EMITOR: Jurnal Teknik Elektro

Photovoltaic System Performance Analysis with the Application of Hybrid Maximum Power Point Tracking Based on Incremental Conductance (INC)

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Abstract – *It requires work to maximize photovoltaic (PV) power output in order to maximize solar panel input to the battery and avoid overcharging or overdischarging. A technique to determine the value of the maximum power point (MPPT) is required in order to enhance the performance of photovoltaic systems and guarantee that solar panels run at the MPP. This study proposes a hybrid MPPT method that combines Incremental Conductance (INC) with Grey Wolf Optimizer (GWO) to improve tracking accuracy and system efficiency under varying environmental conditions. In the application of Standard Test Conditions (STC), a comparative analysis was conducted between systems without MPPT, systems using conventional INC-based MPPT, and systems using the proposed hybrid GWO-INC MPPT. The results show that to achieve the maximum power point of the panel, the hybrid method provides superior performance, which gets the maximum power point tracking efficiency value of 64.34% and solar panel efficiency of 12.86%, compared to without using MPPT, which only gets the maximum power point tracking efficiency value of 52.9% with panel efficiency of 10.58%.*

Keywords – *Grey Wolf Optimizer; Incremental Conductance; Maximum Power Point Tracking (MPPT); PV System; INC-based MPPT.*

TO convert solar energy into electrical energy, PV (photovoltaic cell) is used [1–3]. Photovoltaic is an environmentally friendly renewable energy source. The PV's output current and voltage are affected by the intensity of the sun [4]. In order to maximize the power that photovoltaic systems can produce, power optimization techniques are crucial.

Maximum Power Point Tracking (MPPT) is one of the solar charge controller systems found in PV panel systems to produce maximum power. The MPPT controller can increase the current value that will enter the battery. This value can vary depending on the weather conditions on that day, the measured temperature, the battery charge status, and other factors using various supporting methods [5–7]. Maximum Power Point Tracking (MPPT) is a crucial technique for optimizing power output in photovoltaic (PV) systems. Various MPPT methods have been developed, including conventional approaches like Perturb and Observe (P&O) and Incremental Conductance (IC), as well as intelligent techniques using artificial neural networks and fuzzy logic [8, 9]. MPPT controllers can achieve efficiencies over 90% and significantly reduce battery charging time [10, 11]. Implementation often involves microcontrollers, DC-DC converters, and PWM signals [12, 13]. The effectiveness of MPPT systems has been demonstrated through both simulations and hardware implementations, showing improved performance under varying environmental conditions [14]. Recent advancements include IoT integration for remote monitoring and control [13]. MPPT techniques continue to evolve, with hybrid approaches showing promise for enhanced efficiency despite increased complexity and cost [8].

The advantage of the Incremental Conductance (INC) method is that it can show better results than the Perturb and Observe (P&O) method under changing environmental conditions. INC is also able to provide dynamic mathematical models to describe nonlinear properties [15]. The solar panel output optimization method can utilize a nature-inspired algorithm integrated into the DC-DC converter. The algorithm is needed to obtain global power by adjusting the duty

The manuscript was received on July 2, 2025, revised on July 18, 2025, and published online on July 25, 2025. Emitor is a Journal of Electrical Engineering at Universitas Muhammadiyah Surakarta with ISSN (Print) 1411 – 8890 and ISSN (Online) 2541 – 4518, holding Sinta 3 accreditation. It is accessible at https://journals2.ums.ac.id/index.php/emitor/index.

cycle, which is a key part of the switching mechanism in the converter circuit [16].

To simulate the social structure and hunting behavior of wolves in both local and global search processes, the Grey Wolf Optimizer (GWO) algorithm is applied. The GWO algorithm can converge faster than other nature-inspired algorithms [16].

In this study, the authors aim to compare and simulate the power output under three conditions: without MPPT, with Incremental Conductance-based MPPT, and with a hybrid GWO-INC MPPT. The simulation utilizes a buck-boost converter integrated with GWO in MATLAB to ensure that solar cells operate at their optimum point.

I. Research Methods

Previous research related to this study is conducted by Ammar et al. with the title *"Metaheuristic Optimization of Fractional Order Incremental Conductance (FO-INC) Maximum Power Point Tracking (MPPT)"*, which discusses the optimization of panel power values using metaheuristic-based maximum power point tracking and fractional incremental conductance control. The research found that the use of MPPT by applying the INC method only obtained an efficiency result of 75.9%, whereas using the FO-INC + PSO method resulted in 90.2% efficiency, and the FO-INC + ALO variable step achieved an efficiency of 98.1% [15].

i. PV Panel

Solar cells are devices that use the photovoltaic principle to convert solar energy into electrical energy. These cells continuously absorb sunlight energy at a certain intensity. Photovoltaic cells, or PV cells, are essentially large-area photodiodes. Due to their large surface area, these devices generate higher voltages and currents than typical photodiodes and are more sensitive to incoming light [17].

ii. Principle of Solar Radiation

Radiation is the energy from sunlight exposure that reaches the earth's surface. Photon particles carry the energy that constitutes radiation. A solar energy collection device captures the energy contained in each unit of solar radiation. The solar constant—the amount of solar energy that reaches the earth's atmosphere—is approximately 1350 W/m^2. The sunlight that reaches the earth's surface is around 1000 W/m^2 [18].

Morning and evening sunlight angles are less optimal than midday, so the power received varies accordingly with weather conditions. The power-to-voltage (P-V) and current-to-voltage (I-V) curves change in response to variations in solar intensity and ambient temperature, as illustrated in Figure 1. The power generated by solar panels based on solar radiation is expressed as:

The performance of a photovoltaic (PV) system can be evaluated using several key equations.

$$P_{in} = G \times A \tag{1}$$

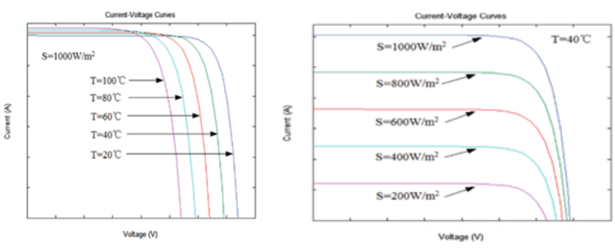
Equation (1) represents the calculation of the input power (P_{in}) received by the solar panel, which is the product of solar irradiance (G) measured in watts per square meter (W/m^2) and the surface area of the panel (A) in square meters (m^2). This equation indicates the total solar energy incident on the panel.

$$P_{out} = I_{out} \times V_{out} \tag{2}$$

Equation (2) is used to determine the output power (P_{out}) of the solar panel, calculated as the product of the output current (I_{out}) in amperes and the output voltage (V_{out}) in volts. This reflects the electrical power generated by the solar system after converting sunlight into electricity.

$$\text{Efficiency }(\%) = \frac{P_{out}}{P_{in}} \times 100 \tag{3}$$

Equation (3) defines the conversion efficiency of the solar panel in percentage. It is obtained by dividing the output power (P_{out}) by the input power (P_{in}) and multiplying by 100. This efficiency indicates how effectively the solar photovoltaic system converts solar energy into usable electrical energy.
where G is the solar radiation intensity (W/m^2) and A is the panel surface area (0.6 m^2).



(a) (b)

Figure 1: Characteristics of PV Curves Based on Environmental Factors [2, 19, 20]. (a) Current vs Voltage Curve due to Temperature (b) Current vs Voltage Curve due to Radiation

iii. Maximum Power Point Tracking (MPPT)

A technique called Maximum Power Point Tracking (MPPT) is used to determine the maximum operating point of solar cells and ensure they continue operating at that point. A typical MPPT operation for a solar panel system is illustrated in Figure 2 [21–23].

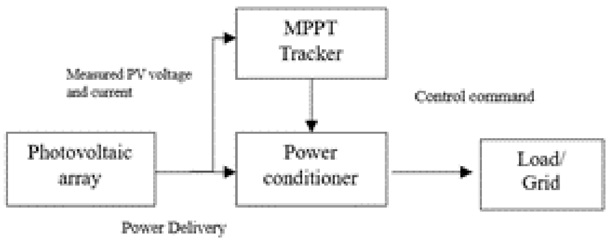


Figure 2: Block Diagram of MPPT Topology in Solar Panel System [21].

The block diagram of the designed INC-GWO hybrid MPPT system consists of solar panels, a buck-boost circuit, and a resistive load, as shown in Figure 3.

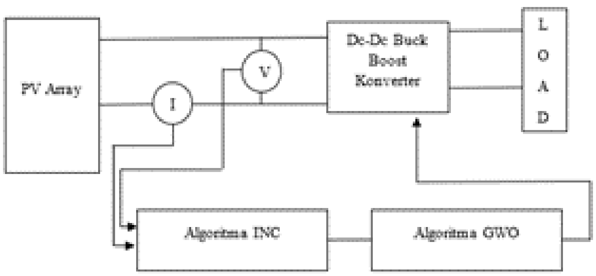


Figure 3: Block Diagram of Hybrid MPPT INC System Design.

iv. *Buck-Boost Converter*

DC-DC converters that can produce output voltages either higher or lower than the input voltage are called buck-boost converters. The duty cycle is an important parameter that determines the minimum required inductance and capacitance in the circuit. The duty cycle is given by:

$$D = \frac{V_{out}}{V_{in} + V_{out}} \tag{4}$$

The converter in this study operates in Continuous Conduction Mode (CCM), and the minimum inductance (L) can be estimated using:

$$L > \frac{V_{in} \times D^2}{\Delta I_L \times f_s} \tag{5}$$

where L is the minimum inductance (H), f_s is the switching frequency (Hz), and ΔI_L is the peak-to-peak ripple current.

The minimum capacitance (C) required in the buck-boost converter is calculated based on the output voltage ripple:

$$C > \frac{I_o \times D^8}{\Delta V_o \times f} \tag{6}$$

where I_o is the output current, ΔV_o is the output voltage ripple, and f is the switching frequency [24].

In making the buck-boost converter simulation design, variables such as input voltage and the minimum and maximum output values are determined. The design specifications used are the result of calculations, as shown in Table 1.

Table 1: Buck-Boost Converter Design Specifications

Specification	**Value**
Input Voltage (VI)	18–25 volt
Maximum Output Voltage (VO_{max})	14.5 volt
Maximum Output Current (IO_{max})	4 A
Switch Frequency	50 kHz
Voltage Ripple (V_r/V_o)	1%
Resistance (Ω)	3
Duty Cycle	10% – 90%
Value of Inductor Used (L)	31 μH
Value of Capacitor Used (C_o)	261 μF

v. *Incremental Conductance*

One approach for tracking the maximum power point is the Incremental Conductance (INC) method. The voltage at the maximum power point can be matched by adjusting the array terminal voltage based on the slope of the PV array power curve. This operational concept is illustrated in Figure 4 [18, 25, 26].

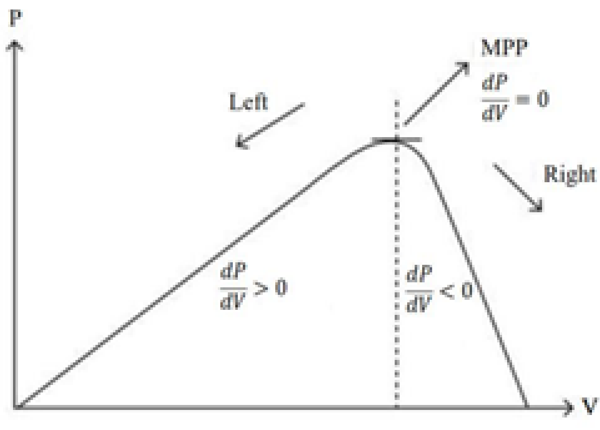


Figure 4: INC Working Point Chart [18, 25, 26].

The converter integrated with MPPT is combined with the PV module design to form a complete PV system using the INC method, as shown in Figure 5.

vi. *Grey Wolf Optimizer*

Alpha (α), beta (β), delta (δ), and omega (ω) are members of the grey wolf's social hierarchy. Grey wolf

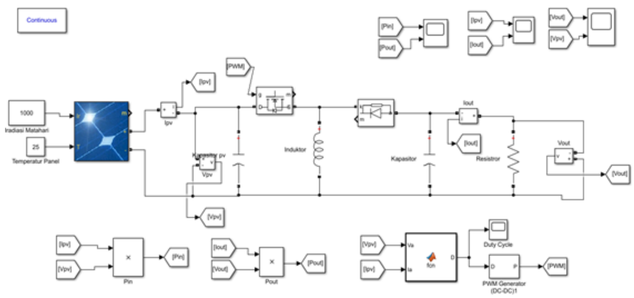


Figure 5: PV Panel System Design with INC Algorithm.

packs use a hierarchical optimization model to determine when to attack prey, with the alpha wolf as the leader guiding the group toward the best solution [27].

When the absolute value of the vector A exceeds 1, the wolves abandon their current prey and begin searching for a more profitable target, simulating exploration behavior. The duty cycle position update for each wolf can be formulated as follows:

$$D_i(k+1) = D_i(k) - a \times e \quad (7)$$

Where:

- $D_i(k)$ is the position of the i^{th} grey wolf at iteration k,
- a is the coefficient vector controlling convergence,
- e is the distance vector between the grey wolf and prey.

The solar panel system utilizing the GWO-INC-based algorithm integrated with the buck-boost converter is illustrated in Figure 6.

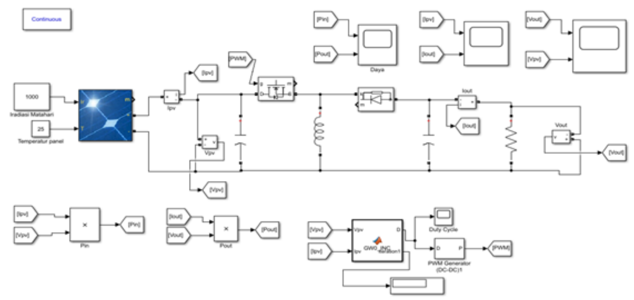


Figure 6: GWO-INC-based MPPT Simulation Design.

vii. *Solar Radiation and Panel Temperature Data*

The system testing was conducted over a 15-day period from 09:00 to 16:00, with measurements taken every 15 minutes. The collected data on solar radiation and panel temperature is presented in Table 2.

II. Results and Discussion

Table 2: Solar Radiation and Panel Temperature Data

Time (WIB)	Solar Radiation (W/m^2)	Panel Temperature (°C)
9:00	497.5	29.3
9:15	695.1	37.0
9:30	806.6	35.8
9:45	983.5	43.2
10:00	1066.2	45.7
10:15	1114.8	41.3
10:30	1200.0	45.7
10:45	1270.7	41.3
11:00	1236.3	40.6
11:15	1217.6	48.6
11:30	1220.0	44.1
11:45	363.4	42.9
12:00	1357.9	47.7
12:15	1141.7	44.3
12:30	175.4	33.0
12:45	183.3	40.2
13:00	1033.2	45.6
13:15	1023.1	42.2
13:30	1059.8	46.5
13:45	1154.7	48.4
14:00	1089.4	44.8
14:15	883.5	48.2
14:30	939.1	42.1
14:45	847.6	38.7
15:00	846.5	42.1
15:15	916.6	42.4
15:30	684.1	37.2
15:45	723.3	38.9
16:00	858.8	35.1

i. *Testing Results of Buck-Boost Converter*

The results of the buck-boost converter simulation are presented in Table 3.

Table 3: Simulation Results of Buck-Boost Converter Design

Duty Cycle (%)	V_{out} (V)	I_{out} (A)	Efficiency (%)
40	12.49	2.49	93.7
70	35.5	7.10	95.8

From Table 3, it can be observed that when the duty cycle is below 60%, the converter acts in buck mode ($V_{out} < V_{in}$), and when the duty cycle is above 60%, it acts in boost mode ($V_{out} > V_{in}$). The simulation results are consistent with the theory that buck-boost converters regulate voltage by adjusting the duty cycle.

ii. *Analysis of MPPT Simulation Results Using Incremental Conductance*

Simulation tests were carried out from 09:00 to 16:00. The collected data, including panel voltage (V_{pv}), current (I_{pv}), and power (P_{pv}), along with the corresponding values using the Incremental Conductance (INC) MPPT method, are presented in Table 4.

Table 4: Simulation Result of INC based MPPT Tracking

Time (WIB)	V_{panel} (V)	I_{panel} (A)	P_{panel} (W)	V_{INC} (V)	I_{INC} (A)	P_{INC} (W)
9:00	21.89	1.94	42.47	10.69	3.56	38.06
9:15	21.86	1.99	43.50	10.80	3.60	38.88
9:30	21.89	2.39	52.32	11.86	3.95	46.85
9:45	21.10	3.12	65.83	13.39	4.46	59.72
10:00	20.90	3.00	62.70	13.00	4.39	57.07
10:15	21.51	3.12	67.11	13.41	4.47	59.94
10:30	21.38	2.92	62.43	12.90	4.30	55.47
10:45	21.74	3.10	67.39	13.50	4.50	60.75
11:00	21.84	2.99	65.30	13.23	4.41	58.34
11:15	19.90	3.47	69.05	12.90	4.31	55.60
11:30	20.25	3.53	71.48	13.17	4.39	57.82
11:45	20.23	1.52	30.75	8.80	2.96	26.05
12:00	21.23	3.15	66.87	13.37	4.45	59.50
12:15	21.30	3.00	63.90	13.20	4.43	58.48
12:30	20.61	0.79	16.28	6.40	2.13	13.63
12:45	20.00	0.78	15.60	6.30	2.10	13.23
13:00	20.98	3.10	65.04	13.30	4.44	59.05
13:15	21.24	3.15	66.91	13.50	4.49	60.62
13:30	20.99	3.00	62.97	13.00	4.40	57.20
13:45	21.00	2.88	60.48	12.75	4.25	54.19
14:00	21.18	3.10	65.66	13.20	4.40	58.08
14:15	20.43	3.06	62.52	13.00	4.34	56.42
14:30	21.06	3.14	66.13	13.40	4.47	59.87
14:45	21.89	2.21	48.38	11.38	3.79	43.13
15:00	21.60	2.18	47.09	11.23	3.74	42.00
15:15	20.61	3.40	70.07	13.40	4.50	60.30
15:30	21.80	1.99	43.38	10.78	3.60	38.81
15:45	21.78	1.99	43.34	10.78	3.59	38.70
16:00	21.51	3.14	67.54	13.40	4.48	60.03

The output power comparison between the panel's native performance and that obtained through INC-based MPPT is shown in Figure 7.

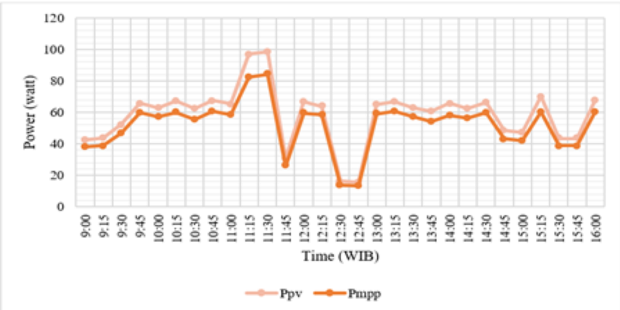


Figure 7: Comparison of Panel Power and INC-based MPPT Output

From the data, it can be concluded that the efficiency of the solar panel system increases as the output power approaches the theoretical input power. The efficiency is highly influenced by the proper selection of components according to standard solar panel specifications. A significant deviation in panel characteristics can result in decreased efficiency.

iii. Analysis of MPPT Simulation Using Hybrid (GWO-INC)

Based on simulations under real-world solar radiation and panel temperature conditions, Table 4 (not shown here for brevity) presents values for V_{pv}, V_{out}, I_{pv}, and I_{out} under Hybrid GWO-INC MPPT operation.

iv. Analysis of MPPT Simulation Using Hybrid (GWO-INC)

Based on the simulation results under varying solar radiation and temperature conditions, the Hybrid GWO-INC MPPT performance data is summarized in Table 5.

Table 5: Simulation Result of Hybrid GWO-INC-based MPPT Tracking

Time (WIB)	V_{panel} (V)	I_{panel} (A)	P_{panel} (W)	$V_{GWO\text{-}INC}$ (V)	$I_{GWO\text{-}INC}$ (A)	$P_{GWO\text{-}INC}$ (W)
9:00	21.25	2.10	44.63	10.74	3.58	38.45
9:15	20.98	2.55	53.50	11.78	3.93	46.30
9:30	20.84	3.27	68.15	13.30	4.44	59.05
9:45	20.00	3.85	77.00	14.20	4.74	67.31
10:00	20.69	3.20	66.21	13.00	4.36	56.68
10:15	21.20	3.14	66.57	13.10	4.38	57.38
10:30	20.97	3.12	65.43	13.00	4.34	56.42
10:45	20.90	4.06	84.85	14.80	4.96	73.41
11:00	21.43	3.20	68.58	13.30	4.44	59.05
11:15	20.77	3.10	64.39	12.80	4.29	54.91
11:30	20.59	4.00	82.36	14.70	4.90	72.03
11:45	18.46	1.40	25.84	7.63	2.54	19.38
12:00	20.50	4.00	82.00	14.70	4.89	71.88
12:15	20.97	3.16	66.27	13.10	4.36	57.12
12:30	20.36	0.67	13.64	7.69	1.90	14.61
12:45	19.90	0.68	13.53	5.70	1.91	10.87
13:00	20.48	3.40	69.63	13.40	4.48	60.03
13:15	20.48	3.80	77.82	14.20	4.73	67.17
13:30	20.56	3.25	66.82	13.20	4.39	57.95
13:45	20.69	3.08	63.73	12.80	4.27	54.66
14:00	20.86	3.12	65.08	13.00	4.33	56.29
14:15	20.00	3.20	64.00	12.90	4.30	55.47
14:30	20.82	3.06	63.71	12.90	4.29	55.34
14:45	20.73	3.25	67.37	13.25	4.42	58.57
15:00	20.45	3.23	66.05	13.10	4.36	57.12
15:15	20.58	3.30	67.91	13.30	4.43	58.92
15:30	20.28	3.18	64.49	12.94	4.31	55.77
15:45	20.13	3.38	68.04	13.20	4.44	58.61
16:00	21.04	3.31	69.64	13.40	4.50	60.30

The comparison of output power between the panel and the GWO-INC MPPT system is shown in Figure 8.

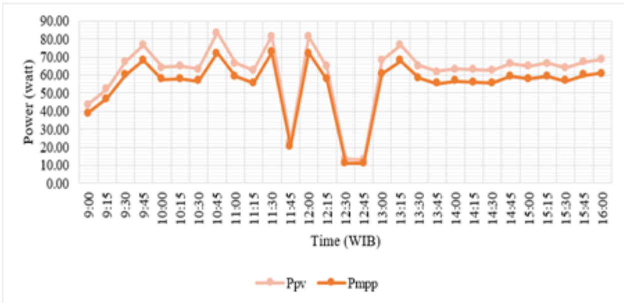


Figure 8: Comparison of Panel Power and GWO-INC Based Tracking Results

The GWO-INC hybrid algorithm yields higher power output compared to the INC-only method. As with the previous method, efficiency is maximized when the output power closely matches the input, which is influenced by proper component selection. Significant variations in panel characteristics may cause efficiency degradation.

v. Performance Test Under Standard Test Conditions (STC)

To evaluate optimization performance under Standard Test Conditions (STC), where solar radiation is

1000 W/m^2 and panel temperature is 25°C, simulations were conducted without MPPT, using INC, and using the hybrid GWO-INC. The results are shown in Table 6.

Table 6: STC Condition Performance Test Result Data

Description	Without MPPT	MPPT INC	MPPT GWO-INC
P_{ideal} (W)	120	120	120
I_{out} (A)	3.1	3.3	4.1
V_{out} (V)	13.8	14.15	15.23
V_{pv} (V)	22.75	22.63	21.7
I_{pv} (A)	3.1	3.3	4.1
Time Period (s)	0.5	0.5	0.5

vi. *Efficiency Analysis*

Using Equations (1) to (3), the efficiencies of the solar panel and MPPT tracking are calculated as follows.

Without MPPT:

$$P_{in} = 1000 \text{ W/m}^2 \times 0.6 \text{ m}^2 = 600 \text{ W}$$
$$P_{out} = 4.6 \text{ A} \times 13.8 \text{ V} = 63.48 \text{ W}$$
$$\eta_{\text{panel}} = \frac{63.48}{600} \times 100 = 10.58\%$$
$$\eta_{\text{MPPT}} = \frac{63.48}{120} \times 100 = 52.9\%$$

With MPPT (INC):

$$P_{out} = 4.7 \text{ A} \times 14.15 \text{ V} = 66.505 \text{ W}$$
$$\eta_{\text{panel}} = \frac{66.505}{600} \times 100 = 11.08\%$$
$$\eta_{\text{MPPT}} = \frac{66.505}{120} \times 100 = 55.42\%$$

With Hybrid MPPT (GWO-INC):

$$P_{out} = 5.07 \text{ A} \times 15.23 \text{ V} = 77.216 \text{ W}$$
$$\eta_{\text{panel}} = \frac{77.216}{600} \times 100 = 12.86\%$$
$$\eta_{\text{MPPT}} = \frac{77.216}{120} \times 100 = 64.34\%$$

The summary of the calculations is presented in Table 7.

Table 7: Efficiency Comparison: MPPT Tracking and Panel Output

Description	η_{MPPT} (%)	η_{panel} (%)
Without MPPT	52.9	10.58
MPPT (INC)	55.42	11.08
Hybrid MPPT GWO-INC	64.34	12.86

The hybrid GWO-INC MPPT provides superior output power and adapts better to environmental changes compared to systems without MPPT or with conventional INC. However, under certain test points, the INC method yielded slightly better instantaneous efficiency, likely due to dynamic conditions.

III. Conclusion

Based on the tests and analysis conducted, the following conclusions can be drawn:

1. Solar radiation significantly affects the output voltage and current of solar panels, while panel temperature has a smaller but still relevant effect.
2. Implementing MPPT improves the performance of PV systems. In this study, the GWO-INC hybrid MPPT achieved a maximum power point tracking efficiency of 64.34% and a panel efficiency of 12.86%.
3. Without MPPT, the system only reached 52.9% MPPT efficiency and 10.58% panel efficiency.

Acknowledgment

The authors would like to express their deepest gratitude to Allah SWT for providing health and opportunity. Appreciation is also extended to our parents for their continued support, and to Universitas Bengkulu for the facilities provided. It is hoped that this paper contributes to a better understanding of maximum power point tracking in solar energy systems through the application of the GWO-INC hybrid method.

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