Design and Implementation of Zeta Converter for Solar Charger using Fuzzy Logic Controller

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Abstract: In this paper discusses detail design of Zeta converter as battery charging with fuzzy logic control using a Photovoltaic (PV) source. The voltage generated by the PV is unstable, a DC-DC converter is needed to regulate the input voltage to the battery. In this paper proposed a zeta converter to increase or decrease the voltage so output voltage stable for battery charging. Zeta converter is expected to reduce ripples in the output voltage and minimize voltage disturbances during switching. In this paper, the control method used is the Fuzzy Logic Controller (FLC). Fuzzy Logic Controller is effective for voltage control which is expected to produce a stable output of Zeta converter. The concept of battery charging so that the battery can be charged properly is using the constant voltage method, which is the method of charging the battery with a constant flowing voltage. The results of the calculation of energy conversion from solar panels to this proposed design require battery energy storage of 12 V / 20 AH. So, it is necessary to set the battery charging voltage 120% of the nominal battery voltage. Based on simulation result, the proposed method can maintain the output voltage according to the setting point for battery charging 14.4 volt so that the proposed method can be used as a solar charger.

1 INTRODUCTION

Solar energy is one of the renewable energy sources that has been widely developed in recent years. Photovoltaic (PV) modules are components that can convert energy obtained from the sun into electrical energy in the form of DC voltage. The electrical energy produced by PV can be used directly or stored in batteries. Utilization of batteries for solar energy storage must pay attention to the charging voltage used. In the battery charging technique with the Constant Voltage (CV) method, the charging voltage used ranges from 110% - 130% of the nominal battery voltage (Wu and Hu, 2016); (Forest et al., 2017); (Liu and Makaran, 2009).

Many types of converters can be used as battery chargers (Kumar and Jain, 2013); (Han et al., 2018); (Patnaik et al., 2018). Buck Converter is a type of converter that can lower the DC voltage (Ismail et al., 2010). This converter can be used if the input voltage is higher than the battery charge voltage. While the Boost Converter is a type of converter that can increase the DC voltage (Bendaoud et al., 2017). These two types of converters are not suitable if implemented for solar chargers (Gao et al., 2019).For the implementation of the solar charger, a converter is used that can increase and decrease the voltage, because the output voltage of PV is very volatile and depends on sunlight conditions. Buck-Boost Converter is a converter that is usually used for solar chargers (Banaei and Bonab, 2019). However, the resulting voltage ripple is large enough that it will affect the efficiency of the solar charger. The output voltage generated from this converter also has a reverse polarity. So, in this study, it is proposed to use Zeta Converter as a solar charger.

Zeta Converter can work like a Buck-Boost Converter, which can increase or decrease the incoming DC voltage based on the amount of PWM duty cycle ignited in the switching components. Zeta Converter has better performance than Buck-Boost Converter (Zhu et al., 2020); (Murthy-Bellur et al., 2010); (Sunarno et al., 2019). Zeta converter is the development of the buck boost converter by producing a low output voltage ripple and the polarity is the same with the input voltage polarity of the converter. To maintain the output voltage from the Zeta Converter to match the battery charging voltage setting point, a Fuzzy Logic

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Controller is used.

Fuzzy Logic Control (FLC) is one of the system control methods that is currently widely used. This is one of the advantages of FLC so that the controller design is easier to do by relying only on logical rules (Ismail et al., 2010); (Bendaoud et al., 2017); (Ofoli and Rubaai, 2006). In this study, FLC is used to regulate the amount of PWM duty cycle that will be ignited in the switching component. So that the proposed method can produce a stable Zeta Converter output voltage with a fluctuating PV input voltage.

2 SYSTEM DESCRIPTION

One of the dc-dc converters that can be used to adjust the voltage on the solar panels to produce maximum power on the solar panels is the zeta converter. When the voltage on the PV is less than 18.2 V, the converter will work by adjusting the duty cycle and increasing the voltage to produce a stable 14.4 V with fuzzy logic controller. When the voltage on the PV is greater than 18.2 V, the converter will adjust the duty cycle and lower the voltage.

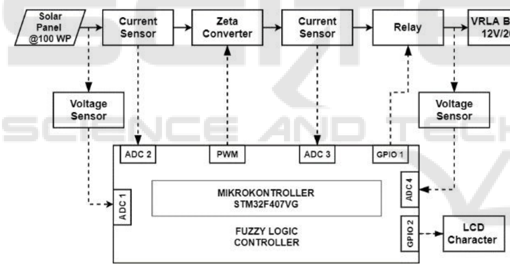

Figure 1: Design block diagram of the system.

The topology of the zeta converter battery charging system used is shown in Fig. 1. The system input is a PV with a maximum power capacity of 100 WP. During the simulation, the values of irradiance and temperature are changed to find out how the response generated by the zeta converter.

2.1 Solar Panel

Solar panels will convert the absorbed solar energy into DC electrical energy voltage. Solar panels of photovoltaic, which produces electrical energy from light intensity. The working process of solar panels begins when sunlight is captured by the PV and absorbed by p and n type semiconductor materials (p- n junction semiconductor) resulting in the release of electrons. Things that affect the amount of power produced by PV are light intensity (irradiation) and temperature of the PV module. This semiconductor consists of atomic bonds in which there are electrons as the basic constituent. Large power of photovoltaic is expressed in Watt peak (WP). The equivalent circuit of photovoltaic can be shown in Fig. 2. The mathematical equation for the PV module can be expressed as:

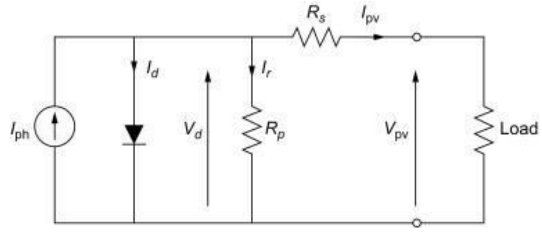

Figure 2: Equivalent circuit of PV module.

$$I = I_{ph} - I_s\left(exp\frac{q.(V+I.R_s)}{N.k.T} - 1\right) - \frac{(V+I.R_s)}{R_{sh}} \quad (1)$$

Where,

I_{pv} = output power pv module (A)
I_{ph} = generated current (A)
I_s = saturation reverse current (A)
q = electron charge ($1.6 \times 10^{-9}C$)
V = output voltage PV (V)
R_s = series resistance (Ω)
R_{sh} = shunt resistance (Ω)
K = Boltzmann constant ($1.38 \times 10^{-23}J/K$)
T = junction temperature in kelvin (K)
N = ideality factor of diode

The parameters of PV used in this system are presented in Table 1.

Table 1: Parameters of Solar Panel.

Parameter	Value
Maximum Power (P_{max})	100 W
Current at P_{max} (I_{max})	5.47 A
Voltage at P_{max} (V_{mp})	18.2 V
Short Circuit Current (I_{sc})	5.91 A
Open Circuit Voltage (V_{oc})	22.5 V
Maximum System Voltage	1000 V

2.2 Zeta Converter

Zeta converter is a fourth-order DC-DC converter made up of two inductors and two capacitors and capable of operating in either step-up or step-down mode. The Zeta converter works like a buck-boost, which can increase or decrease the incoming DC voltage based on the size of the PWM duty cycle that is ignited in the switching component. The polarity between the input and output voltages is the same and also has two operating stages in one period. The first stage is when the switch (MOSFET) is on and the others off. This converter consists of two inductors L1 and L2 and two capacitors C1 and C2, a switch (MOSFET), and a resistive load. The output of the zeta converter has a small ripple. Equivalent circuit of zeta converter as shown in Fig. 3.

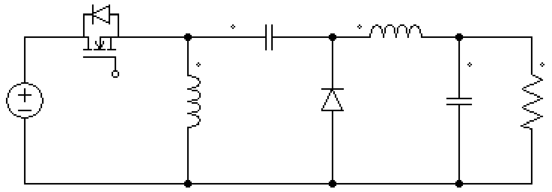

Figure 3: Equivalent circuit of Zeta Converter.

It is having two operating modes with respect to ON and OFF condition of switch zeta converter. In mode 1 switch closed condition is shown in Fig. 4.

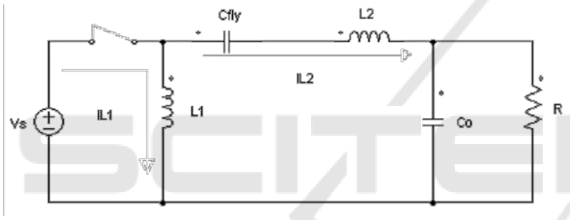

Figure 4: Mode 1.

When switch closed (ON) inductors L1 and L2 are charged and work at t_{on} start from t=0 until t=DT, The mathematical equation for a current in inductor can be expressed as:

$$\frac{dIl}{dt} = \frac{Vl}{L} \tag{2}$$

The value of the inductor current change as the end of ON condition is

$$\Delta I_{Lon} = \int_0^{DT} dIL = \int_0^{DT} \frac{Vl}{L} dt = \frac{Vi\,DT}{L} \tag{3}$$

Then further condition is in mode 2 switch open (OFF) is shown in Fig.5.

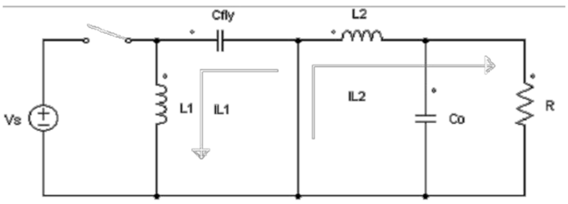

Figure 5: Mode 2.

In the switch is open (OFF), the mathematical equation for a current inductor can be expressed as:

$$\frac{dIl}{dt} = \frac{Vo}{L} \tag{4}$$

That the current changes in when the switch is open which can be written as

$$\Delta I_{Loff} = \int_0^{(1-D)T} dIL = \frac{Vo(1-D)T}{L} \tag{5}$$

Energy stored in the inductor must be the same at the beginning and the end of switching, the formula for energy in the inductor can be written in equation 6.

$$E = \frac{1}{2} L I_L^2 \tag{6}$$

The energy stored must be equal to 0 in each cycle,

$$\Delta I_{Loff} + \Delta I_{Lon} = 0 \tag{7}$$

By substitution ΔI_{Lon} andΔI_{Loff}, and assuming 100% efficiency, the duty cycle for a zeta converter operating in CCM is given by,

$$D = \frac{V_{out}}{V_{in} + V_{out}} \tag{8}$$

Where,
V_{in} = Input voltage (V)
V_{out} = Output voltage (V)
IL = The inductor current (A)
T = Period (s)
D = Duty cycle (%)
L = Inductor (H)

The parameter selection for designing Zeta converter are given in Table 2.

Table 2: Parameter of Zeta Converter.

No	Parameter	Value
1	Input Voltage	18.2 V
2	Output Voltage	14.4 V
3	Input Current	5.47 A
4	Output Current	3 A
5	Duty Cycle	44 %
6	Capacitor C_1	2291 µF
7	Capacitor C_2	102.21 µF
8	Inductor L_1	212.56 µH
9	Inductor L_2	212.56 µH
10	Load Resistance	4.8 Ω
11	Switching Frequency	40 kHz

The waveforms for voltage and current flowing through the components of the Zeta topology are shown in Fig. 6.

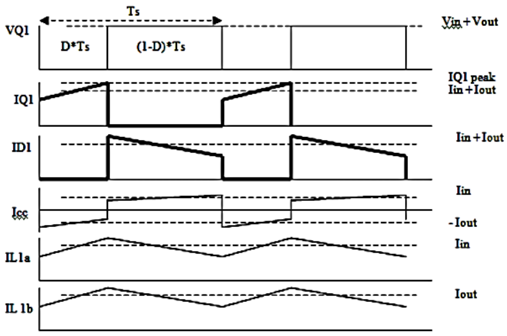

Figure 6: Waveform of current and voltage zeta converter.

2.3 Fuzzy Logic

The characteristic of fuzzy controller can be formed with a linguistic variable control rule based on the topology of the converter. To produce an output constant voltage from the zeta converter according to the set point, the role of a control is fuzzy logic. The fuzzy control will adjust the duty cycle output of zeta to produce an output voltage that matches on 14.4 V. A fuzzy controller design can be performed in 3 steps.

- **Step1:** Choose fuzzy input and output variables and their membership functions.
- **Step2:** Express the inference rules linking input and output variables.
- **Step3:** Defuzzification of the output parameter.

The fuzzy control will compare the detected output voltage value with the specified set point, that the “error” and “delta error” values are obtained. Fuzzy logic with a method used to enter an input to an output using the if-then equation. The if-then equation is the rule base of fuzzy logic.

Before making the rule base, enter the fuzzy input and output fuzzy logic first. Inside the input and output there is a membership function. The output membership function value is the duty cycle.

As the fuzzification process there are two inputs variables, input error and delta-error. The membership function input error variable is shown in Fig.7.

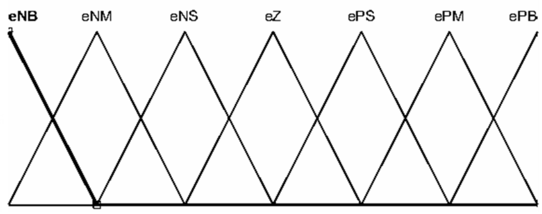

Figure 7: Membership function (error).

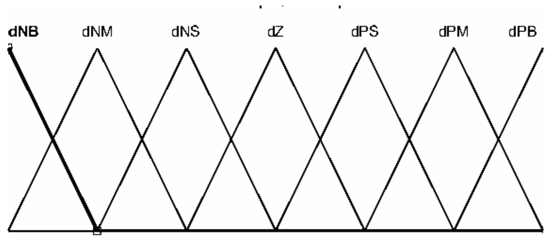

Figure 8: Membership function (delta-error).

There is also the membership function input delta-error variable show in Fig.8.

The objective of this journal is to control the output voltage of zeta converter. The error and delta-error of the output voltage will be the inputs of fuzzy logic controller. These two inputs are divided into seven groups; NB (Negative Big), NM (Negative Medium), NS (Negative Small), Z (Zero), PS (Positive Small), PM (Positive Medium), PB (Positive Big) and its parameter. These fuzzy control rule base for error and delta-error can be referred in the table that is shown in Table 3 as below:

Table 3: Rule base of fuzzy logic.

$e/\Delta e$	NB	NM	NS	Z	PS	PM	PB
NB	NB	NB	NM	NM	NM	NS	Z
NM	NB	NM	NM	NM	NS	Z	PS
NS	NM	NM	NM	NS	Z	PS	PM
Z	NM	NM	NS	Z	PS	PM	PM
PS	NM	NS	Z	PS	PM	PM	PM
PM	NS	Z	PS	PM	PM	PM	PB
PB	Z	PS	PM	PM	PM	PB	PB

The last process is defuzzification process. The output of the rule base is in the form of fuzzy values. The defuzzification process is needed to transform a fuzzy value (linguistic variable) into a value in the form of a duty cycle which is used to adjust the switching of the MOSFET converter.

In this strategy, a constant voltage is applied through battery. The charging current reduces with time until the battery voltage arrives its default value. In the experiment, charging is started at (20%) and a constant voltage is applied on the battery.

The disadvantage of this method is existence of a huge increment current in the beginning charging current, which makes this technique hazardous for charging batteries.

3 SIMULATION RESULT

The topology investigated in PSIM environment in order to check their behaviour in open loop as well as close loop configurations. This research is also being developed in real time using hardware, that the use of power parameter from each source in this simulation is adjusted to research on hardware.

3.1 Simulation Model of Zeta Converter

The simulation result of zeta converter open loop system is shown in Table 4. After being simulated, the results of zeta converter open loop simulation shown in Table 4 show that the smallest output voltage error percentage is 0% and the largest error value is 0.5 %. One of the data with a duty cycle of 44% with a fixed input voltage 18.2 V, the resulting output voltage is 14.39 V where the value is close to the set point. And the output current value is 2.99 A. In Fig.8, the output voltage waveform in an open loop produces 14.39 V and the waveform is unstable and has a ripple voltage.

Table 4: Open loop simulation results.

Duty Cycle	Vin (V)	Iin (A)	Vout Theory (V)	Vout (V)	Iout (A)	% error Vo
0.2	18.2	0.24	4.55	4.54	0.94	0.2
0.3	18.2	0.7	7.8	7.79	1.62	0.1
0.4	18.2	1.69	12.13	12.13	2.52	0
0.44	18.2	2.38	14.4	14.39	2.99	0
0.5	18.2	3.8	18.2	18.19	3.79	0.5

is in Fig.11. The results from a close loop with an irradiance value is 1000 W/m^2. The Condition of irradiance are able to produce a charging voltage of 14.4 volt and the wave results are able to steady state at conditions in accordance with the set point.

The voltage open loop of zeta converter is depicted by Fig.9.

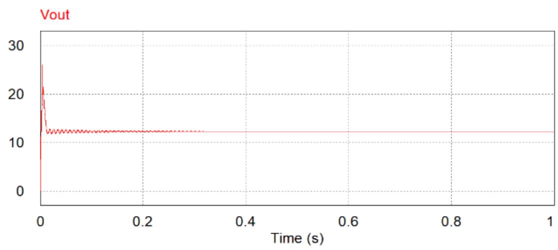

Figure 9: Output voltage open loop of zeta converter.

Simulation of zeta converter is carried out before being given control with a fixed input voltage value 18.2 V and the duty cycle value changes. The copyright form is located on the authors' reserved area.

The zeta converter simulation with fuzzy logic control as battery charging using simulation on PSIM. The second simulation is zeta converter integrated with PV and fuzzy logic control is shown in Fig.10.

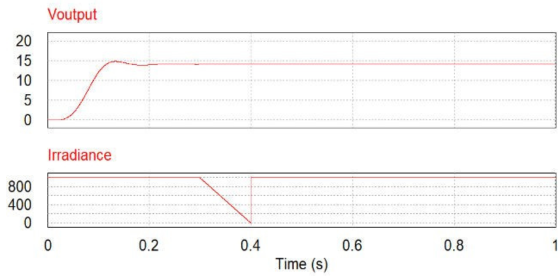

Figure 10: Zeta converter close loop simulation circuit with fuzzy logic controller.

The input source is a PV with a power of 100 WP. A load used is a resistor with a value according to the converter calculation which is assumed to be a lead acid battery. The voltage close loop of zeta converter

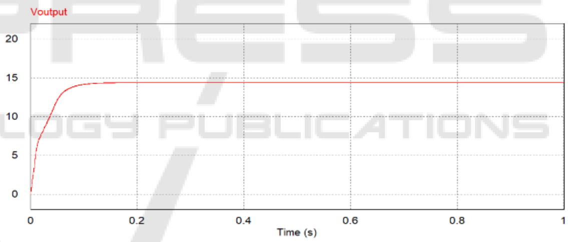

Figure 11: Output voltage close loop of zeta converter.

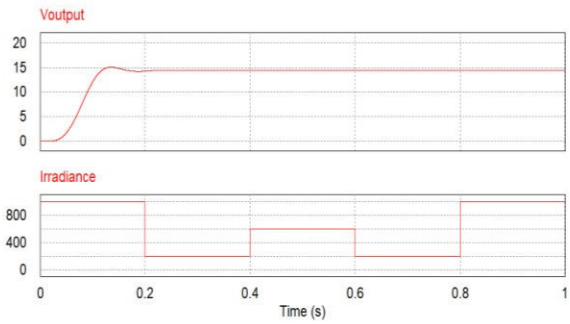

Figure 12: The relationship between voltage and irradiance.

Fig.12. is the relationship between voltage and irradiance during conditions close loop system with fuzzy logic. Can be seen that when given varies

irradiance starting from 1000 W/m2 at t=0s to 0.2s, followed by 200 W/m2 at 0.2s to 0.4s, followed by 600 W/m2 at 0.4s to 0.6s, followed by 200 W/m2at t=0.6s to 0.8s, and 1000 W/m2 at t=0.8s to 1s. The output voltage value constant at 14.4 volt.

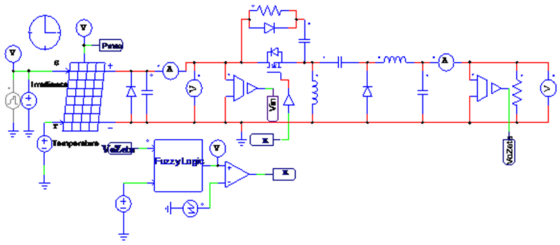

Figure 13: Output voltage response when disturbed at 0.4s on the irradiance 1000 W/m^2.

The result of the output voltage response when disturbed is shown in Fig.13. The input side of the PV being disturbed at 0.4 s. When using fuzzy logic control, the circuit produces a stable output voltage of 14.4 volts. At t=0s to t=1s using the maximum irradiance is 1000 W/m^2.

Table 5: Close loop simulation results.

Irradiance (W/ m^2)	Vin (V)	Iin (V)	Vo Setpoint (V)	Vo (V)	Iout (A)	error Vo (%)
1000	19.9	4.1	14.4	14.39	2.99	0.06
800	19.5	4.2	14.4	14.39	2.99	0.06
600	18.8	4.3	14.4	14.39	2.99	0.06
500	18.2	4.4	14.4	14.39	2.99	0.06

Comparison between open loop and close loop in Table 4 and table 5 shows that the open loop circuit has a slightly higher voltage deviation. Zeta converter close loop circuit has lower voltage deviation and has smaller voltage ripple which can prove that it is a better performance in controlling voltage with fuzzy logic for charging battery.

4 CONCLUSIONS

This paper presents design and implementation of zeta converter for battery charging using fuzzy logic controller. Based on close loop simulation, the performance of zeta converter system is able to produce a stable output voltage of 14.4 volt supplied by solar panel. Although the irradiance value varies, fuzzy logic control used 49 rule bases works according to the design for charging 12 V / 20 Ah lead acid battery with an output current of 3 A. The fuzzy logic approach to design a controller for zeta converter gives a good response output voltage in simulation. The average error value of the result of close loop simulation is 0.06 %. Zeta converter is able to stabilize and regulate the output voltage according to the desire set point.

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