MPPT based on Fuzzy Logic Controller for Photovoltaic System using PSIM and Simulink

E N Yaqin[1]*, A G Abdullah[1] , D L Hakim[1], and A B D Nandiyanto[2]

[1]Electrical Engineering Department, Universitas Pendidikan Indonesia

[2]Departemen Pendidikan Kimia, Universitas Pendidikan Indonesia

*elkonurulyaqin@gmail.com

Abstract: Maximum Power Point Tracking (MPPT) is a control technique for finding the maximum power point generated by photovoltaic system. This paper presents the design and simulation of MPPT based on Fuzzy Logic Controller for photovoltaic system. Simulations are performed on R load and battery. Batteries are modelled in equivalent circuits using trembly model. PSIM is used as the main circuit and Simulink as the control circuit connected by SimCoupler. The results show that the power can reach maximum value in various irradiance and temperature conditions, both on R load and battery.

1. Introduction

The development of technology on renewable energy is growing rapidly. One of them is solar power plant photovoltaic system. Photovoltaic power plant has many advantages, including: it does not require fuel, minimize power losses on the transmission line, free of air and sound pollution, and easy to implement in remote areas away from power plants [1][2]. Furthermore, photovoltaic power plant is suitable for use, both on home electricity usage or on grid power generation [3].

Photovoltaic has a nonlinear characteristic between current and voltage. The energy produced by photovoltaic is highly dependent on the condition of irradiance and temperature [4]. The photovoltaic system should always work at maximum power point conditions even though irradiance and temperature are changing [5]. To obtain maximum efficiency values various methods are developed, which are Solar Tracker and Maximum Power Point Tracking (MPPT) methods [6]. The Solar Tracker method works by using a mechanical system to adjust the photovoltaic in order to follow the direction of the sun [7]. However, in its application requires considerable power [8]. In the MPPT method, a controlled DC-DC converter circuit is used to reach the maximum power point [9]. This MPPT method does not require large power so it is more efficient to apply [10]. The maximum power point on a photovoltaic system can be found if the DC-DC converter is well controlled by the MPPT algorithm [11]. Some of the commonly used MPPT algorithms include: Perturb and Observe, Incremental Conductance, Open-Circuit Voltage, Short-Circuit Current, Fuzzy Logic Controller, Artificial Neural Network, and any other methods [12].

Several studies on MPPT have been investigated over the last few years. In [13], comparison of Perturb and Observe, Incremental Conductance, and Constant Voltage methods are performed under varying temperature, irradiance and load conditions. The results show that the Incremental Conductance method provides the best performance. In another study, the Perturb and Observe, Incremental Conductance, and Constant Voltage methods produced considerable oscillations. Good results are demonstrated by the artificial intelligence method which is Fuzzy Logic Controller [14]. In [15], comparison of Perturb and Observe, PI controller, and Fuzzy Logic Controller was described. Fuzzy Logic Controller gives smooth and small fluctuation signal results in steady state conditions. Furthermore, Fuzzy Logic Controller has a relatively simple design and does not require mathematical models [16]. Besides, MPPT with Perturb and Observe method was used on photovoltaic system for charging lead-acid type batteries. The results of simulation show that the system provides good performance in charging the battery [17]. Therefore, this study aims to prove that the MPPT based on Fuzzy Logic Controller for photovoltaic system can work well in various irradiance and temperature conditions, both on R load and battery.

2. System design and methods

The system configuration used in this paper is shown in Fig. 1. Voltage and current generated from the photovoltaic system, converted by buck converter in order to adapt to battery or R load characteristics. The duty cycle value of the buck converter is adjusted by the voltage and current of the controlled photovoltaic by MPPT based on Fuzzy Logic Controller (FLC) to get maximum power.

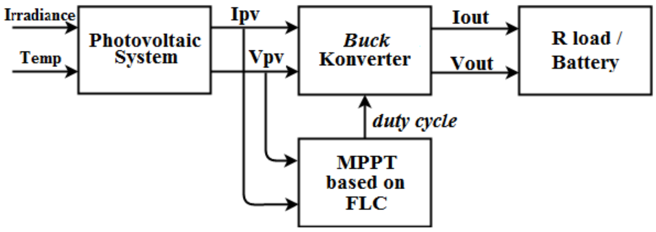

Figure 1. MPPT system configuration.

Further explanation of the used method has been divided into five parts: photovoltaic model, battery model, buck converter design, fuzzy logic controller design, and SimCoupler usage.

2.1. Photovoltaic model

In general, photovoltaic can be modelled as an equivalent circuit as in Fig. 2 with the mathematical equations of Eq. (1) to Eq. (5) [18].

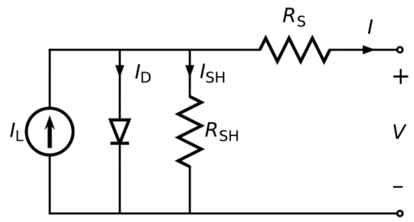

Figure 2. Photovoltaic equivalent circuit.

$$I_T = N_p I_L - N_p I_{sat}[\exp\left\{\frac{q(V_{mpp}+(I_{mpp}.R_S))}{N_S.A_D.k.T_{pv}}\right\} - 1] \quad (1)$$

$$I_L = [I_{sc} + K_i(T_{pv} - T_r)]\frac{\lambda}{1000} \quad (2)$$

$$K_i = \frac{I_{sc} \cdot I_{scTC}}{100} \quad (3)$$

$$I_{sat} = I_{rs}[\frac{T_{pv}}{T_r}]^3 \exp\left[\frac{qo.Eg}{A_D.k}\left\{\frac{1}{T_r} - \frac{1}{T_{pv}}\right\}\right] \quad (4)$$

$$I_{rs} = \frac{I_{sc}}{[\exp\left\{\frac{q.V_{OC}}{N_S.A_D.k.T_{pv}}\right\} - 1]} \quad (5)$$

With I_T as the total current generated, I_L as the current generated photovoltaic, I_{sc} as the short circuit current, I_{scTC} as the short circuit current in the coefficient temperature, I_{sat} as the saturation current of the diode, I_{rs} as module reverse saturation current, λ as irradiance, T_{pv} as photovoltaic temperature, T_r as temperature reference = 298.15°K, A_D as ideality factor, E_g as band gap, K_i as photovoltaic module short circuit current, N_s as the number of cells in 1 module (series), N_p as the number of cells in 1 module (parallel), I_{mpp} as the current at maximum power, V_{mpp} as the voltage at maximum power, q as the electron charge = 1.6 x 10^{-19}C, q_o as the constant = 1.6 x 10^{-19}J/eV, k as Boltzmann constant = $1{,}3805x10^{-23}$J/K, V_{oc} as a voltage in the open circuit, R_S as a series resistance, and R_{sh} as parallel resistance.

The photovoltaic used is a product from ASE Americas, Inc. with two ASE-50-DG/16 models connected in parallel. The specification of the photovoltaic is shown in Table 1. The characteristics generated by photovoltaic depend on the irradiance and temperature conditions. Fig. 3 shows the characteristic curve of power to the voltage on the irradiance variation with temperature 25°C. Fig. 4 shows the characteristic curve of power to the voltage on the variation temperature with irradiance 1000 W/m^2.

Table 1. Photovoltaic Specification

Photovoltaic	ASE Americas, Inc.
Model	ASE-50-DG/16
Open circuit voltage	20.2 Vdc
Short circuit current	3.3 Adc
Voltage at maximum power	16.8 Vdc
Current at maximum power	3.0 Adc
Maximum power	50 Wdc

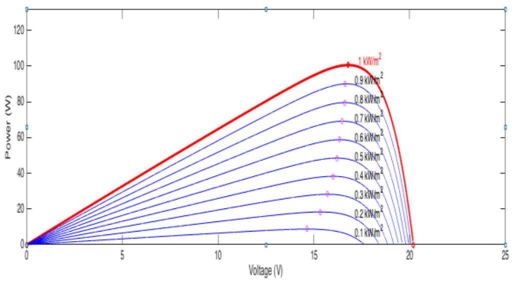

Figure 3. P-V curve at irradiance varies.

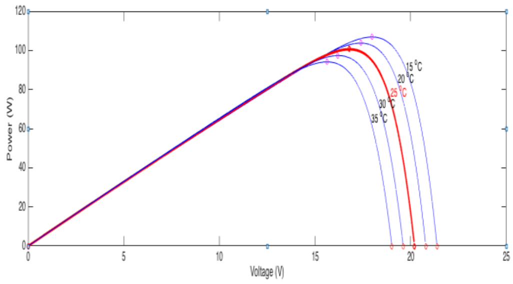

Figure 4. P-V curve at temperature varies.

2.2. Battery model

Battery modelling can be presented as experimental, electrochemical, and equivalent circuit. However, experimental and electrochemical models cannot represent the State of Charge (SOC) in batteries, whereas equivalent circuit model can represent SOC and voltage characteristics of the battery. SOC is a representation of both storage and the usage in percent. In the equivalent circuit model, the batteries are modelled by a controlled voltage source connected in series with resistors as in Fig. 5 with the equations shown in Eq. (5) to Eq. (10) [19][20].

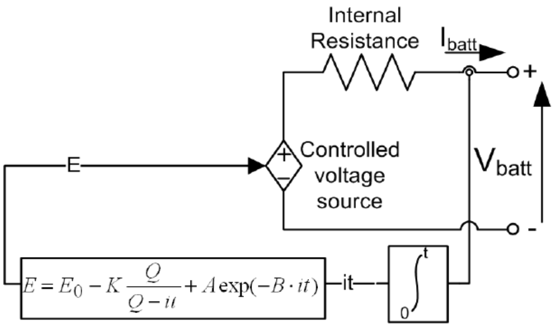

Figure 5. Battery equivalent circuit [19].

$$E = E_o - K\frac{Q}{Q-\int I_t dt} + A.exp(-B\int I_t\, dt) \quad (5)$$

$$E_o = V_{full} + K + R_i - A \quad (6)$$

$$K = \frac{(V_{full} - V_{nom} + \left(A\left(exp(-B.Q_{nom})\right)\right) - 1)).(Q - Q_{nom})}{Q_{nom}} \quad (7)$$

$$A = V_{full} - V_{exp} \quad (8)$$

$$B = \frac{3}{Q_{exp}} \quad (9)$$

$$SoC = \frac{Q - \int I_t dt}{Q} \quad (10)$$

With E as the no-load voltage, E_0 as the battery constant voltage, V_{nom} as the nominal voltage, V_{exp} as the exponential zone voltage, V_{full} as the full voltage, Q as the battery capacity, Q_{nom} as the nominal battery capacity, Q_{exp} as the exponential zone battery capacity, R_i as the internal resistance, $\int I_t\, dt$ as the actual battery charge, K as the polarization resistance, A as the exponential zone amplitude, and B as the exponential zone time constant inverse.

The battery used is a product of GS Astra with a 55D26R/N50Z model of three pieces which are connected in parallel. Each battery has a 60Ah charge capacity and a 12V voltage. The parameters used in battery model are shown in Table 2. The battery modeling test is conducted by providing a current source of 9A for the charging process, while the discharging process is modeled by installing a resistor load of 1.4Ω. The characteristics generated from the model are shown in Fig. 6 and 7.

Table 2. Battery Parameter

Parameter	Value
Q	180 Ah
V	12 V
A	0.8 V
B	0.078 $(\text{Ah})^{-1}$
E_o	13.69 V
R_i	8.3 mΩ
K	0.164 V

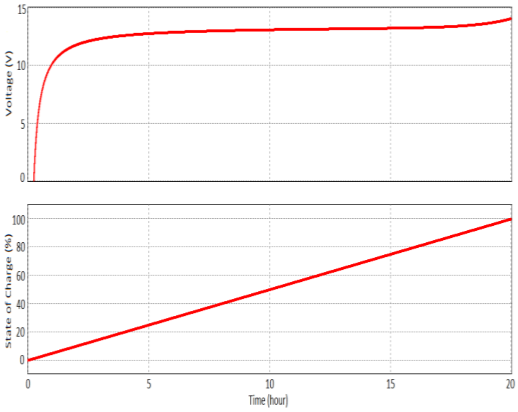

Figure 6. Charging condition.

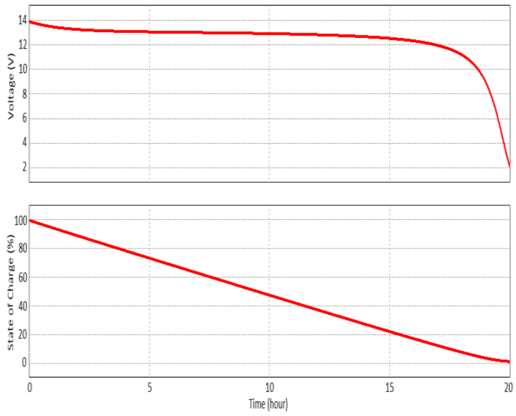

Figure 7. Discharging condition.

2.3. Buck converter design

Buck converter is used as a step down voltage that connects the photovoltaic to the battery as well as to the R load. The main circuit of the buck converter consists of inductors, capacitors, diodes, and electronic switches that can be MOSFETs. The circuit is shown in Fig. 8 whereas the determination of its parameter values is shown in Eq. (11) to Eq. (13) [21].

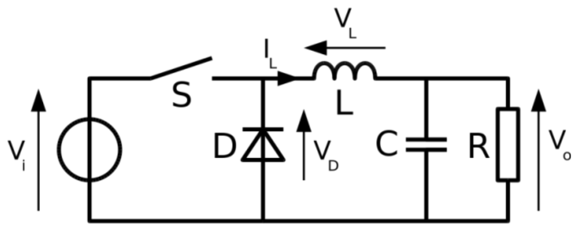

Figure 8. Buck converter circuit.

$$V_o = V_i . D \qquad (11)$$

$$L = \frac{V_o(1-D)}{\Delta i_L . f} \qquad (12)$$

$$C = \frac{1-D}{8L\left(\frac{\Delta V_o}{V_o}\right)(f^2)} \qquad (13)$$

With V_o as the output voltage, V_i as the input voltage, D as the duty cycle, L as the value of the inductor, f as the frequency on the switch, Δi_L as the ripple current on the inductor, C as the value of the capacitor, and ΔV_o as the output voltage ripple.

To make the system includable in all conditions, the applied voltage value is the highest one. The voltage value becomes a reference to determine the value of duty cycle, inductor, and capacitor. It is assumed that the ripple on the inductor current is 0.1% and the ripple at the output voltage is 0.2%. The parameter values of the buck converter used are shown in Table 3.

Table 3. Buck Converter Parameter

Parameter	Value
f	50 kHz
L	4.9 mH
C	0.71 uF

2.4. Fuzzy logic controller design

In the MPPT configuration, Fuzzy Logic Controller (FLC) is used to determine the duty cycle of the buck converter. In general, the input on the FLC is error value and changes in error. The main parts of the FLC include: fuzzification, system inference, rule base and defuzzification. The block diagram of the FLC is shown in Fig. 9.

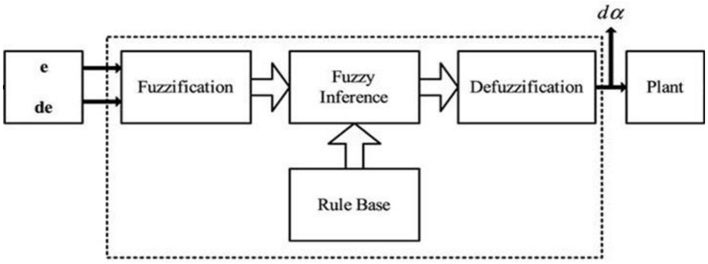

Figure 9. Block diagram of Fuzzy Logic Controller.

The value of error and changes in error used, obtained from the value of current and voltage generated by photovoltaic. The value is defined in Eq. (14) and Eq. (15) [22].

$$e(k) = \frac{P(k)-P(k-1)}{V(k)-V(k-1)} \quad (14)$$

$$\Delta e(k) = e(k) - e(k-1) \quad (15)$$

With e(k) as the error value at the (k) sampling time, e(k-1) as the error value at the (k-1) sampling time, and $\Delta e(k)$ as the changes in error, as well as the value of power (P), and voltage (V).

Fuzzy logic inference system and membership functions used in the fuzzy set in both form and number are initialized based on trial and error method [23]. Fuzzification of error values and changes in error is shown in Fig. 10 and 11, while defuzzification of the changes in duty cycle values is shown in Fig. 12. The rule base used are shown in Table 4.

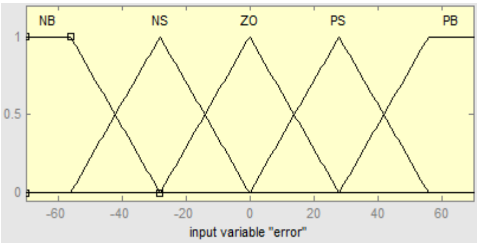

Figure 10. Membership function plots for error.

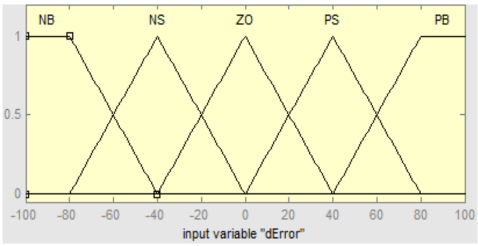

Figure 11. Membership function plots for changes in error.

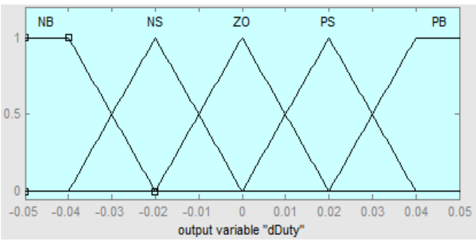

Figure 12. Membership function plots for changes in duty cycle.

Table 4. Rule base.

E\dE	NB	NS	ZO	PS	PB
NB	ZO	ZO	PB	PB	PB
NS	ZO	ZO	PS	PS	PS
ZO	PS	ZO	ZO	ZO	NS
PS	NS	NS	NS	ZO	ZO
PB	NB	NB	NB	ZO	ZO

2.5. SimCoupler

Designing of photovoltaic model, buck converter, and battery are simpler to do on PSIM than Simulink. However Fuzzy Logic Controller cannot be designed on PSIM. SimCoupler is a plug-in that could help to connect Simulink with PSIM [24][25]. SimCoupler's Simulink usage is shown in Fig. 13, while in PSIM shown in Fig. 14.

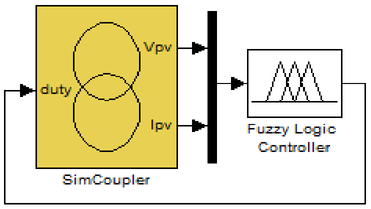

Figure 13. SimCoupler's Simulink usage.

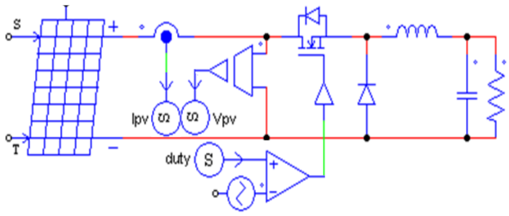

Figure 14. SimCoupler's PSIM usage.

3. Results and discussion

Simulations are performed on R load of 2,644Ω and on previously described batteries (part 2.2). Conditions used are on various irradiance and temperature. The first condition is carried out at temperature 25°C and irradiance varies in order of 1000W/m^2, 500W/m^2, 800W/m^2, 300W/m^2, 700W/m^2, 200W/m^2, 600W/m^2, 900W/m^2, 400W/m^2, dan 100W/m^2. The second condition is carried out at irradiance 1000W/m^2 and temperature varies with temperature rise of 5°C in the range of 15°C to 35°C. The main circuit with the R load is shown in Fig. 15, whereas the battery is shown in Fig. 16. The control circuit in Simulink is shown in Fig. 17. The results of the simulation on R load are discussed in part (3.1) and the results of the battery simulation are discussed in part (3.2).

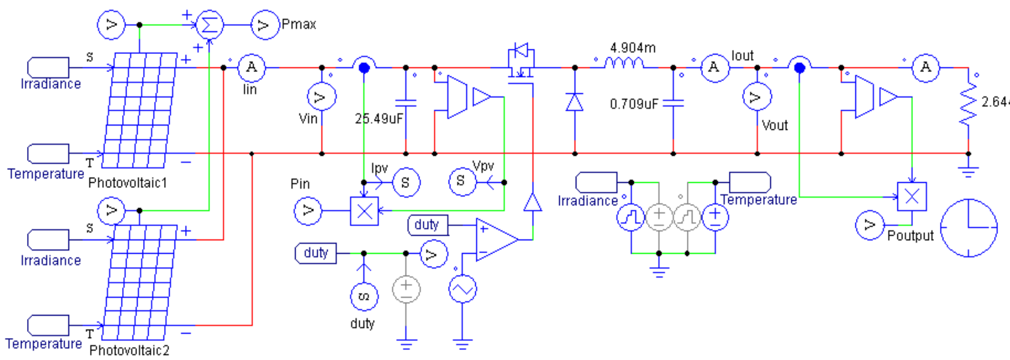

Figure 15. Main circuit of R load test.

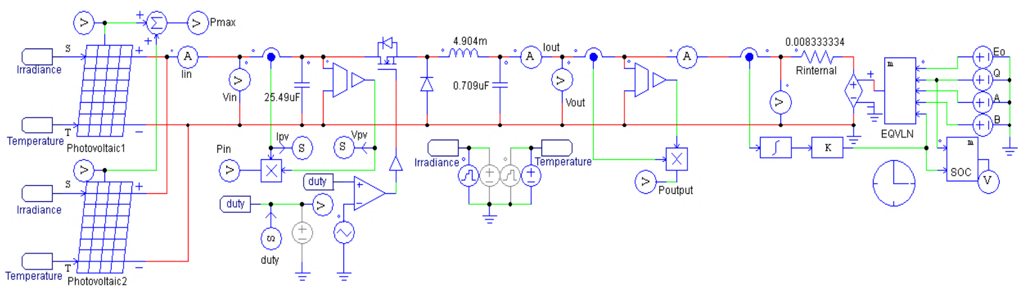

Figure 16. Main circuit of battery test.

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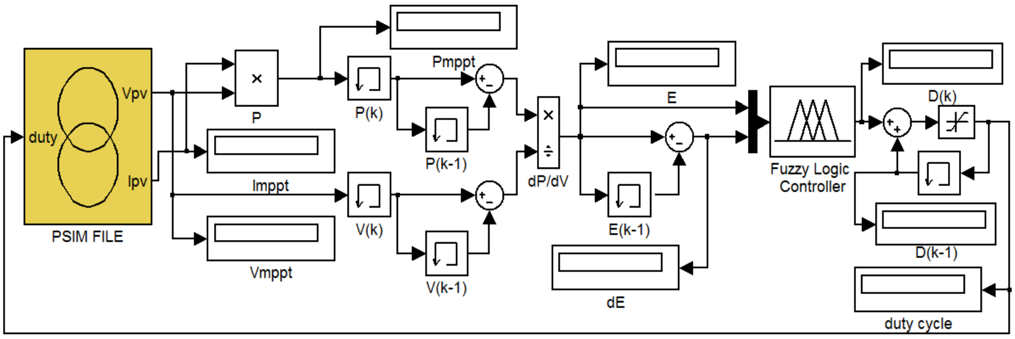

Figure 17. Control circuit.

3.1. R load test

Simulation results on the first conditions with varying irradiance are shown in Fig. 18 (without MPPT) and Fig. 19 (with MPPT). The blue color is the maximum reference value of the photovoltaic while the red color is the generated power from the simulation. The effect of MPPT on this condition is evident from the resulting power curve. Without MPPT, maximum power can be achieved only under 1000W/$\boldsymbol{m}^2$ irradiance conditions. This is because the used R load is in the maximum state under STC. In the use of MPPT, the resulting power can achieve maximum value well.

Simulation results on the second condition with varying temperatures are shown in Fig. 20 (without MPPT) and Fig. 21 (with MPPT). In this condition the effect of MPPT is not so significant. This is because the temperature variation does not affect the generated power, so that the R load is still close to the maximum power point.

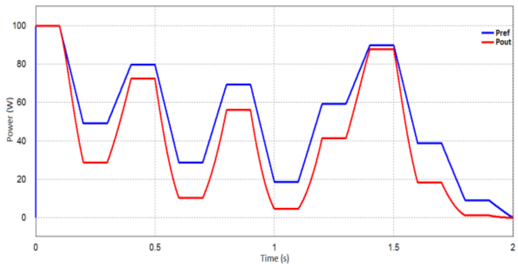

Figure 18. Results of R load test in various irradiance (Without MPPT).

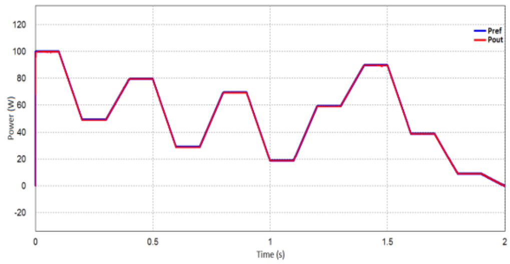

Figure 19. Results of R load test in various irradiance (With MPPT).

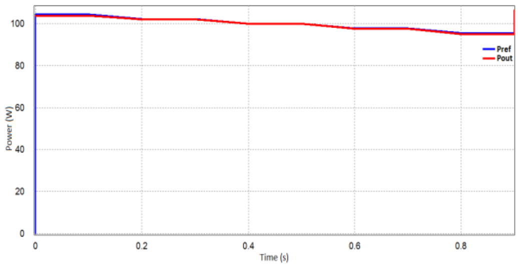

Figure 20. Results of R load test in various temperature (Without MPPT).

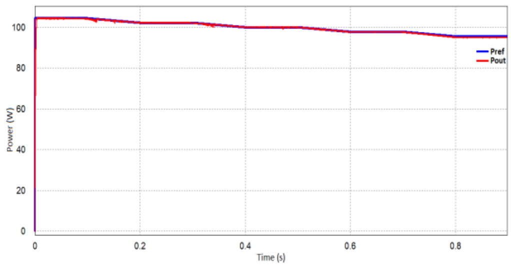

Figure 21. Results of R load test in various temperature (With MPPT).

From the simulation test results shown in Fig. 18 to Fig. 21, the power comparison of each condition is shown in Table 5 and Table 6.

Table 5. Power comparison in various irradiance (R load)

Irradiance (W/m^2)	Temp (°C)	Without MPPT (W)	With MPPT (W)	Reference (W)
1000	25	100.00	99.99	100.00
500	25	28.77	49.04	49.11
800	25	72.44	79.69	79.70
300	25	10.36	28.72	28.76
700	25	56.19	69.47	69.46
200	25	4.61	18.71	18.74
600	25	41.41	59.25	59.29
900	25	87.96	89.85	89.86
400	25	18.42	38.85	38.91
100	25	1.15	8.94	8.95

Table 6. Power comparison in various temperature (R load)

Irradiance (W/m^2)	Temp (°C)	Without MPPT (W)	With MPPT (W)	Reference (W)
1000	15	103.82	104.4	104.41
1000	20	102.08	102.22	102.22
1000	25	100.00	99.99	100.00
1000	30	97.64	97.64	97.78
1000	35	95.06	95.06	95.52

3.2. Battery test

Fig. 22 and 23 show the simulation results under the first condition with varying irradiance. In Fig. 22 the simulation is conducted without MPPT while in Fig. 23 the simulation is done by using MPPT. Without MPPT, maximum power can be achieved only under irradiance conditions of $100W/m^2$ and $200W/m^2$. This is because the generated voltage by the photovoltaic is close to the battery voltage. In the use of MPPT, the power generated can follow the reference value well.

Simulation results on the second condition with varying temperature are shown in Fig. 24 (without MPPT) and Fig. 25 (with MPPT). Unlike the R load, the effect of MPPT is evident under these conditions. This is because the generated voltage by the photovoltaic tends to be different with the battery voltage.

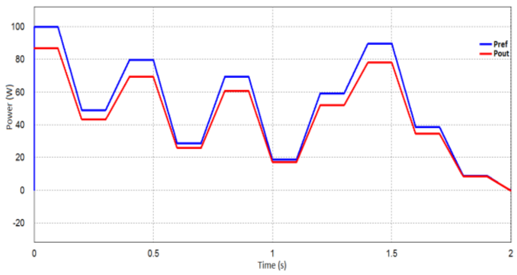

Figure 22. Results of battery test in various irradiance (Without MPPT).

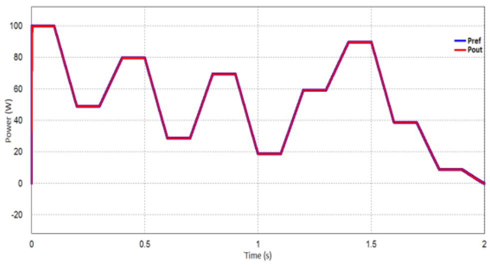

Figure 23. Results of battery test in various irradiance (With MPPT).

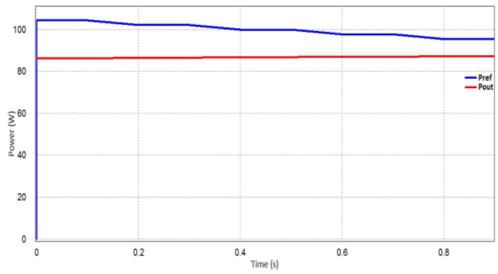

Figure 24. Results of battery test in various temperature (Without MPPT).

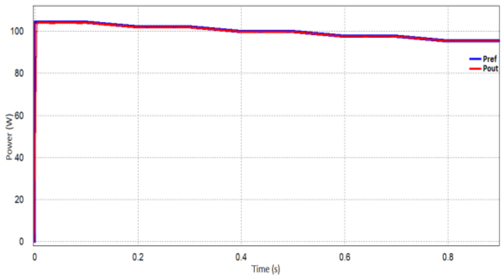

Figure 25. Results of battery test in various temperature (With MPPT).

From the simulation test results shown in Fig. 22 to 25, a power comparison is obtained for each of the conditions shown in Table 7 and Table 8.

Table 7. Power comparison in various irradiance (Battery)

Irradiance (W/m^2)	Temp (°C)	Without MPPT (W)	With MPPT (W)	Reference (W)
1000	25	86.91	99.82	100.00
500	25	43.31	49.08	49.11
800	25	69.46	79.66	79.70
300	25	25.91	28.75	28.76
700	25	60.74	69.47	69.47
200	25	17.21	18.73	18.74
600	25	52.02	59.28	59.29
900	25	78.19	89.8	89.86
400	25	34.61	38.89	38.91
100	25	8.52	8.94	8.95

Table 8. Power comparison in various temperature (Battery)

Irradiance (W/m^2)	Temp (°C)	Without MPPT (W)	With MPPT (W)	Reference (W)
1000	15	86.29	104.15	104.41
1000	20	86.63	101.98	102.22
1000	25	86.91	99.82	100.00
1000	30	87.12	97.63	97.78
1000	35	87.22	95.42	95.52

4. Conclusion

The paper has presented the design and simulation of MPPT based on Fuzzy Logic Controller for photovoltaic system using PSIM and Simulink. It can be concluded that the use of MPPT in photovoltaic system can work well on various irradiance and temperature, either at R load or battery. The resulting average efficiency on a system with R load in temperature varies is 99.85%, and in irradiance varies is 98.71%, while on a system with battery in temperature varies is 98.81%, and in irradiance varies is 99.01%.

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