ANFIS-based MPPT Controller Design on Boost Converter to Improve Photovoltaic System Performance

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ABSTRACT

The efficiency of the photovoltaic system is very low ranging from 9-17% in areas with low irradiation while the investment costs are quite high. In addition, the power output of the photovoltaic system is highly volatile due to change in irradiation, weather, cloud movement, and temperature. This research proposes the MPPT method based on ANFIS in the photovoltaic system for transient behavior analysis and system efficiency improvement. The results of the proposed method were compared with the MPPT Perturb & Observe (P&O) method. Each MPPT method was applied to a boost converter connected to a photovoltaic module with a capacity of 150 Wp to adjust the duty cycle using Simulink simulation in MATLAB. The irradiation and temperature data for 3 consecutive days were from Saturday to Monday, September 4 to 6, 2021. The simulation results show that the transient time of ANFIS MPPT is 6.23 times faster than that of P&O MPPT. The efficiency of ANFIS-based MPPT is higher than MPPT P&O. At 917.3 W/m2 of irradiation, the output power of the boost converters are 132.09, and 111.69 Watt for the ANFIS-based MPPT controller, and the P&O method MPPT, respectively.

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1. INTRODUCTION

Indonesia has an average solar energy potential of 3.45 -5.74 kWh/m2 per day. West Nusa Tenggara as one of the provinces in Indonesia that has the potential for solar energy above the national average, which is 3.76 -5.94 kWh/m2 per day [1]. This encourages the development of new innovations in building photovoltaic systems. The main obstacle in the development of solar power plants is the investment cost of the photovoltaic system. Besides that, because the efficiency of solar power plants is very low in the range of 9 - 17% in areas with low irradiation [2]. In addition to low irradiation, the efficiency of the photovoltaic system is also influenced by environmental factors such as temperature, solar radiation illumination, humidity and the inappropriate position of the photovoltaic module to the earth [3]. To improve the performance of photovoltaic systems, several studies have been carried out, one of which is the development of the Maximum Power Point Tracking (MPPT) method, both in hardware and software. MPPT has an important role to optimize the operation of photovoltaic systems in various weather conditions.

The maximum power tracking technique is important for two reasons, firstly because of the position of the panels on the earth's surface and secondly because of the nonlinearity of the photovoltaic cells. The right panel position to get optimum irradiation, while getting maximum power transfer requires a controller that can change the load resistance to be the same as the photovoltaic module's internal resistance. The photovoltaic system placed above the house with the same slope as the roof of the house produces a less than optimum output power [3]. The placement of the panels also has an impact on the temperature of the panels, where the temperature of the solar panels affects the efficiency, the higher the temperature the lower the efficiency and vice versa [4]. The conventional MPPT method can increase the efficiency of photovoltaic systems such as the MPPT P&O method and IC on a 1500 Wp solar cell using a SEPIC converter. The output power of the system using the P&O method is greater than that of the IC at the same irradiation, but the transient time of the IC is shorter than that of the P&O at the sudden change of irradiation [5]. With the development of artificial intelligence techniques, controllers for MPPT are updated with intelligence techniques. Artificial intelligence techniques such as Fuzzy Logic, Neural Network and ANFIS can produce better tracking speed than conventional methods [6]. Power converters for DC/DC systems such as boost converters in photovoltaic systems are controlled with the Adaptive Neuro Fuzzy Inference System MPPT to get high efficiency [7]. The DC/DC converter is coupled with an inverter for connection to the grid, conventional MPPT methods such as P&O can work optimally [8]. MPPT based on fuzzy logic generates a duty cycle for boost converter control. The simulation on the MPPT is to determine the effect of changes in the value of the capacitor in the converter output circuit on the solar panel output power. As a result, at 1000 W/m2 irradiation, the smaller the capacitor value, the larger the resulting power ratio [9]. MPPT Fuzzy Logic control method is also better than Hill Climbing method in terms of transient time [10]. However, when compared to the MPPT of the Artificial Neural Network method, the MPPT of the Fuzzy Logic method has a smaller power ratio [11]. The MPPT algorithm is fully reviewed from conventional techniques, artificial intelligence and swarm optimization such as particle swarm optimization, Gray Wolf Optimizer-Crow Search Algorithm and its monitoring system to facilitate understanding of control techniques in MPPT [12].

This study aims to design an ANFIS-based MPPT controller on a boost converter to improve photovoltaic system performance. The assessed system performance is the output power of the boost converter and the transient time due to sudden changes in irradiation. The MPPT Perturb & Observe (P&O) method was used as a comparison method. To describe the results of this research, this article is compiled in the first part is an introduction, followed by a boost converter for photovoltaic systems, and the ANFIS-based MPPT controller design procedure in parts 2 and 3, respectively. Part 4 is the results and discussion, and part 5 is the conclusion.

2. BOOST CONVERTER FOR PHOTOVOLTAIC SYSTEM

A Boost converter is a DC-DC converter to increase the output voltage from the source. This converter is required to meet load voltage requirements and reduce load current. It is cheaper to invest in cables for supplying power from a source to load. Fig. 1 is the topology of the boost converter [13].

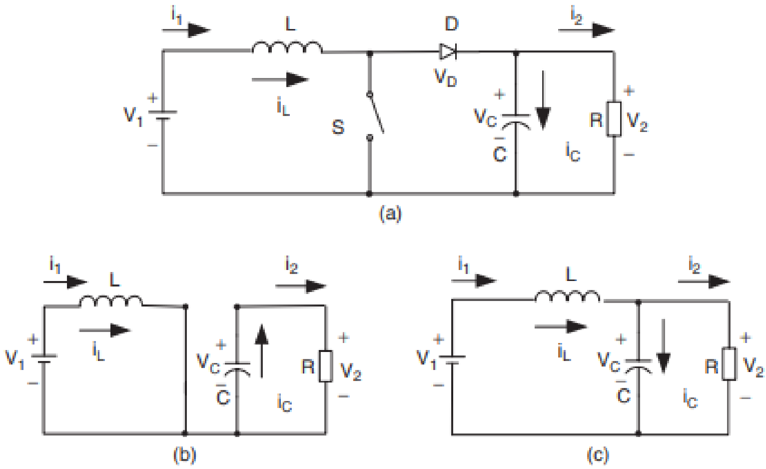


Fig. 1. Boost converter: (a) circuit diagram; (b) switch-on equivalent circuit; and (c) switch-off equivalent circuit.

There is an on/off switch in one period as shown in Fig. 1(b) and 1(c). The output voltage and current equations based on the on/off switch can be written in equations 1 and 2.

$$V_2 = V_1\left(\frac{1}{1-D}\right) \tag{1}$$

where V_1, V_2, and D are input voltage, output voltage, and time the switch is on, respectively.

$$I_2 = I_1(1-D) \tag{2}$$

where I_1, and I_2 are input current, and output current, respectively.

Photovoltaic module parameters are a maximum power (P_{max}), an open-circuit voltage (V_{OC}), an optimum operating voltage (V_{mpp}), a short circuit current (I_{sc}), an optimum operating current (I_{mpp}), a number of cells, a temperature coefficient of V_{OC}, and a temperature coefficient of I_{SC}. This photovoltaic module parameter affects the boost converter parameter values such as the type of switch, inductor and capacitor values. The type of switch, the inductor value, and the capacitor value determine the switching speed, the output current continuous or discontinuous, and the output ripple voltage, respectively.

The type of switch in this study is an Insulated Gate Bipolar Transistor (IGBT). IGBT has a switching frequency range of 20 to 50 kHz. This study uses a switching frequency of 20 kHz. Equations 3 and 4 are the formula for calculating the values of an inductor, and capacitor for continuous current, and output ripple voltage [14], respectively.

$$L_{min} = \frac{D(1-D)^2(R)}{2f} \tag{3}$$

Where L_{min}, R, and f are the minimum value of inductor that makes the inductor current is continuous, resistance load, and switching frequency, respectively.

$$C = \frac{D}{R(\Delta V_2/V_1)f} \tag{4}$$

Where C, and $\Delta V_2/V_1$ are a value of capacitor, and an output ripple voltage, respectively.

The resistance load (R) can be calculated from the boost converter output power. If the design of the output power of the boost converter is equal to the maximum power of the photovoltaic module, then the value of R can be calculated using equation 5.

$$R = \frac{(V_2)^2}{P_{max}} \tag{5}$$

3. ANFIS-BASED MPPT CONTROLLER DESIGN PROCEDURE

The output power of the photovoltaic module is not linear with respect to the irradiation and electrical load of the module, so to get the maximum output power, a method called maximum power point tracking (MPPT) is needed. Fig. 2(a) and 2(b) show MPPT versus photovoltaic curve [15] and MPPT scanning operations [16], respectively. Fig. 2(a) describes the maximum power transfer that can be obtained from a photovoltaic module if the load resistance (R) is the same as the photovoltaic internal resistance (R_{in}). So that the controller works to scan the output voltage of the photovoltaic to get the maximum power transfer, Fig. 2(b).

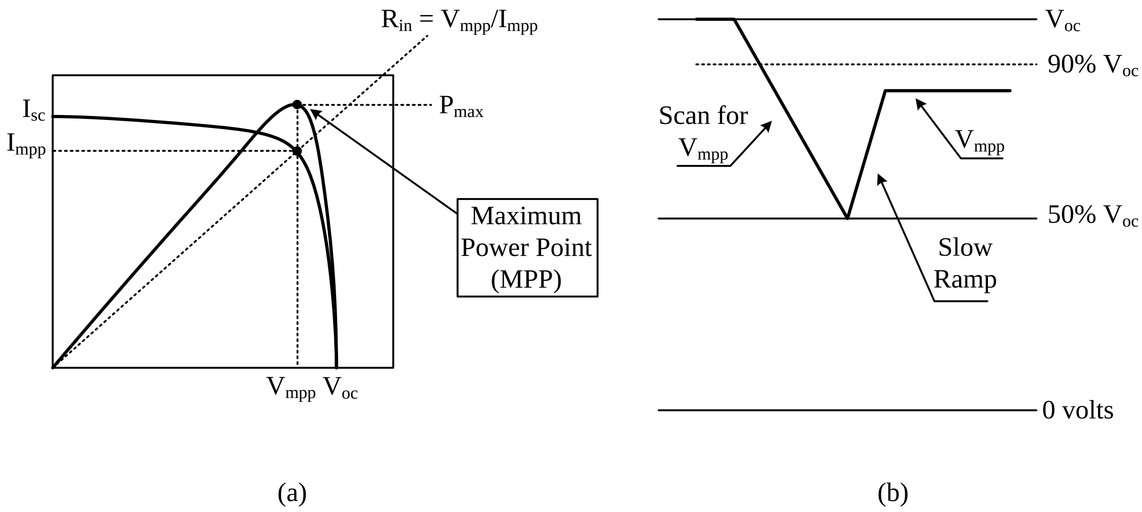


Fig. 2. MPPT for photovoltaic: (a) MPPT versus photovoltaic curve; (b) MPPT scanning operations

The MPPT design is based on ANFIS as a controller to drive the IGBT (on/off switch) on the boost converter. This controller aims to obtain an equivalent load resistance on the input side of the boost converter with an equal value to the internal resistance of the photovoltaic module for various changes in irradiation. Fig. 3 is a photovoltaic system with an ANFIS-based MPPT controller. MPPT ANFIS consists of two inputs and one output. ANFIS model is fuzzy Takagi-Sugeno with the number of membership functions for each input is 5 and Trimf type. The input data for ANFIS training are irradiation and temperature. Each of the data is generated as many as 1000 data randomly in the range 0-1000 W/m2 and 15 - 40 ^{o}C for irradiation and temperature, respectively. The formulas for generating the input data are in equations 6 and 7. The output data (V_{ref}) for training is obtained from the maximum voltage (V_{mpp}) of the photovoltaic module plus the temperature coefficient value of the open-circuit voltage (V_{oc}) multiplied by the difference in room temperature (25 ^{o}C) to the ANFIS data input temperature. V_{ref} formula shows in equations 8.

$$G_i = rand^{*}(G_{max} - G_{min}) + G_{min} \tag{6}$$

Where G_i, G_{max}, and G_{min} are irradiation, maximum irradiation, and minimum irradiation.

$$T_i = rand^{*}(T_{max} - T_{min}) + T_{min} \tag{7}$$

Where T_i, T_{max}, and T_{min} are temperature, maximum temperature, and minimum temperature.

$$V_{ref} = V_{mpp} + \beta(T - T_s) \tag{8}$$

Where β, T, and T_s are temperature coefficient value of the open-circuit voltage (V_{oc}), temperature, and room temperature (25 ^{o}C).

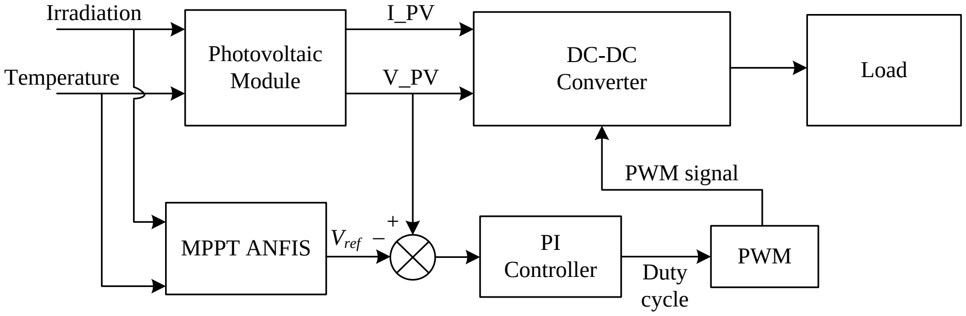
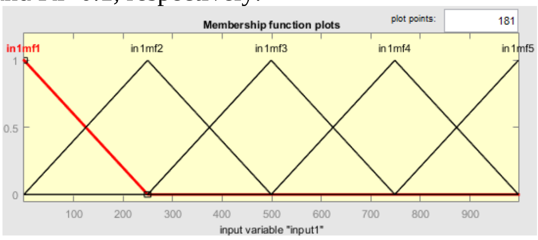
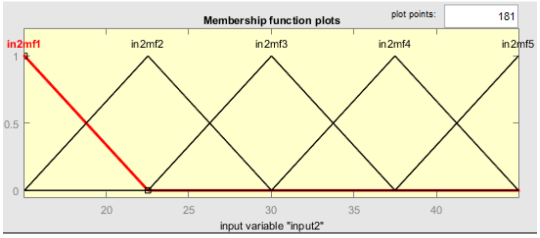


Fig. 3. Photovoltaic system design with ANFIS-based MPPT controller

The membership functions of irradiation and temperature are shown in Fig. 4(a) and 4(b). Fig. 4(c) and 4(d) are structure and the I/O surface of the ANFIS-based MPPT Controller. The Proportional Integral (PI) controller parameter in this study was obtained by the heuristic method. The values of Kp, and Ki are 0.8, and Ki=0.1, respectively.



(a)



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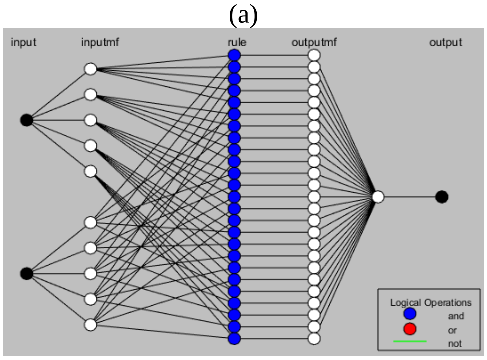

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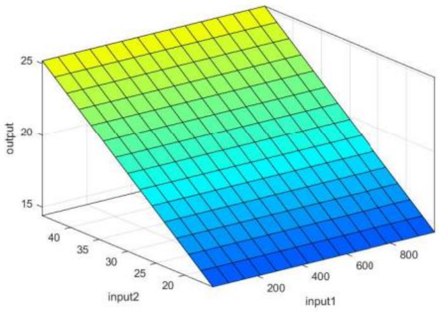


(d)

Fig. 4. ANFIS-based MPPT controller training results: (a) membership functions of irradiation; (b) membership functions of temperature; (c) structure; (d) I/O surface

4. RESULTS AND DISCUSSION

4.1. Photovoltaic Module Specifications

The photovoltaic module in this research is Solarimba SRB150M with a capacity of 150 Wp. The specifications of the Solarimba SRB150M photovoltaic module are shown in Table 1. Fig. 5 shows the characteristic curve of the module.

Tabel 1. Specifications of Solarimba SRB150M photovoltaic module

Parameter	Value
Maximum Power ($P_{max\text{-}STC}$)	150 Wp
Open Circuit Voltage (V_{OC})	21,6 V
Optimum Operating Voltage (V_{mpp})	18 V
Short Circuit Current (I_{SC})	9,17 A
Optimum Operating Current (I_{mpp})	8,33 A
Number of Cells	36
Temperature Koefisien of V_{oc}	-0,34 %/^{o}C
Temperature Koefisien of I_{sc}	0,045 %/^{o}C

*Standard test conditions – iradiance 1000 W/m2 dan moduls tempetrature 25 ^{o}C

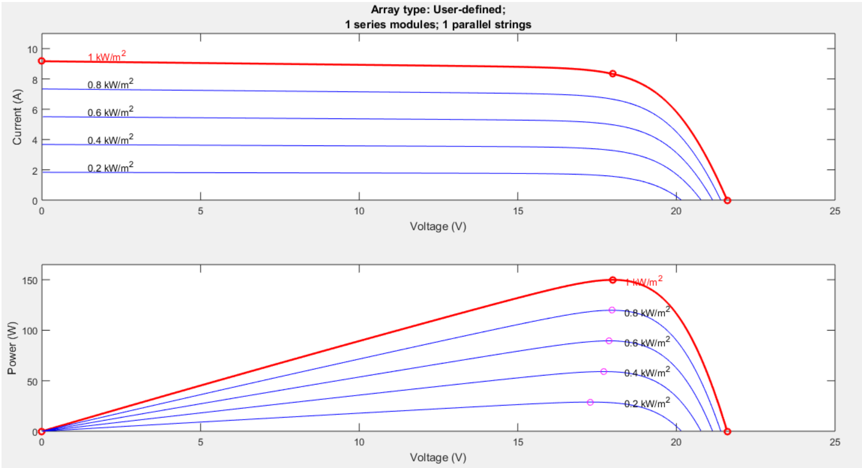


Fig. 5. Characteristic curve of the Solarimba SRB150M photovoltaic module

4.2. Irradiation and Temperature Data

Temperature data on the photovoltaic-module and irradiation were obtained by direct measurement every hour from 09.00 to 16.00. Measurements were carried out three days in a row, from Saturday to Monday, September 4-6 2021. The measurement data are shown in Table 2. The highest irradiation was 917.3 W/m2 on Monday, September 6, 2021 at 12.00 and the highest temperature of the photovoltaic module was 35.5 °C on Sunday, 5 September 2021 at 13.00.

Tabel 2. Irradiation and temperature measurement results

Time	Saturday, September 4, 2021		Sunday, September 5, 2021		Monday, September 6, 2021	
	Irradiation (W/m^2)	**Temp. (°C)**	**Irradiation (W/m^2)**	**Temp. (°C)**	**Irradiation (W/m^2)**	**Temp. (°C)**
09:00	246.9	29.9	329.4	29.7	462.8	30.6
10:00	395.2	31.3	494.6	33.0	575.8	32.1
11:00	490.2	31.9	714.1	34.5	763.3	33.5
12:00	901.4	34.3	867.6	34.9	**917.3**	34.6
13:00	905.9	35.3	915.8	**35.5**	587.3	32.8
14:00	838.9	35.1	838.3	35.2	762.3	33.9
15:00	544.6	33.0	634.3	34.7	678.8	32.7
16:00	369.9	31.4	368.6	33.0	407.9	30.7

4.3. Boost Converter and Its Test Results

The boost converter is designed for a capacity of 150 Watts. The input and output voltages are 16 and 80 V, respectively. Equations 1 to 5 are used to calculate the boost converter circuit parameters for continuous current. The boost converter circuit parameters from the calculation results are shown in Table 3. Table 4 shows the results of the boost converter test. For an input voltage of 16 V, an increase in duty cycle (D) causes the output voltage to increase. A duty cycle of 10% to 80% causes the output voltage to increase from 16.97 to 78.80 V.

Tabel 3. Boost-converter circuit parameters

Parameter	**Value**
Power	150 W
Input Voltage	16 V
Output Voltage	80 V
Resistance Load	42 Ω
Inductor	0,34 mH
capacitor	750 µF

Tabel 4. Boost-converter test results by changing the duty cycle

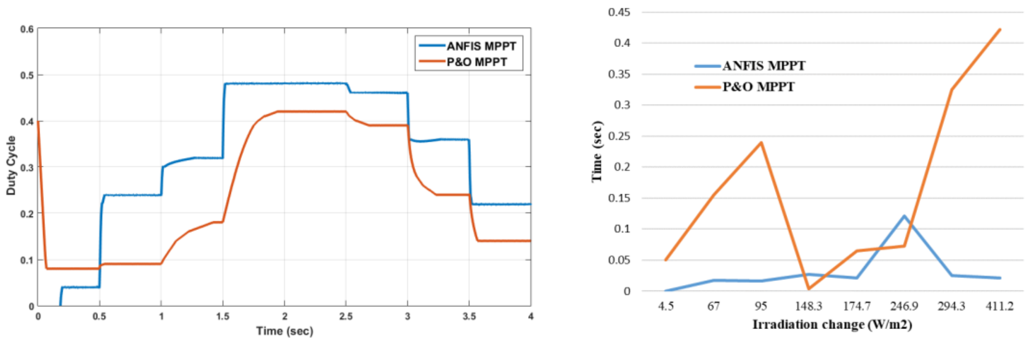
Input Voltage	Duty Cycle							
	Output Voltage							
	10%	20%	30%	40%	50%	60%	70%	80%
16 V	16.97 V	19.19 V	22.05 V	25.85 V	31.17 V	39.15 V	52.41 V	78.80 V

4.4. Photovoltaic system performance results

The performance of the photovoltaic system using the ANFIS-based MPPT controller is displayed on three consecutive days according to the irradiation and temperature data on that day. MPPT P&O is used as a comparison of system performance to show the effectiveness of the design of the ANFIS-based MPPT controller.

Based on the irradiation and temperature data on Saturday, September 4, 2021, in Table 2, the performance of the ANFIS-based MPPT controller is shown in two outcome variables. The result variables are the transient time of the controller output and the output power of the photovoltaic system. The transient time of the controller output is a change in the duty cycle time from one duty cycle to the next due to changes in irradiation and temperature in the photovoltaic module. The duty cycle is the output of the PI controller on the ANFIS-based MPPT. MPPT P&O method as a comparison to show the performance of the MPPT controller based on ANFIS.

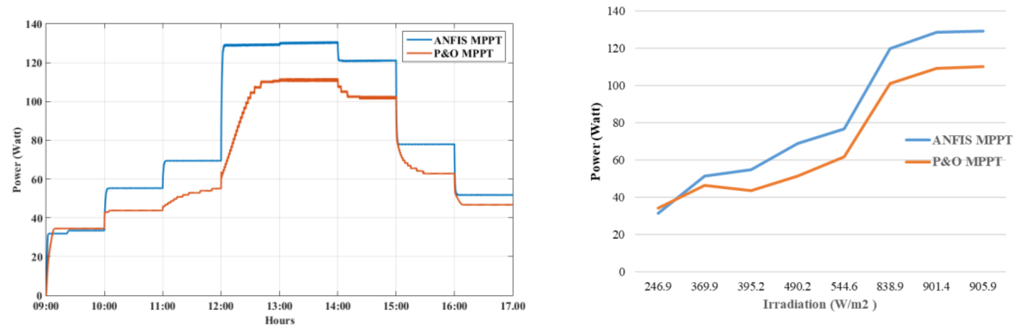
Fig. 6 shows the transient time on the duty cycle due to changes in irradiation and temperature on Saturday, September 4, 2021. Fig. 6(a) is the duty cycle transient time of the MPPT controller based on ANFIS vs. MPPT using the P&O method. These results show that the transient time of the duty cycle in the photovoltaic system with the ANFIS-based MPPT controller is shorter than the MPPT of the P&O method. Fig. 6(b) shows that the irradiation changes in the ANFIS-based MPPT controller are almost the same for small and large irradiation changes. While the MPPT of the P&O method, the increase in irradiation changes causes the transient time to be longer.



(a) (b)

Fig. 6. ANFIS MPPT vs. P&O transient time on Saturday, September 4, 2021: (a) Transient time every change of duty cycle; (b) Transient time trend due to irradiation change

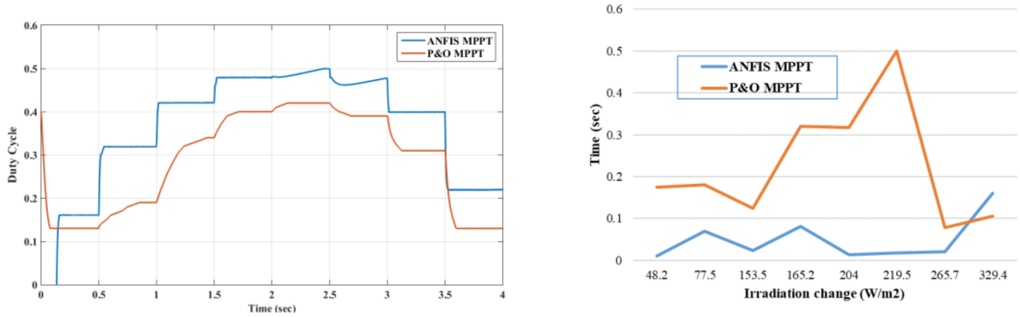
Fig. 7 shows the output power of the boost converter from 09.00 to 17.00 on Saturday, September 4, 2021. The ANFIS-based MPPT controller produces a higher output power of the boost converter than the MPPT using the P&O method for all irradiations and temperatures, in Fig. 7(a). Fig. 7(b) shows an increase in irradiation causing an increase in the output power of the boost converter for both control methods.



(a) (b)

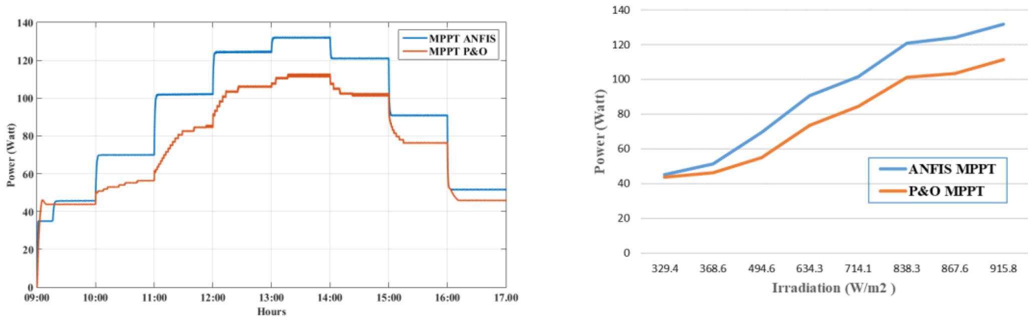
Fig. 7. ANFIS MPPT vs. P&O output power of boost converter on Saturday, September 4, 2021: (a) Hourly output power; (b) Output power trend due to irradiation

Based on the irradiation and temperature data on the second day, Sunday 5 September 2021, the transient time of the duty cycle in the photovoltaic system with the MPPT controller based on ANFIS is shorter than the MPPT P&O method for all conditions of irradiation change. However, for the initial operating conditions of the controller (irradiation change from 0 to 329.4 W/m2) this is not the case as shown in Fig. 8(a) and (b). Fig. 9(a) shows the output power of the boost converter using the MPPT controller based on ANFIS is greater than the MPPT of the P&O method for all irradiations and temperatures for the second day. Both of MPPTs show that the power output of the boost converter increases with increasing irradiation, as shown in Fig. 9(b).



(a) (b)

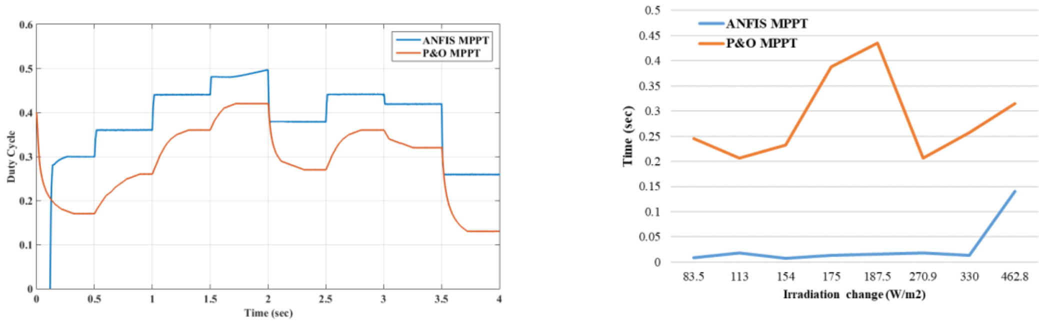
Fig. 8. ANFIS MPPT vs. P&O transient time on Sunday, September 5, 2021: (a) Transient time every change of duty cycle; (b) Transient time trend due to irradiation change



(a) (b)

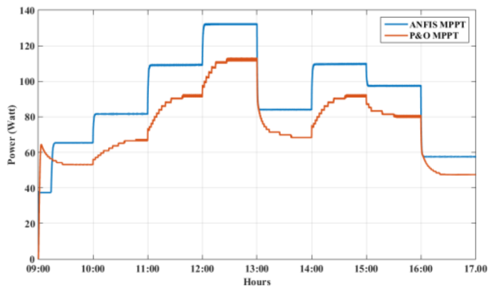
Fig. 9. ANFIS MPPT vs. P&O output power of boost converter on Sunday, September 5, 2021: (a) Hourly output power; (b) Output power trend due to irradiation

Furthermore, the irradiation and temperature data on the third day, Monday, September 6, 2021, were used as input data for the photovoltaic system simulation. The simulation results for the transient time and boost converter output power are shown in Fig. 10 and 11. As in the previous day's simulation results, the transient time due to changes in irradiation on the ANFIS-based MPPT controller is shorter than the P&O method MPPT and the output power of boost converter on the MPPT-based controller ANFIS is greater than MPPT of P&O method.

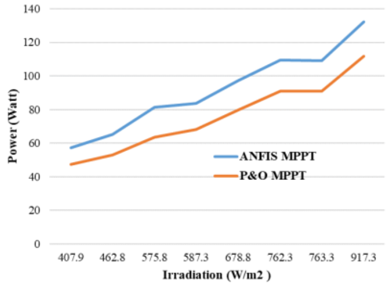


(a) (b)

Fig. 10. ANFIS MPPT vs. P&O transient time on Monday, September 6, 2021: (a) Transient time every change of duty cycle; (b) Transient time trend due to irradiation change



(a)



(b)

Fig. 11. ANFIS MPPT vs P&O output power of boost converter on Monday, September 6, 2021: (a) Hourly output power; (b) Output power trend due to irradiation

The simulation results of the performance comparison of the ANFIS-based MPPT controller and MPPT of the P&O method on the photovoltaic system with irradiation and temperature data for three days are shown in Table 5 and Table 6 for the transient time, and the output power of the boost converter, respectively. The mean transient times for the first, second, and third days were 0.167, 0.225, and 0.286 sec. for P&O MPPT, while for ANFIS MPPT was 0.031, 0.049, and 0.029 sec. The mean transient time for the three days was 0.2260, and 0.0363 for the P&O MPPT, and ANFIS MPPT, respectively. So the transient time of ANFIS MPPT was 6.23 times shorter than P&O MPPT. The shortest transient time from all simulation results was 905.9 W/m2 irradiation for ANFIS MPPT and 395.2 W/m2 irradiation for P&O MPPT.

Table 5. Transient time comparison of ANFIS MPPT vs P&O MPPT

Saturday, September 4, 2021			Sunday, September 5, 2021			Monday, September 6, 2021		
Irradiation (W/m2)	**Transient time (s)**		**Irradiation (W/m2)**	**Transient time (s)**		**Irradiation (W/m2)**	**Transient time (s)**	
	MPPT P&O	**MPPT ANFIS**		**MPPT P&O**	**MPPT ANFIS**		**MPPT P&O**	**MPPT ANFIS**
246.9	0.073	0.121	329.4	0.105	0.160	462.8	0.315	0.140
395.2	**0.004**	0.027	494.6	0.321	0.081	575.8	0.207	0.018
490.2	0.240	0.016	714.1	0.500	0.017	763.3	0.435	0.016
901.4	0.422	0.021	867.6	0.124	0.023	917.3	0.233	0.008
905.9	0.050	**0.000**	915.8	0.175	0.010	587.3	0.257	0.013
838.9	0.155	0.017	838.3	0.181	0.070	762.3	0.388	0.013
544.6	0.325	0.025	634.3	0.317	0.013	678.8	0.245	0.009
369.9	0.065	0.021	368.6	0.078	0.021	407.9	0.207	0.018
Average transient time	0.167	0.031		0.225	0.049		0.286	0.029

Table 6. The output power of boost converter comparison of ANFIS MPPT vs P&O MPPT

Saturday, September 4, 2021			Sunday, September 5, 2021			Monday, September 6, 2021		
Irradiation (W/m2)	**Power (Watt)**		**Irradiation (W/m2)**	**Power (Watt)**		**Irradiation (W/m2)**	**Power (Watt)**	
	MPPT P&O	**MPPT ANFIS**		**MPPT P&O**	**MPPT ANFIS**		**MPPT P&O**	**MPPT ANFIS**
246.9	34.32	31.69	329.4	43.61	45.15	462.8	52.92	65.10
395.2	43.62	54.98	494.6	55.08	69.68	575.8	63.61	81.32
490.2	51.69	68.95	714.1	84.52	101.74	763.3	91.02	108.97
901.4	109.32	128.61	867.6	103.49	124.25	**917.3**	**111.69**	**132.09**
905.9	110.32	129.42	915.8	111.48	131.96	587.3	68.27	83.78
838.9	101.14	119.97	838.3	101.12	120.90	762.3	90.95	109.48
544.6	61.94	76.95	634.3	73.51	90.63	678.8	79.82	97.24
369.9	46.51	51.53	368.6	46.45	51.42	407.9	47.26	57.35

The values in bold in Table 6 indicate the highest boost converter output power for both MPPTs. The highest output power occurred at the highest irradiation. The highest irradiation occurred on the third day at 12.00, which was 917.3 W/m2. The boost converter outputs power are 132.09 and 111.69 for ANFIS MPPT, and P&O MPPT, respectively.

5. CONCLUSION

ANFIS-based MPPT controller showed better performance than MPPT using the P&O method. The average transient time of the ANFIS-based MPPT controller is shorter than that of the MPPT using the P&O method. The mean transient times were 0.0363 and 0.2260 sec. for the ANFIS-based MPPT controller and the P&O method MPPT, respectively. So, transient time of ANFIS MPPT is 6.23 times faster than that of P&O MPPT. The efficiency of the ANFIS-based MPPT controller is higher than the MPPT of the P&O method. The output power of the boost converter is highest at 917.3 W/m2 of irradiation. In this irradiation, the output power of the boost converter is 132.09, and 111.69 Watt for the ANFIS-based MPPT controller, and the P&O method MPPT, respectively.

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