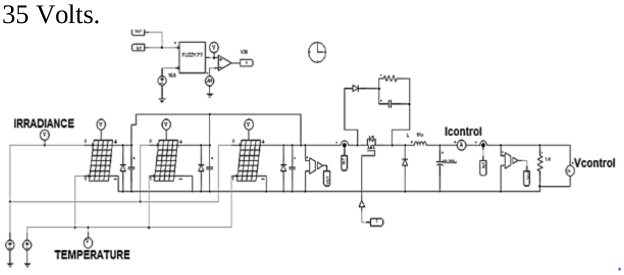

Fig. 9. Buck converter circuit

From Fig. 9. The system is simulated using 3 PVs with a power of 200 WP each. Actually 1 PV in this simulation has been set like 2 real PVs of 100 WP each installed in series. The Vmp voltage is 35 volts, and the Imp current is 5.72 amperes in each solar cell. This system is simulated using PSIM software. After simulating it can be seen the response of the system when using the control and when not using the control so that the form of the response can be compared. In this first simulation, a buck converter simulation without using control was carried out with a duty cycle of 48%. The response of the buck converter output current without control can be seen in Fig. 10 where the converter output current is not the same as the 12 A setpoint and the converter output voltage is also not the same as the 16.8 V.

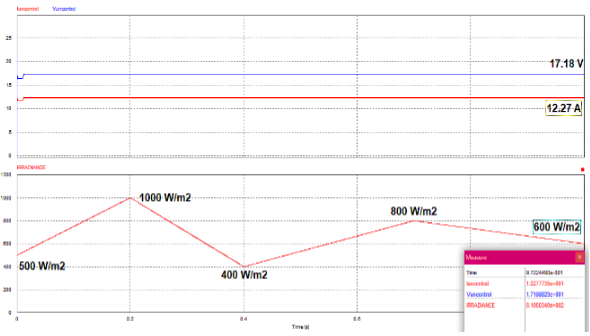

Fig. 10. System response without control for current output and voltage output on a duty cycle 48

Fig. 11 shows the simulation of a buck converter using control in constant current mode when given a disturbance in two PVs on the irradiance side. Condition 1 is given disturbance at 0, 0.2, 0.4, 0.7, 1 seconds. The resulting output current response is stable when given a disturbance.

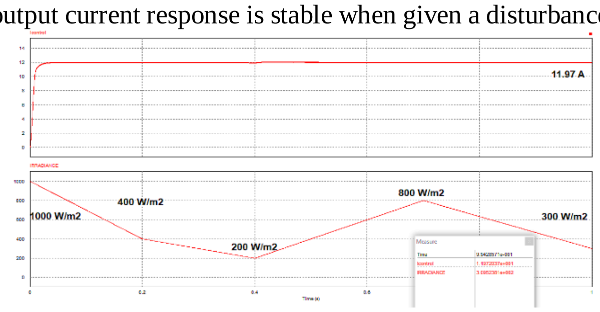

Fig. 11. Output current response when disturbed on the irradiance side

Fig. 12 shows the simulation of a buck converter using control in constant current mode when given a disturbance in two PVs on the irradiance side. Condition 2 is given disturbance at 0, 0.2, 0.4, 0.7, 1 seconds. The resulting output current response is stable when given a disturbance.

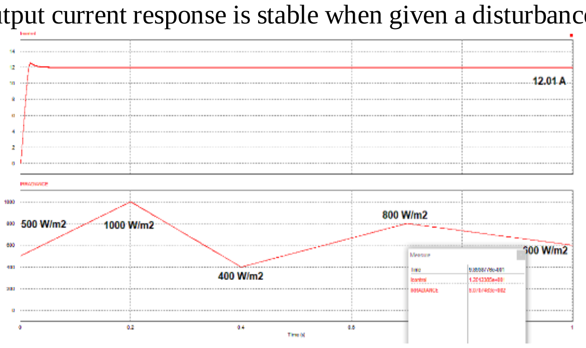

Fig. 12. Output current response when disturbed on the irradiance side

Fig. 13 shows the simulation of a buck converter using control in constant current mode when given a disturbance in two PVs on the irradiance side. Condition 3 is given disturbance at 0, 0.2, 0.4, 0.7, 1 seconds. The resulting output current response is stable when given a disturbance.

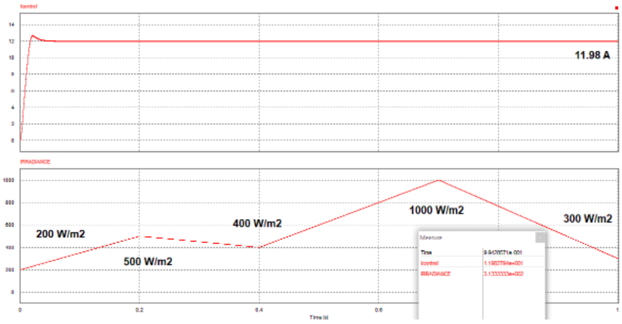

Fig. 13. Output current response when disturbed on the irradiance side

Fig. 14 shows the simulation of a buck converter using control in constant voltage mode when given a disturbance in two PVs on the irradiance side. Condition 1 is given disturbance at 0, 0.2, 0.4, 0.7, 1 seconds. The resulting output current response is stable when given a disturbance.

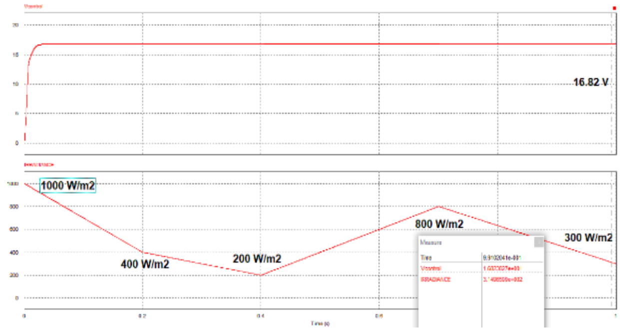

Fig. 14. Output current response when disturbed on the irradiance side

Fig. 15 shows the simulation of a buck converter using control in constant voltage mode when given a disturbance in two PVs on the irradiance side. Condition 1 is given disturbance at 0, 0.2, 0.4, 0.7, 1 seconds. The resulting output voltage response is stable when given a disturbance.

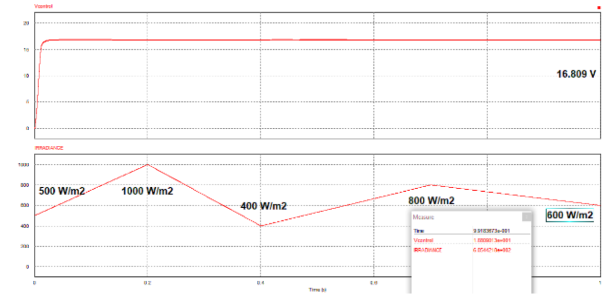

Fig. 15. Output current response when disturbed on the irradiance side

Fig. 16 shows the simulation of a buck converter using a control in constant voltage mode when given a disturbance in two PVs on the irradiance side. Condition 3 is given disturbance at seconds 0, 0.2, 0.4, 0.7, 1 seconds. The resulting output voltage response is stable when given a disturbance.

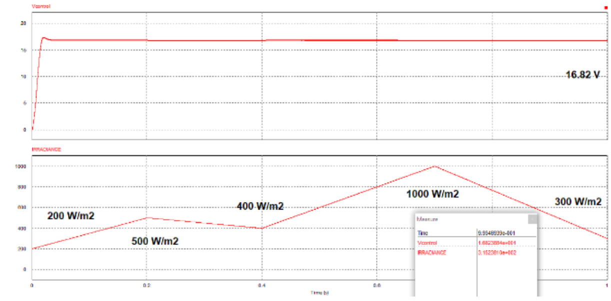

Fig. 16. Output current response when disturbed on the irradiance side

In Fig. 17, we try to control the buck converter using PI control, where the PI value is obtained from the tuning process after running open-loop simulation. Thr current output response when using control produces a stable current. Fig. 18 shows the comparison of output current response between fuzzy controlled converter (red line) and PI controlled converter (blue line). The output response generated using the PI controller has a small overshoot while the output response from the fuzzy controller doesn't. The error generated from the fuzzy control is 0.233% while the error generated from the PI control simulation is 0.258%.

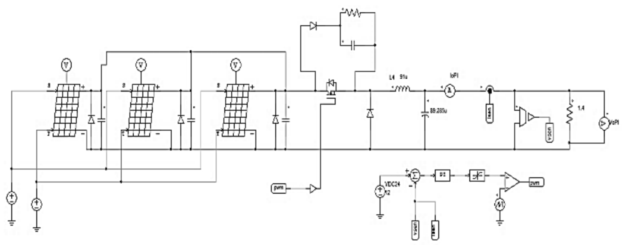

Fig. 17. Buck converter circuit with PI control

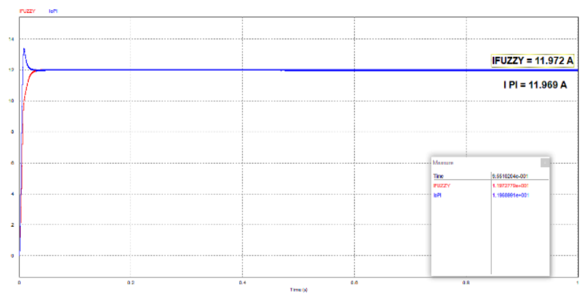

Fig. 18. Comparison of output current response between fuzzy control and PI control

TABLE IV. SYSTEM RESULTS USING THE FUZZY LOGIC CONTROLLER IN CONSTANT CURRENT MODE

Constant Current Mode				
No.	**Condition**	**Output(A)**	**Setpoint(A)**	**%Error**
1	1	11.97	12	0.25%
2	2	12.01	12	0.083%
3	3	11.98	12	0.167%

TABLE V. SYSTEM RESULTS USING THE FUZZY LOGIC CONTROLLER IN CONSTANT VOLTAGE MODE

Constant Current Mode				
No.	**Condition**	**Output(V)**	**Setpoint(V)**	**%Error**
1	1	16.82	16.8	0.119%
2	2	16.809	16.8	0.053%
3	3	16.82	16.8	0.119%

TABLE VI. COMPARISON BETWEEN PI AND FUZZY

Condition	Parameter Output Response		
	Rise Time	Settling Time	Steady State Error
PI	0.008979	0.0318367	0.26%
FUZZY	0.025306	0.0293877	0.23%

From Table 4 and Table 5 the buck converter simulation results are obtained using fuzzy logic control. Where the simulation is given interference on the Irradiance side. With a setpoint current of 12 A in constant current mode and a set point of 16.8 V in constant voltage mode, a change in condition from condition 1 to condition 3 shows that the range of error percentage output current is between 0.083 - 0.25% and the range of error percentage output voltage is between 0.053 - 0.119%. The comparison between PI control and Fuzzy control are shown in Table 6. PI control has faster rise time than Fuzzy control but has slower settling time than fuzzy control. But Fuzzy control has smaller steady state error.

Fig. 19. Simulation results of battery charging with fuzzy logic controller control

From Fig. 20. The battery charging using buck converter simulation results are obtained using fuzzy logic control. Where the specified simulation time is 2700 seconds (45 minutes). The simulation starts when the SOC is 10.04% and at the end of the simulation time the SOC is 85.78%. Current ripple error was 8.3%.

IV. CONCLUSIONS

Simulation of fast charging of buck converter with fuzzy logic control has been presented. The simulation results show that the system is functioning properly. Fuzzy control can accelerate the increase in time and keep the output of the buck converter stable. The system maintains a stable current in constant current mode and the system maintains a stable output voltage in constant voltage mode. This control has also been able to make the converter to produce current with a charge rate of 1C from the 12V 12Ah battery capacity which is 11.987 Ampere. The error for control in constant current mode ranging from 0.083-0.25%, while the error for control in constant voltage mode ranging from 0.053 - 0.119%. While the simulation of charging battery, The SOC on this battery increased by 75.74% in 45 minutes and the current error was 8.3%. This error is relatively small so that the fuzzy controller in this system can control the buck converter to produce a charging rate of 1C which is 12 Amps with decent precision.The contact type sensor installed parallel to the PD source location resulted in the impulse waveform that was more accurate than the nonparallel contact sensor. This indicates that the perfection level of impulse waveform may reveal the PD location in the oil-filled tank. The acoustic and current waveforms do not depend on each other. However, the closer electrode gap distance equivalently causes longer acoustic and current duration. In addition, the current is not influenced by the PD source location.

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