Enhanced performance of PV systems using a smart discrete solar tracker with fuzzy-ant colony controller

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ABSTRACT

A solar tracker is a combination of mechanical and electrical systems that can be used to move a solar panel to follow the sun's direction. This solar tracker system is expected to optimize the output power of photovoltaics. Based on existing research, many solar tracking systems have been developed using active tracking methods to increase the power consumption of the components of solar trackers. Therefore, a passive solar tracking system was used to reduce the solar tracker's internal energy consumption. In this study, a passive smart discrete solar tracker was designed with 3 positions and 5 tracking positions based on a fuzzy-ant colony controller (ACO). The design of a passive solar tracker based on a fuzzy-ACO has a performance index (average) of 0.45 s, a settling time of 0.701 s, a maximum overshoot of 0.5%, and a steady-state error of 0.05%. From the design, the 3-position passive solar tracker with fuzzy-ACO control can increase efficiency with a gross energy gain of 42.79% for 10 hours compared to a fixed PV. The 5-position passive solar tracker using fuzzy-ACO control increased the efficiency with a gross energy gain of 43.99%.

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1. INTRODUCTION

Energy by automatically following the direction of incoming sunlight [1], [2]. By rotating the solar panel, the photon energy absorption from the Sun can be maximized. In general, solar trackers are of two types: active and passive [3]. Active solar trackers have a working principle based on the position of the sun via the light-dependent resistor (LDR) sensor found in photovoltaic (PV) systems. However, the weakness of the active solar tracker is that it is susceptible to scattered light, which can interfere with the LDR sensor readings and is influenced by cloudy weather. In addition, passive solar trackers can function under these conditions, where a passive system uses the movement of the sun's position. The passive tracking method does not involve direct measurements of the physical quantities of an object but is based on astronomical calculations.

The solar trackers can be classified according to the number of rotation axes. Solar trackers based on the rotation axis are divided into two, namely, one-axis and two-axis [4]. A single-axis solar tracker consists of a single axis from one of the horizontal or vertical angles, by changing the position at the pitch angle (east and west) according to changes in the elevation angle of the sun. A two-axis solar tracker is a solar tracking system that changes the position of the pitch and yaw angles so that it can track the sun from east to west and north to south, so that it can be used anywhere in the world [5], [6]. These two-axis solar trackers provide higher efficiency than single-axis solar trackers that use only one actuation device (e.g., motor).

Thus, solar trackers are a solution to increase the power of solar panels. However, energy utilization has not been carried out optimally because currently developed technology has not been significant in increasing the efficiency of solar panels, and internal energy consumption has not been considered. Continuous solar tracking is complex and incurs significant energy costs. Therefore, a discrete solar tracker must reduce internal energy consumption [7]–[9].

This research refers to several previous studies, one of which was conducted by Smirnov *et al.* [10], by designing a solar tracker using discrete-position tracking. This study compares the efficiency of discrete trackers with fixed trackers and continuous solar trackers [10]. The solar tracker used in this research is a passive tracker; thus, supporting data is needed to model the sun's movement. Compared with a fixed photovoltaic (PV), the 2-position discrete solar tracker exhibits 40-50% higher efficiency. De Sá Campos developed a single-axis solar tracker with a discrete position system [11]. The simulation of solar radiation conducted by Alvarado *et al.*, [9] which is an energy gain of 23.4% over a fixed panel, can be achieved with a 15° angular resolution and two discrete positions using start-stop limit switches. Adding more discrete positions increased the gain to 29.2% with three, 30.3% with four, and 31.9% with five. The higher angular resolution increases the number of algorithmic combinations and thus the energy gain [9]. Fitriyanah and Abadi [12] researched a two-axis passive solar tracker using a type-2 fuzzy logic controller (FLC) based on bacterial foraging optimization (BFO) to increase the efficiency of the PV. The results show that the type-2 FLC exhibits better performance than the type-1 FLC. The solar tracker efficiency proposed during the trial period was 67.9% that of the fixed system.

Remoaldo *et al.* [13] compared the performance of solar panels using conventional control methods, the perturb and observe (P&O) algorithm, with that of control methods using artificial intelligence FLC fuzzy logic can enhance the P&O algorithm by enabling faster adaptation to variable environmental conditions, quicker tracking of the maximum power point (MPP), and maintaining stable performance at the MPP, resulting in higher energy generation. From this research, it can be concluded that the use of control methods based on artificial intelligence can further improve system performance compared to conventional methods [14]–[17]. From the four studies that have been carried out, in this research, a passive smart discrete solar tracker with three and five positions was designed with a tracking method that is relatively cheap, easy to maintain, and has high work efficiency based on a fuzzy-ant colony controller (ACO) with the hope of increasing accuracy solar tracker tracking using MATLAB/Simulink software.

2. METHOD

The data required in this research encompasses both modeling and simulation of passive solar tracker systems. The collected data included astronomical parameters such as the altitude angle of the sun, which were used to determine the optimal orientation of the solar panels. Additionally, data from the direct current (DC) motors is gathered based on the motor specifications, including the torque, voltage, and current ratings, to ensure that the motor selection aligns with the system’s mechanical requirements. The solar panel data are based on the panel dimensions, experiments, and controllers.

2.1. Data collection and sun position modeling

During passive tracking, astronomical calculations are performed. In this research, the sun altitude angle is the set point value used in the solar tracker system. The altitude angle can be determined by knowing the position of the sun from the data collection location. The astronomical parameters used to determine the altitude angle of a research location are latitude and longitude [18]. Sun position data were collected at the Sepuluh Nopember Institute of Technology (ITS) physics engineering, ITS Sukolilo campus, Surabaya, from 07.00 WIB (Western Indonesian Time) until 17.00 WIB. The latitude and longitude data at the research site were obtained using the SunCalc org application. To ensure the accuracy of the obtained data, the coordinates of the SunCalc results were validated using global positioning system (GPS) measurements at the ITS Sukolilo campus in Surabaya. The astronomical parameters (latitude and longitude positions of the primary data collection research location located on the ITS Sukolilo campus with latitude and longitude positions of 7.282953° and 112.796503°, respectively). This location is an open area where there are no trees or buildings that block direct sunlight from passing through the solar panels. The following modeling of the sun position is performed mathematically in (1)-(8) [19].

$$\theta_z = cos^{-1}(sin\,\delta\, sin\,\phi + cos\,\delta\, cos\,\omega\, cos\,\phi) \tag{1}$$

$$\alpha\ = 90 - \theta_z \tag{2}$$

$$\gamma = cos^{-1}\left(\frac{cos\,\delta\, cos\,\omega\, sin\,\varphi}{sin\,\theta_z} - \frac{sin\,\delta\, cos\,\varphi}{sin\,\theta_z}\right) \quad (3)$$

The declination angle can be calculated using (4).

$$\delta = 23{,}45 \sin\left[360\ \frac{(284+n)}{365}\right] \quad (4)$$

If the parameters on the tracking surface are the incidence angle (θ_i), pitch angle (β), and yaw angle (γ_s), they can be calculated using (5).

$$\theta_i = cos^{-1}(cos\,\theta_z \cos\beta + sin\,\theta_z \sin\beta \cos(\gamma_s - \gamma) \quad (5)$$

$$\gamma_s = \sigma_{ew}\,\sigma_{ns}\,\gamma_{so} + \left(\frac{1-\sigma_{ew}\,\sigma_{ns}}{2}\right)\sigma_w\ 180° \quad (6)$$

$$\beta = \theta_z \quad (7)$$

$$\gamma = \gamma_s \quad (8)$$

Where n: days in a year (1 year = 365 days), β: surface slope, γ: surface azimuth, γs: solar azimuth, θz: zenith angle, δ: declination, ω: clock angle, and ϕ: latitude.

2.2. Data collection and DC motor modeling

The sun-tracking system on solar panels uses an actuator in the form of a DC motor, which is used as the pitch-angle driver of the solar panels. A DC motor is used to move the solar panel from east to west and vice versa (pitch angle) [5]. The DC motor used in this system is a DC motor with a voltage of 12 V. Data collection on DC motors determines the parameters to be used in the modeling of solar trackers in Simulink. The parameters used for modeling include the voltage constant (Ke), torque constant (Kt), motor inertia (Jm), motor resistance (R), motor inductance (L), and viscous friction coefficient (Bm). Data were collected by providing inputs in the form of voltages ranging from 2 to 12 V. Then, the DC motor rpm value was obtained from each voltage, which was then used to find the value of the DC motor parameters, as shown in Table 1.

Table 1. DC Motor Parameters

Parameters	DC motor
Resistance (R) Ohm	2.055
Inductance (L) Henry	0.005833
voltage constant (Ke) Vol.sec./rad	28.52839
Torque constant (Kt) Nm/A	28.52839
Moment of inertia (J) Nms^2	45.66596
Coefficient of friction (B) Nms/rad	0.678999

The modeling of DC motors uses the basic laws of physics, which consist of electrical and mechanical DC motor models, which are derived using Kirchhoff's Law II on rotation [20].

$$(s) = R_a.I_a(s) + L_a.I_a(s)S + Kb.\omega(s) \quad (9)$$

$$V_a(s) - Kb.\omega(s) = I_a(s)(R_a + L_a\,S) \quad (10)$$

$$I_a = \frac{V_a(s) - Kb.\omega(s)}{(R_a + L_a S)} \quad (11)$$

$$I_a = V_a(s) - Kb.\omega(s)\frac{1}{(R_a + L_a S)} \quad (12)$$

$$K_t.I_a(s) = I_m.\omega(s)S - B_m.\omega(s) \quad (13)$$

$$\omega(s) = \frac{K_t.I_a}{J_m.s + B_m} \quad (14)$$

$$\omega(s) = K_t . I_a \frac{1}{J_m . s + B_m} \quad (15)$$

2.3. Data retrieval and solar panel modeling

The input data used in solar panel modeling in MATLAB/Simulink include solar radiation and temperature. Radiation and temperature values were obtained from direct field measurements. Furthermore, several parameters obtained from the PV module datasheet were used in the solar panel modeling as shown in Table 2.

Table 2. Solar panel parameters

Parameter-parameter	Parameter value
Temperature Coefficient of short circuit voltage (Φ)	-0.0036 V/ºC
Temperature Coefficient of short circuit current (μ)	0.00053 A/ºC
Pmax (maximum power)	250 W
PV internal resistance (Rpv)	0.15603 Ohm
Imp (maximum power current)	8.34 A
Vmp (maximum power voltage)	30 V
Voc (open circuit voltage)	36.8 V
Isc ++ (short circuit current)	9 A

Based on Kirchhoff's Current Law, current can be calculated with the equation [21].

$$I = I_{ph} - I_d - I_{sh} \quad (16)$$

Ideally, Ish = 0 because Rsh ≈ ∞, so (11) can be rewritten as (17).

$$I = I_{ph} - I_d = I_{ph} - I_o \left[exp\left(\frac{V + IR_{pv}}{V_T}\right) - 1 \right] \quad (17)$$

I and V can be represented as functions of radiation and temperature as (18)-(21).

$$I = \left[\mu \left(\frac{S}{S_{ref}}\right) (T - T_{ref}) + \left(\frac{S}{S_{ref}} - 1\right) I_{sc} \right] + I_{mp} \quad (18)$$

$$V = -\phi(T - T_{ref}) - R_{pv}(I - I_{mp}) + V_{mp} \quad (19)$$

$$\phi_{ref} = \frac{2V_{mp} - V_{oc}}{\frac{I_{sc}}{I_{sc} - I_{mp}} + ln\left(1 - \frac{I_{mp}}{I_{sc}}\right)} \quad (20)$$

$$R_{pv} = \frac{\phi_{ref} ln\left(1 - \frac{I_{mp}}{I_{sc}}\right) + V_{oc} - V_{mp}}{I_{mp}} \quad (21)$$

I and V can be represented as functions of radiation and temperature as shown in (18) and (19). The values of S_ref = 1000 W/m^2, T_ref = 25 °C, and Rpv can be found in (21), and the values of the other parameters can be seen in the solar panel specification data given in Table 2. Based on the calculated values from the equivalent circuit equation and the solar panel parameter values obtained from the solar panel specifications/datasheets, modeling was carried out in Simulink MATLAB.

2.4. Design of a fuzzy ant-colony control system

The control system developed in this research is the fuzzy-ACO control system, which is used as a control system for passive solar trackers. The controlled variable is the pitch angle. There are several components in the system, and the block diagram of the passive solar tracker control system can be explained in Figure 1. The input from the passive solar tracker consists of 2 pieces, namely error and error differences, which are defined in (22) and (23) [5]:

$$e(k) = \alpha_S - \theta_S \quad (22)$$

$$\Delta e(k) = e(k) - e(k-1) \quad (23)$$

where $e(k)$ is the current error and $e(k-1)$ is the previous error. The output is a pulse width modulation (PWM) signal whose value varies from -255 to 255. This signal was used to regulate the reference voltage of the DC motor as an actuator in the modeling of the passive smart solar tracker.

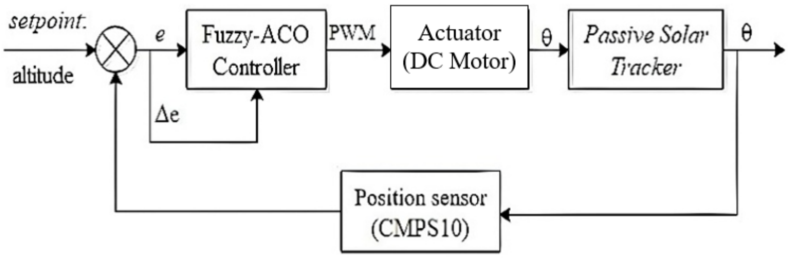

Figure 1. Block diagram of the solar tracker system

2.5. Fuzzy membership function

In this process, membership functions and the number of fuzzy numbers are formed. The input membership function is a triangle. There are 5 membership functions: negative big (NB), negative small (NS), zero (ZE), positive small (PS), and positive big (PB) [22].

The control modeling on the solar tracker aims to improve the performance of the solar tracker so that the motor has high speed and accuracy, and there is no oscillation when it reaches a set point. Therefore, the solar tracker can have higher performance if it uses the FLC-ACO control system rather than using FLC control without optimization, or compared to solar panels in a fixed state [23]–[25]. The membership function in Figure 2 is optimized using ACO. After optimization, the input membership function with the optimized parameters is obtained as shown in Figure 3.

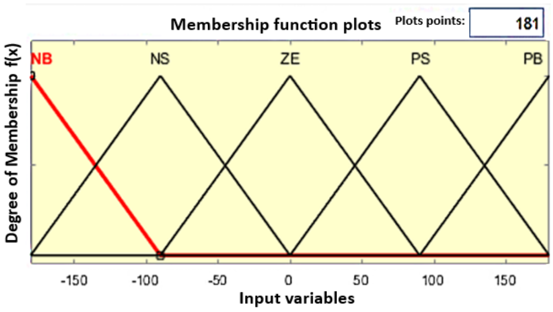

Figure 2. Membership function of fuzzy error and delta error

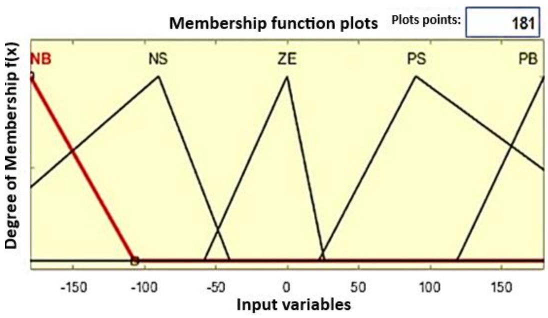

Figure 3. FLC-ACO membership function error and delta error

3. RESULTS AND DISCUSSION

Testing was conducted on solar trackers with 3-positions and 5-positions, and their performance was compared with that of a fixed PV system. The parameters analyzed include the rise time, steady-state time, maximum overshoot, and steady-state error. The performance test aims to determine the improvement in PV panel performance with a solar tracker, which is done by measuring the voltage, current, and output power of the PV panel. The energy efficiency increase resulting from the passive solar tracker system was also calculated.

3.1. Setpoint test results on passive solar tracker

The performance measurement criteria for control observed in the setpoint test were the rise time, settling time, maximum overshoot, and steady-state error. The setpoint test on the passive solar tracker is conducted by providing an input value in the form of a step value representing the altitude angle. The setpoint test on the passive discrete solar tracker is represented by 30°, 45°, and 60°. Figure 4 shows the results of the motor pitch-angle output response to the input altitude angle.

Figure 4 shows the fuzzy-ACO response to three elevation angle set points: (a) 30°, (b) 45°, and (c) 60°. The blue curve represents the fuzzy control, whereas the red curve represents the fuzzy-ACO control. The control response using fuzzy-ACO can reach the set point based on the three graphs, and the resulting error is smaller than that of the fuzzy controller before optimization. The performance indexes of the fuzzy and fuzzy-ACO control responses are presented in Table 3.

Table 3 shows that the error produced by fuzzy-ACO was smaller than that of the fuzzy control (around 0.1%, with a difference of around 0.03% compared to fuzzy. In the fuzzy control response, there is an overshoot of 1.5%, while in the fuzzy-ACO response, the maximum overshoot value is 0.5%, which means that in the fuzzy-ACO control, there are fewer oscillations that prevent it from reaching the set point. Thus, from the overall response produced, it can be concluded that the fuzzy-ACO control has a faster response in reaching the set point with a smaller error value than the fuzzy control.

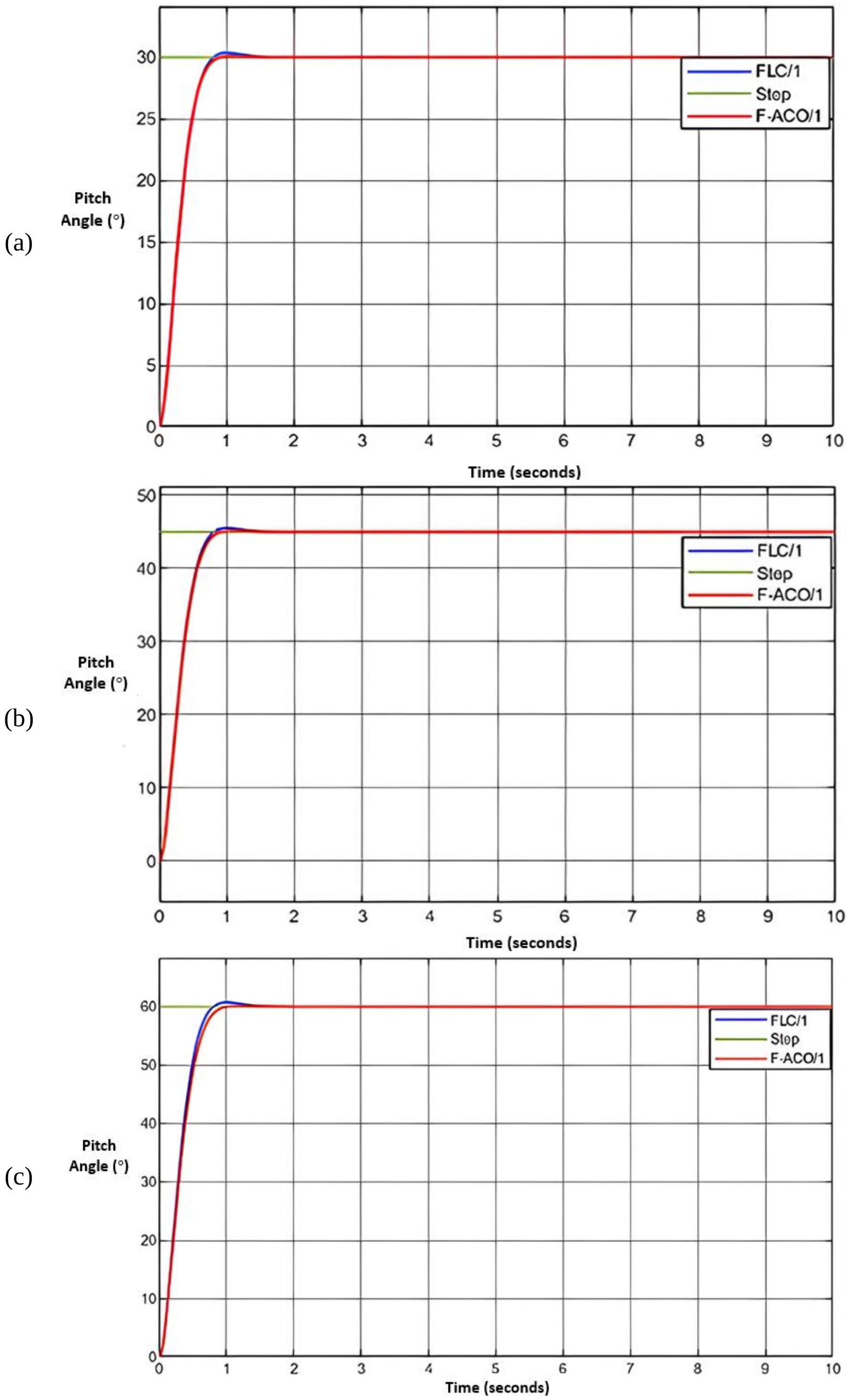

Figure 4. Set point test on the solar tracker: (a) 30°, (b) 45°, and (c) 60°

Table 3. Performance index nn passive solar tracker pitch angle

Performance index	Set point 30˚		Set point 45˚		Set point 60˚	
	Fuzzy	F-ACO	Fuzzy	F-ACO	Fuzzy	F-ACO
Rise time (second)	0.464	0.453	0.465	0.474	0.461	0.500
% error steady state	0.1	0.07	0.07	0.04	0.07	0.03
%Maximum overshoot	1.5	0.5	1.5	0.5	1.5	0.5
Settling time (s)	0.647	0.635	0.642	0.664	0.719	0.805

3.2. Setpoint tracking test

The tracking test on the sun-tracking system determines the response of the system to a changing set point. Altitude-angle tracking testing by providing an initial input with a PV pitch-angle position of 0°. In the tracking test, the input was given in the form of variations in the altitude-angle set points. The results of the altitude-angle tracking test are shown in Figure 5.

At the beginning of the set-point tracking test, the pitch angle was given a set-point value of 30° and then increased to 45° and 60°. Figure 5 shows that the results of the pitch-angle tracking response for the fuzzy-ACO control system can follow changes in the sun's altitude angle well. From the results of the altitude angle tracking test on the passive solar tracker, we conclude that the fuzzy-ACO controller can be applied and produces a good response; thus, it can be applied to this system.

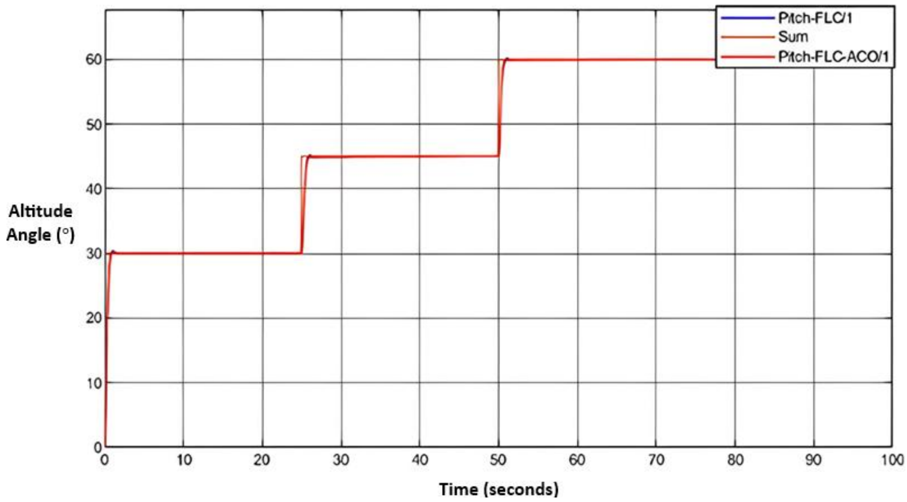

Figure 5. Tracking test response set point altitude angle

3.3. Determining the movement time of the 3-position solar tracker

In accordance with the tracking concept of the discrete solar tracker, the angles that determine the movement of the solar tracker are determined by astronomical calculations from the data collection location. To determine when the sun tracking system changes position, the operating time is divided into 3, namely 07.00–10.00 WIB, 11.00–13.00 WIB, and 14.00–17.00 WIB. After optimizing using ACO on fuzzy boundaries, 3 angles with the highest optimum radiation and power output were identified based on the 3-time sections were determined to determine the position of the solar tracker. The results of optimization in the form of the 3 most optimal angles are the altitude-angle set points for the movement of the passive solar tracker into 3 positions. The 3 optimum positions were set at 10.00, 12.00, and 14.00, precisely at angles of 52.12°, 58.87°, and 42.74°. The solar tracker moving at 10.00 will then be referred to as position 1, the solar tracker moving at 12.00 will then be referred to as position 2, and the solar tracker moving at 14.00 will then be referred to as position 3. The solar tracker moves at and around this position.

3.4. Determining the movement time of the 5-position solar tracker

The 5-position discrete solar tracker system was determined by dividing the tracker operating time from 07.00-17.00 WIB into 5-time sections: 07.00–08.00, 09.00–10.00, 11.00–12.00, 13.00–14.00, and 15.00 – 17.00 WIB. Similarly, with the 3-position discrete solar tracker, after optimization using ACO on fuzzy boundaries, 5 angles with the most optimum radiation and power output can be identified based on the 5-time sections that have been determined to determine the position of the solar tracker. The results of optimization in the form of the 5 most optimal angles are the altitude angle set points for the movement of the passive solar tracker into 5 positions. The 5 optimum positions are at 08.00 WIB, 10.00 WIB, 12.00 WIB, 13.00 WIB, and 15.00 WIB, precisely at angles of 29.96°, 52.12°, 58.87°, 52.79°, and 30.77°, respectively. The 5-position discrete solar tracker that moves at 08:00 a.m. will be referred to as position 1, the solar tracker that moves at 10.00 will be referred to as position 2, the solar tracker that moves at 12.00 will be referred to as position 3, the solar tracker that moves at 13.00 will be referred to as position 4, and the solar tracker moving at 15.00 will then be referred to as position 5.

3.5. Performance test of 3-position passive solar tracker with fuzzy control

The output from the 3-position passive solar tracker has a maximum voltage (solar noon) of 29.91 V and a maximum current of 8.35 A. The maximum voltage occurred at t = 301 min at the time of solar noon and an altitude position of 66.71°. The average current storage on a fixed PV is 3.89 A, while on a solar tracker it is 5.53 A.

Figure 6 shows that the solar tracker's output power curve is greater than that of the fixed PV. The maximum power produced by the solar tracker was 249.7759 watts at t = 300 min, and the PV fixed was 209.04 watts. The energy produced by the fixed PV was 1052.84 Wh, and the amount of energy produced by the passive solar tracker was 1459.56 Wh. Therefore, the efficiency increase of the gross energy gain is 38.63%.

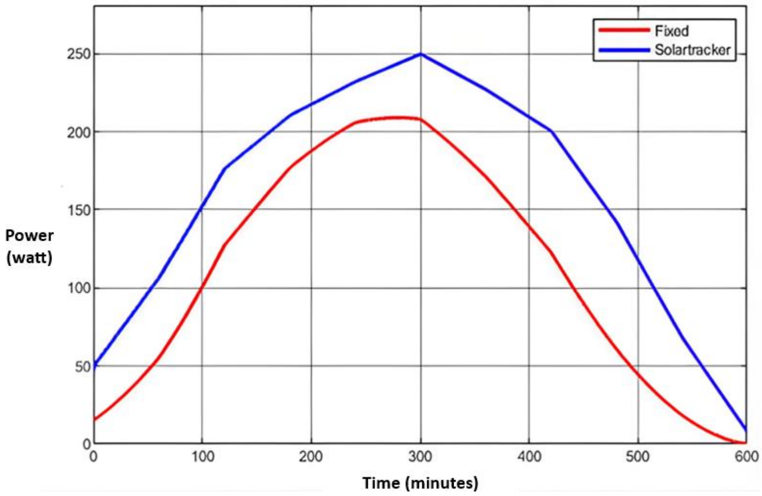

Figure 6. Output power response of 3-position solar tracker and fixed PV

3.6. Performance test of 3-position passive solar tracker with fuzzy-ACO control

The output from the passive solar tracker has a maximum voltage (solar noon) of 29.92 V and a maximum current of 8.41 A. The maximum voltage occurred at t = 301 min at the time of solar noon and an altitude position of 66.71°. The average current storage on a fixed PV is 3.89 A, whereas that on a solar tracker is 5.57 A.

The maximum power produced by the solar tracker was 251.54 watts = 301 minutes, and the fixed PV was 209.04 watts, as shown in Figure 7. The energy efficiency of the fixed PV and solar tracker can be calculated from the output power. The energy produced by the fixed PV was 1052.84 Wh, and the energy produced by the passive solar tracker was 1503.42 Wh. Therefore, the gross energy gain efficiency is 42.79%.

3.7. Performance test of 5-position passive solar tracker with fuzzy control

The output from the passive solar tracker has a maximum voltage (solar noon) of 29.91 V and a maximum current of 8.37 A. The maximum voltage occurred at t = 301 min at the time of solar noon and an altitude position of 66.71°. The average current storage on a fixed PV is 3.89 A, whereas that on a solar tracker is 5.61 A.

Figure 8 shows that the maximum power produced by the solar tracker was 250.3 W at t = 300 min, and the fixed PV was 209.04 watts. The energy efficiency of the fixed PV and solar tracker can be calculated from the output power. The amount of energy produced by the fixed PV was 1052.84 Wh, and the amount of energy produced by the passive solar tracker was 1469.27 Wh. Therefore, the efficiency increase of the gross energy gain efficiency is 39.55%.

3.8. Performance test of 5-position passive solar tracker with fuzzy-ACO control

The output from the passive solar tracker has a maximum voltage (solar noon) of 29.92 V and a maximum current of 8.42 A. The maximum voltage occurred at t = 301 min at the time of solar noon and an altitude position of 66.71°. The average current storage on a fixed PV was 3.89 A, whereas that on a solar tracker was 5.56 A.

Figure 9 shows the output of the solar tracker 5 position using F-ACO and PV fixed. The maximum power produced by the solar tracker was 251.54 W at t = 300 min, and the fixed PV was 209.04 watts. The energy efficiency of the fixed PV and solar tracker can be calculated from the output power. Therefore, the efficiency increase of the gross energy gain is 43.99%.

3.9. Passive smart discrete solar tracker performance test

A 3 and 5-position passive solar tracker performance test using fuzzy-ACO control was conducted to determine the PV performance between the fixed PV and the designed solar tracker. The output variables from the solar tracker are the output voltage and PV output current, which are then compared with the fixed PV. From the performance test simulation, it can be seen that the gross energy gain efficiency of the solar tracker for fixed PVs increased. Table 4 presents the increase in the energy performance of the 3-position and 5-position passive discrete solar trackers.

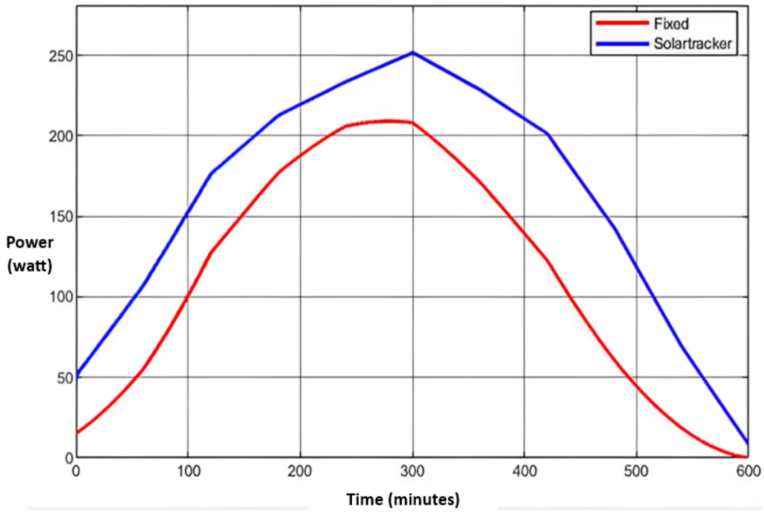

Figure 7. Power response output of solar tracker 3 position F-ACO and PV fixed

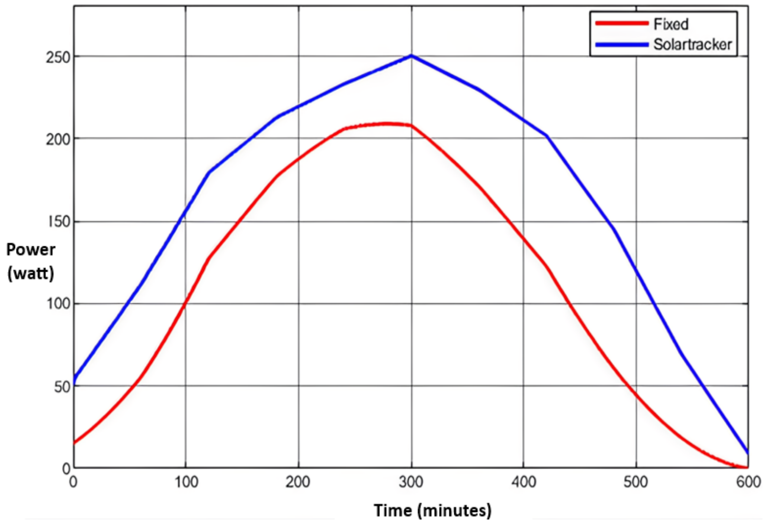

Figure 8. Output power response of 5 position solar tracker and fixed PV

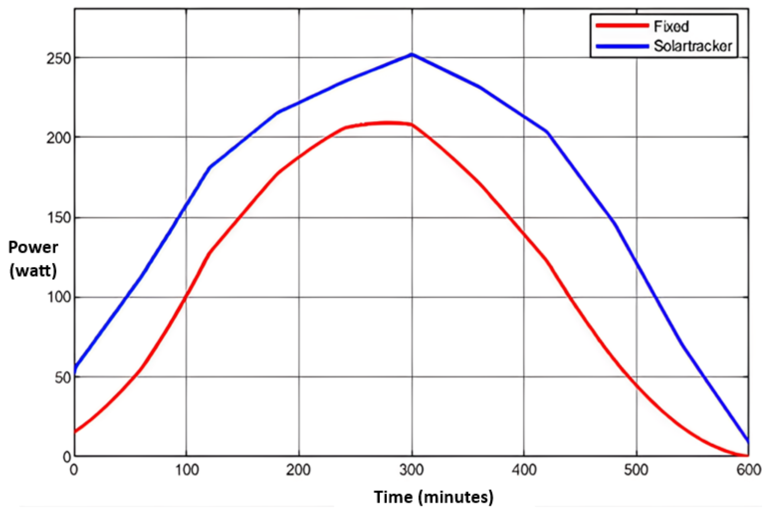

Figure 9. Power response output of solar tracker 5 position F-ACO and PV fixed

Based on Table 4, the 3-position solar tracker with fuzzy control experienced an increase in the gross energy gain efficiency of 38.63% compared to the fixed PV. Meanwhile, if you use F-ACO control, the performance of the solar tracker experiences a greater increase, namely 42.79%. The 5-position solar tracker with fuzzy control experienced an increase in the gross energy gain efficiency of 39.55% compared to a PV in a fixed state. In addition, if you use F-ACO control, the solar tracker performance increases by 43.99%.

From this analysis, it can be seen that when using the fuzzy method and F-ACO, the resulting solar tracker performance is more optimal than that of fixed PV. The solar tracker performance obtained using the 3 and 5-position discrete solar trackers was better with F-ACO than with just fuzzy tracking. This proves that optimization by the ACO algorithm can improve the controller performance.

The fuzzy-ACO algorithm excels because it can automate the parameter tuning process effectively by integrating the ant colony optimization algorithm. Thus, it does not depend on manual tuning. This approach produces a fast, accurate, and adaptive control response to nonlinear conditions. The advantage of fuzzy-ACO over ANFIS-based methods is that it has high adaptability to variable conditions without requiring large computational complexity [23], [26]. Research has been conducted on dusty environmental conditions, i.e., the construction of a PV cleaning robot to improve PV performance [27]. The reliability of DC motors needs to be tested to determine the maintenance intervals and wear of motor components during long-term operation in solar farm installations.

Table 4. Performance improvement of a solar tracker for fixed PV

Type	Fuzzy (%)	F-ACO (%)
Solar tracker 3 positions	38.63	42.79
Solar tracker 5 positions	39.55	43.99

4. CONCLUSION

Several parameters of each component in the fuzzy-ACO-based passive solar tracker system were obtained in the form of secondary and experimental data. These parameters include astronomical parameters (longitude and latitude position), DC motor parameters, namely voltage constant (Ke), torque constant (Kt), resistance (R), inductance (L), viscous friction coefficient (Bm), motor inertia (Jm), and motor torque (Tm). The photovoltaic parameters are Ish (shunt current), Rpv (PV equivalent resistance), Rsh (shunt resistance), and Io (saturation current). The design of a passive solar tracker based on fuzzy-ACO has a performance index (average) with a rise time of 0.45 s, a settling time of 0.701 s, a maximum overshoot of 0.5%, and a steady-state error of 0,05%. From the performance index produced by the passive solar tracker with fuzzy-ACO control, it can be concluded that fuzzy-ACO control has a faster response in reaching the set point with a smaller error value than using fuzzy control. Compared with a fixed PV, increasing the power efficiency using fuzzy-ACO on a 3-position passive solar tracker can increase the gross energy gain efficiency by 42.79% over 10 hours compared with a fixed PV. In addition, if FLC control is used, the gross energy gain efficiency will be 38.63% higher than that of the fixed PV. The 5-position passive solar tracker using fuzzy-ACO can increase the gross energy gain efficiency by 43.99%. In addition, if FLC control is used, the gross energy gain efficiency is 39.55% compared to that of the fixed PV.

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AUTHOR CONTRIBUTIONS STATEMENT

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
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R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY

The data supporting the findings of this study are available from the corresponding author, [IA], upon reasonable request.

REFERENCES

[1] O. Melfazen, M. T. Alawity, and D. Dewatama, "Firefly algorithm for optimizing single axis solar tracker," *Kinetik: Game Technology, Information System, Computer Network, Computing, Electronics, and Control*, Nov. 2021, doi: 10.22219/kinetik.v6i4.1338.

[2] A. Alam *et al.*, "Jellyfish search optimization algorithm for MPP tracking of PV system," *Sustainability*, vol. 13, no. 21, p. 11736, Oct. 2021, doi: 10.3390/su132111736.

[3] I. Abadi, R. Delfianti, and M. Ihwani, "Design of an active dual-axis solar tracking system using fuzzy ant colony controller," *International Review on Modelling and Simulations (IREMOS)*, vol. 16, no. 2, p. 62, Apr. 2023, doi: 10.15866/iremos.v16i2.23315.

[4] L. Z. Yang, M. A. M. Yunus, S. Sahlan, and A. Jamali, "Automated dual-axis solar tracking system using fuzzy logic control," in *2023 IEEE 9th International Conference on Smart Instrumentation, Measurement and Applications (ICSIMA)*, IEEE, Oct. 2023, pp. 150–154. doi: 10.1109/ICSIMA59853.2023.10373468.

[5] I. Abadi, D. N. Fitriyanah, and A. U. Umam, "Design of maximum power point tracking (MPPT) on two axes solar tracker based on particle swarm fuzzy," 2019, p. 020041. doi: 10.1063/1.5095293.

[6] M. A. Qasim and V. I. Velkin, "Maximum power point tracking techniques for micro-grid hybrid wind and solar energy systems - a review," *International Journal on Energy Conversion (IRECON)*, vol. 8, no. 6, p. 223, Nov. 2020, doi: 10.15866/irecon.v8i6.19502.

[7] A. Soetedjo and I. B. Sulistiawati, "Implementing discrete model of photovoltaic system on the embedded platform for real-time simulation," *Energies*, vol. 13, no. 17, p. 4447, Aug. 2020, doi: 10.3390/en13174447.

[8] J. P. N. Torres, R. A. Marques Lameirinhas, C. P. Correia V. Bernardo, H. I. Veiga, and P. M. dos Santos, "A discrete electrical model for photovoltaic solar cells—d1mxp," *Energies*, vol. 16, no. 4, p. 2018, Feb. 2023, doi: 10.3390/en16042018.
[9] J. F. Alvarado, E. Betancur, and A. Velasquez-Lopez, "Optimization of single-axis discrete solar tracking," in *2020 9th International Conference on Renewable Energy Research and Application (ICRERA)*, IEEE, Sep. 2020, pp. 271–275. doi: 10.1109/ICRERA49962.2020.9242726.
[10] A. . Smirnov, A. G. Vozmilov, and P. A. Romanov, "Comparison of discrete sun tracking methods for photovoltaic panels," in *2019 International Conference on Industrial Engineering, Applications and Manufacturing (ICIEAM)*, IEEE, Mar. 2019, pp. 1–5. doi: 10.1109/ICIEAM.2019.8742775.
[11] M. H. de Sá Campos and C. Tiba, "NpTrack: a n-position single axis solar tracker model for optimized energy collection," *Energies*, vol. 14, no. 4, p. 925, Feb. 2021, doi: 10.3390/en14040925.
[12] D. N. Fitriyanah and I. Abadi, "Design of bacterial foraging interval fuzzy logic controller on hybrid solar tracker-ocean wave energy converter," *IPTEK The Journal of Engineering*, vol. 7, no. 2, p. 36, Aug. 2021, doi: 10.12962/j23378557.v7i2.a9250.
[13] D. Remoaldo and I. Jesus, "Analysis of a traditional and a fuzzy logic enhanced perturb and observe algorithm for the mppt of a photovoltaic system," *Algorithms*, vol. 14, no. 1, p. 24, Jan. 2021, doi: 10.3390/a14010024.
[14] H. Afghoul, H. Chabana, S. Merah, F. Krim, and A. Harrag, "Comparison study between conventional and advanced mppt based on fuzzy logic and anfis for standalone system," in *2020 6th International Symposium on New and Renewable Energy (SIENR)*, IEEE, Oct. 2021, pp. 1–6. doi: 10.1109/SIENR50924.2021.9631912.
[15] F. Rerhrhaye, I. Lahlouh, Y. Ennaciri, C. Benzazah, A. El Akkary, and N. Sefiani, "New solar mppt control technique based on incremental conductance and multi-objective genetic algorithm optimization," *International Journal on Energy Conversion (IRECON)*, vol. 10, no. 3, p. 70, May 2022, doi: 10.15866/irecon.v10i3.22156.
[16] L. Fan and X. Ma, "Maximum power point tracking of pemfc based on hybrid artificial bee colony algorithm with fuzzy control," *Scientific Reports*, vol. 12, no. 1, p. 4316, Mar. 2022, doi: 10.1038/s41598-022-08327-5.
[17] S. Krishnan G, S. Kinattingal, S. P. Simon, and P. S. R. Nayak, "MPPT in pv systems using ant colony optimisation with dwindling population," *IET Renewable Power Generation*, vol. 14, no. 7, pp. 1105–1112, May 2020, doi: 10.1049/iet-rpg.2019.0875.
[18] L. Mohammad, E. Prasetyono, and F. D. Murdianto, "Performance evaluation of aco-mppt and constant voltage method for street lighting charging system," in *2019 International Seminar on Application for Technology of Information and Communication (iSemantic)*, IEEE, Sep. 2019, pp. 411–416. doi: 10.1109/ISEMANTIC.2019.8884303.
[19] N. Thungsuk *et al.*, "Performance analysis of solar tracking systems by five-position angles with a single axis and dual axis," *Energies*, vol. 16, no. 16, p. 5869, Aug. 2023, doi: 10.3390/en16165869.
[20] M. F. Sigit, R. Ridwan, and S. P. Sari, "PID controller simulation on single axis solar tracking system," *ELKOMIKA: Jurnal Teknik Energi Elektrik, Teknik Telekomunikasi, & Teknik Elektronika*, vol. 11, no. 1, p. 58, Jan. 2023, doi: 10.26760/elkomika.v11i1.58.
[21] Q. Wang and X. Chang, "Maximum power point tracking of pv system under partial shading conditions based on tso-ip&o algorithm," in *2023 3rd International Conference on Energy, Power and Electrical Engineering (EPEE)*, IEEE, Sep. 2023, pp. 155–159. doi: 10.1109/EPEE59859.2023.10351794.
[22] I. Abadi, A. Musyafa', W. Z. Putra, and D. N. Fitriyanah, "Performance analysis of dual axis solar tracker based on fuzzy PID controller on street lighting," in *2020 International Conference on Computer Engineering, Network, and Intelligent Multimedia (CENIM)*, IEEE, Nov. 2020, pp. 257–263. doi: 10.1109/CENIM51130.2020.9297938.
[23] K. Xia, Y. Li, and B. Zhu, "Improved photovoltaic MPPT algorithm based on ant colony optimization and fuzzy logic under conditions of partial shading," *IEEE Access*, vol. 12, pp. 44817–44825, 2024, doi: 10.1109/ACCESS.2024.3381345.
[24] C.-F. Juang, C.-H. Lin, and T. B. Bui, "Multiobjective rule-based cooperative continuous ant colony optimized fuzzy systems with a robot control application," *IEEE Transactions on Cybernetics*, vol. 50, no. 2, pp. 650–663, Feb. 2020, doi: 10.1109/TCYB.2018.2870981.
[25] F. Ye and H. Ren, "Maximum power tracking system for photovoltaic power generation in local shadow environment based on ant colony optimization fuzzy algorithm," *EAI Endorsed Transactions on Energy Web*, vol. 11, Sep. 2024, doi: 10.4108/ew.4487.
[26] N. Priyadarshi, S. Padmanaban, J. B. Holm-Nielsen, F. Blaabjerg, and M. S. Bhaskar, "An experimental estimation of hybrid anfis–pso-based mppt for pv grid integration under fluctuating sun irradiance," *IEEE Systems Journal*, vol. 14, no. 1, pp. 1218–1229, Mar. 2020, doi: 10.1109/JSYST.2019.2949083.
[27] D. N. Fitriyanah, R. D. P. Saputra, I. Abadi, and A. Musyafa, "Optimal cleaning robot on solar panels with time-sequence input based on internet of things," *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 15, no. 1, p. 280, Feb. 2025, doi: 10.11591/ijece.v15i1.pp280-291.

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