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Comparative performance analysis of MPPT algorithms for wind power generation: P&O, INC, and TSR methods

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ABSTRACT

Wind energy has great potential, especially in areas with high wind speeds such as Southeast Aceh. However, wind speed fluctuations reduce turbine efficiency, necessitating maximum power point tracking (MPPT) for optimization. This study compared three MPPT methods perturb and observe (P&O), incremental conductance (INC), and tip speed ratio (TSR) to identify the most effective technique. Using MATLAB Simulink, simulations were conducted with wind speed data from Southeast Aceh and a DC-DC boost converter. Results showed the P&O method performed best, producing 847.83 W at 10 m/s, compared to 702.40 W for INC and 324.35 W for TSR. P&O also achieved the highest current output, reaching 16.45 A, while INC and TSR produced 13.66 A and 6.34 A, respectively. At lower wind speeds, P&O continued to outperform the other methods. This study concludes that the P&O method is the most effective method to improve the efficiency of wind turbines in Southeast Aceh, while INC shows moderate performance and TSR is the least effective method due to fluctuating wind speeds in a short time, so that TSR cannot maintain its maximum value. Therefore, P&O is recommended as the optimal MPPT technique for wind power plants in this region.

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1. INTRODUCTION

Wind energy is a reliable, clean, and ecologically renewable resource whose utilization and transformation are crucial for solving problems such as energy scarcity, environmental degradation, and other issues. Wind energy has become increasingly popular in recent decades due to increasing energy demand and environmental concerns. With continuous innovation and investment, wind energy continues to play a crucial role in the transition to a sustainable energy future [1]-[3]. However, the efficiency of wind energy conversion is highly dependent on wind speed, which fluctuates constantly. These variations result in inconsistent power output, making it necessary to implement optimization techniques to ensure maximum energy extraction from wind turbines [3], [4]. Wind turbines are negatively impacted by wind speed turbulence, which causes parameter changes, power fluctuations, and vibrations. A wind turbine's ability to mitigate disturbances is crucial for capturing optimal power in real time. Consequently, over the past decade, a control method known as maximum power point tracking (MPPT) has been introduced [4]. MPPT is widely used to improve the efficiency of wind turbines by continuously adjusting the system to operate at its optimal power point [5]-[8]. The latest research on MPPT was conducted by comparing the maximum electrical power tracker (MEPT) and the maximum mechanical power tracker (MMPT) and the results showed that both provide high efficiency, namely 99.28% and 98.04%, respectively [9]. Kumar and Chatterjee [10] said that in his research a comparison of the MPPT method was observed that the tip speed ratio (TSR) control method, power signal feedback (PSF) control, and optimal torque (OT) control were methods that responded very quickly compared to others. Combined the perturb and observe (P&O) method and artificial neural network control (NNC), the simulations conducted in this study showed that NNC-based MPPT and P&O control can track and maintain maximum power for any wind speed value. This approach has been proven to contribute to the successful extraction of maximum power from wind energy conversion systems (WECS). Therefore, the developed system has good prospects in WECS network applications [11], [12]. In this study, wind turbine modeling was performed by applying and comparing three MPPT methods to simulate changes in wind speed. The results are expected to contribute to improving wind energy efficiency and provide practical recommendations for optimizing wind power generation systems, especially in locations with turbulent wind conditions [13].

2. METHOD

This study uses a quantitative simulation-based approach to evaluate the performance of the MPPT method in a wind power plant. The research process begins with modeling the wind turbine system using MATLAB/Simulink software. This modeling includes a wind turbine, generator, power converter, and MPPT control to optimize output power. This simulation is designed to test three MPPT algorithms at various wind speed conditions, the modeling of which can be seen in Figure 1.

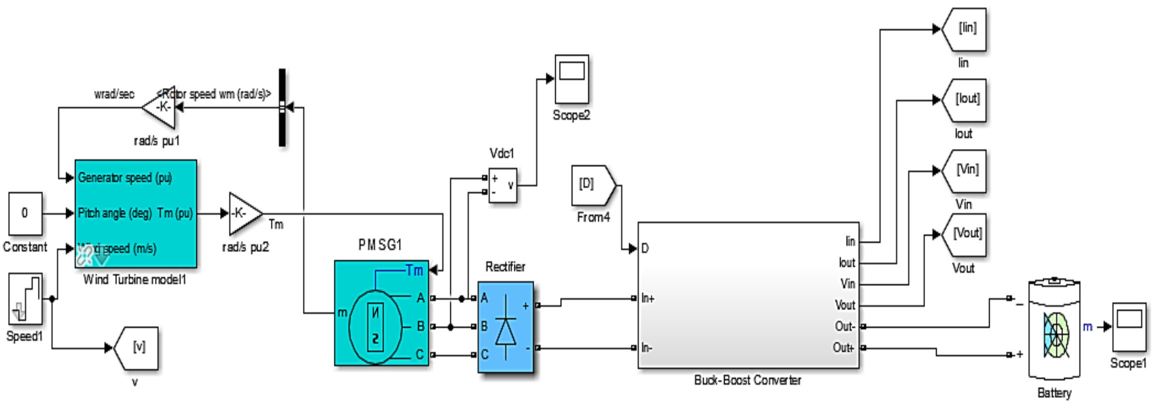


Figure 1. Modelling wind turbine

The simulation output data includes voltage, current, and system output power for each MPPT method. The simulation results are analyzed to calculate the output power efficiency of each MPPT algorithm, aiming to understand the adaptability of each method to dynamic conditions in the field [14]. The independent variable in this study is the MPPT algorithm used, while the dependent variables include system output power, power efficiency, and electrical parameters such as voltage and current generated. System output power is calculated based on the electrical energy successfully extracted from the wind turbine in each MPPT algorithm. Power efficiency is calculated by comparing the actual output power with the maximum power available at a certain wind speed. The secondary data collection method was carried out by accessing wind speed data from the Southeast Aceh region. This data was obtained from an official source, the meteorological agency from NASA POWER data access viewer. The data obtained is in time-series format containing wind speed measurement data from January to December 2023. The data is accessed at https://power.larc.nasa.gov/data-access-viewer/ and is public data that can be accessed for general purposes. This analysis also evaluates the algorithm's response to wind speed variations, focusing on the specific diagram shown in Figure 2.

A 48 V battery was chosen to reduce transmission losses while maintaining system stability. To achieve this voltage, appropriate converter parameters such as inductance (L), capacitance (C), and duty cycle (D) were calculated using (1), (2), and (3). These equations determine the relationship between input and output voltages, ensuring the converter operates efficiently according to system requirements.

- Determining the duty cycle value [15] is expressed as (1), where M_v is ratio V_o of V_s, V_o is voltage output (V), and V_s is voltage input (V).

$$M_v = \frac{V_o}{V_s} = \frac{1}{1-D} \tag{1}$$

$\frac{54}{48} = \frac{1}{1-\mathrm{D}}$
$54(1-\mathrm{D}) = 48\mathrm{D}$
$54 - 54\mathrm{D} = 48\mathrm{D}$
$54 - 54\mathrm{D} = 48\mathrm{D}$
$54 = 54\mathrm{D} + 48\mathrm{D}$
$54 = 102\mathrm{D}$
$\mathrm{D} = \frac{54}{102} = 0.53\%$

- Determining inductance [16] is expressed as (2), where L_b is inductance (H), D is diode, R is resistance (Ohm), and f is frequency (Hz).

$$L_b = \frac{(1-D)^2 R}{2f} \quad (2)$$

$L_b = \frac{(1-0.53)^2 3}{2.500}$
$L_b = \frac{0.6627}{1000}$
$L_b = 0.0006627H = 0.6\ mH$

- Determining capacitance value [17] is expressed as (3), where C_{min} is capacitance (F), D is diode, V_o is output voltage (V), f is frequency (Hz), and R is resistance (Ohm).

$$C_{min} = \frac{DV_o}{V_r Rf} \quad (3)$$

$C_{min} = \frac{0.53\ .\ 54}{0.5\ .3.500}$
$C_{min} = \frac{28.62}{750} = 0.038\ F$

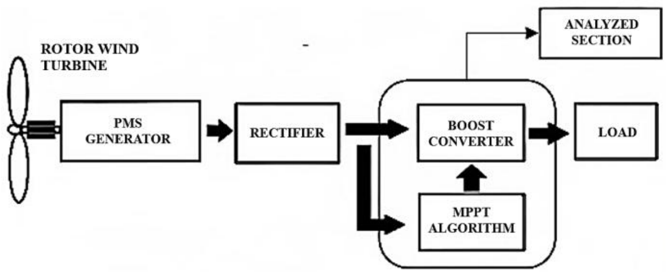


Figure 2. Scheme to be analyzed

The wind power plants system is modeled in MATLAB/Simulink, integrating wind turbines, power converters, batteries, and MPPT algorithms [18]. The power converter, including a rectifier and a DC-DC converter, adjusts the output for storage or load [19]. The operating principle of the buck-boost converter circuit is divided into two operating modes: switch-on and switch-off. During the switch-on state, the diode is reverse-biased, so no current flows through the diode; in this state, the diode voltage (VD) is equal to –(VS + VO). In the switch-off state, the input voltage is disconnected and the diode is forward-biased, causing current to flow from the inductor to the capacitor. In this state, the capacitor is charged. The load receives energy from the inductor, causing a decrease in current in the inductor until the switch is turned back on [20]. The battery stores excess energy to maintain supply stability [21]. The MPPT algorithms—P&O, incremental conductance (INC), and TSR—optimize power extraction by controlling the duty cycle of the DC-DC converter [22]. The simulation evaluated system performance, analyzing power output, voltage, current, and efficiency for each MPPT method.

The wind turbine is designed to operate optimally at an average wind speed of 12 m/s, with a fixed pitch angle of 0 degrees to maximize wind capture. The wind turbine specifications are carried out by considering wind speed as the main input. The wind speed of 12 m/s was chosen by referring to the average wind speed in the Southeast Aceh region, which is recorded at 10.4 m/s. The selection of 12 m/s was made to consider wind speed fluctuations that can occur in the field and to test the system performance under more optimal operational conditions. To regulate the output voltage despite wind speed fluctuations, a buck-boost converter is applied. This converter adjusts the voltage level based on system requirements and consists of main components, including MOSFET switches, diodes, inductors, capacitors, and resistors. The converter is configured with an input voltage of 48 V, an inductance of 0.66 mH, a capacitance of 0.2 μF, a duty cycle of 0.53%, and a resistance of 3 Ω. To support continuous power supply, a 48 V, 10 Ah lithium-ion battery is integrated into the system [23]. This battery technology was chosen due to its high energy density and longer cycle life compared to lead-acid batteries [24]. The battery acts as an energy storage unit, maintaining power delivery even when wind speed fluctuations affect turbine output [25]. The battery model incorporates key parameters such as nominal voltage, charge-discharge limits, and efficiency. This integration of the storage system improves the reliability of the wind power generation system [26].

The simulations compare these models to determine the most effective MPPT strategy for maximizing wind power generation efficiency. Four system models were developed:

i) Without MPPT (baseline model)

The wind turbine output is directly supplied to the load via a buck-boost converter, with no optimization. Output power depends entirely on wind speed variations. Figure 3 shows the baseline system design in MATLAB.

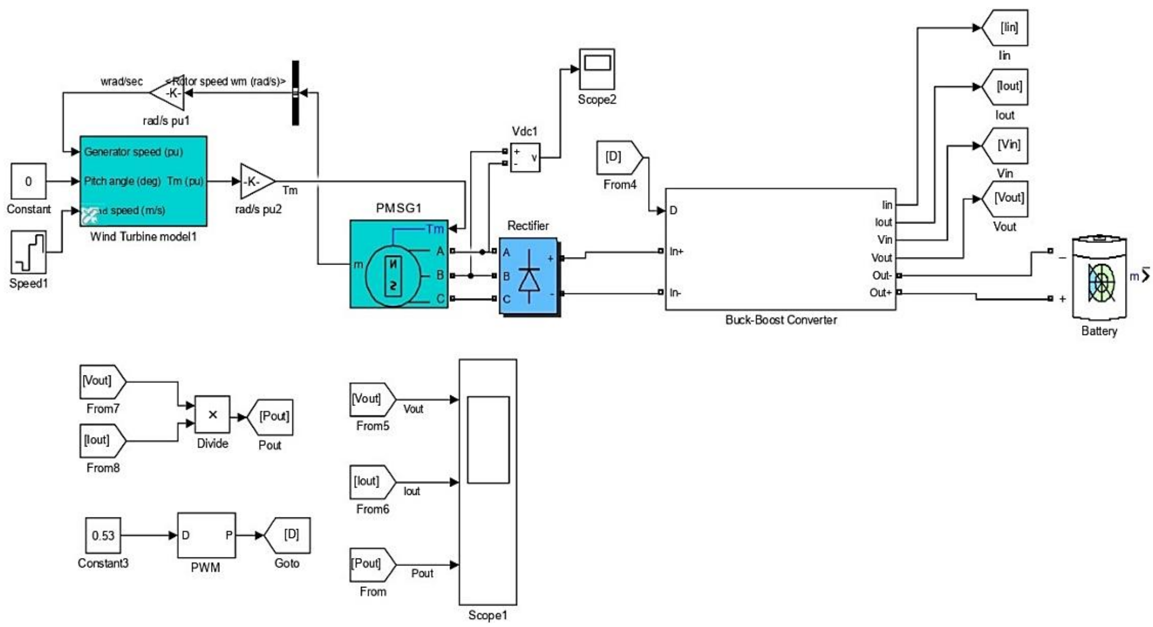
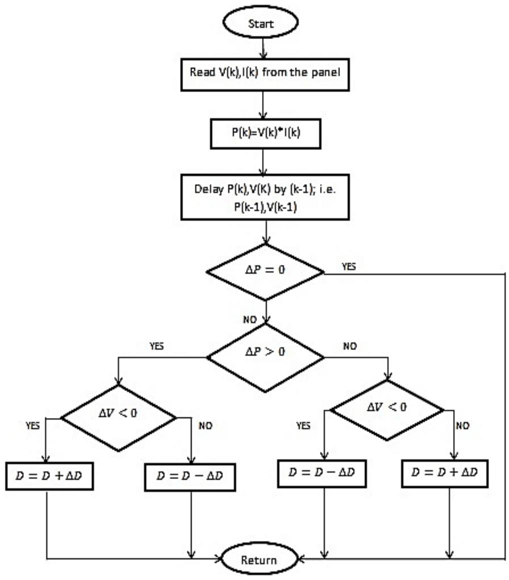


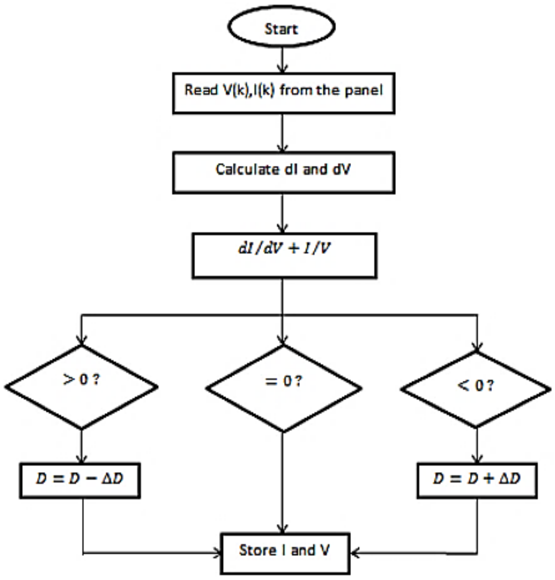
Figure 3. Baseline system design

ii) MPPT uses perturb and observe (P&O) and MPPT uses INC

The most commonly used MPPT algorithm is the P&O method. This algorithm uses a simple feedback setup and few measurable parameters. In this approach, the voltage is periodically perturbed and the corresponding output power is compared with the output power of the previous perturbation cycle. The perturbation and observation method measures and assesses the instantaneous operating region, then based on that region, the reference voltage is increased or decreased so that the system operates near the maximum power point [11]. Since this method only increases or decreases the reference voltage, its implementation is simple. However, this method cannot easily track rapid and immediate changes in environmental conditions. This algorithm can be easily understood through the following flowchart shown in Figure 4(a). In rapidly changing wind conditions, the problems associated with the P&O method are addressed by the INC method. The incremental conductance method can determine when the MPPT has reached the MPP and stops perturbing the operating point. If this condition is not met, the direction in which the MPPT should be perturbed can be calculated using the relationship between dI/dV and –I/V. This relationship is derived from the fact that dP/dV is negative when the MPPT is on the right side of the MPP curve and positive when it is on the left side of the MPP curve. This algorithm determines when the MPPT has reached the MPP, while the P&O oscillates around the MPP. This is a clear advantage over P&O [27]. The disadvantage of this algorithm is that it is more complex than P&O. This algorithm can be easily understood through the following flowchart shown in Figure 4(b).



(a)



(b)

Figure 4. Differences between algorithm flowcharts for (a) flowchart MPPT P&O and (b) flowchart MPPT INC

iii) MPPT using tip speed ratio (TSR)

Controlling rotor speed to maintain optimal TSR relative to wind speed ensures maximum power capture. This method improves efficiency, especially at varying wind speeds [28]. The working principle of MPPT TSR is to compare the actual value with the optimal TSR value to ensure the wind turbine operates optimally at all times. This method is a direct method for MPPT control. This method offers a simple concept, a more flexible controller design, and easier speed tracking performance improvements. However, real-time wind speed measurement is essential, which increases system costs. Furthermore, fluctuating wind speeds can cause deviations from the maximum power point. Therefore, two additional aspects need to be added to improve this algorithm: sophisticated mechanical sensors and a control algorithm for fluctuating loads [29]. As shown in Figure 5, the controller controls the inverter output based on the error between the actual TSR, λ, and the optimal TSR, λ, making feedback adjustments through the generator speed, ω opt, to keep λ in the optimal state.

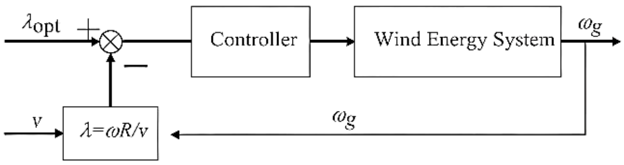


Figure 5. TSR MPPT design

3. RESULTS AND DISCUSSION

3.1. Simulation results for wind power plants without MPPT

The wind power plants system without MPPT operates without power optimization, reflecting its baseline performance. During the simulation, voltage, current, and power output were recorded to assess system behavior. The results are shown in Table 1. The measurement results without MPPT show the voltage, current, and power related to wind speed variations. Table 1 shows a relatively stable voltage, ranging from 51.08 V to 51.35 V, indicating that the generator maintains a nearly constant output despite changes in wind speed. The lowest voltage of 51.08 V occurs at 6 m/s, while the highest voltage of 51.35 V is recorded at 10 m/s. Then the current freezes more significantly, with the lowest value of 3.92 A at 6 m/s and the highest 11.12 A at 10 m/s. As the wind speed increases, the output current increases, which directly affects the power generation. And the output power increases with the wind speed, as shown at 6 m/s, the power is 200.23 W, increases sharply to 469.54 W at 9 m/s, and reaches a peak of 571.01 W at 10 m/s. However, at a speed of 8 m/s, the power drops temporarily to 373.54 W before increasing again.

Table 1. Output parameter values of wind power plants without MPPT

Time (s)	Wind speed (m/s)	Voltage (V)	Current (A)	Power (W)
0	7	51.11	5.56	284.17
2	6	51.08	3.92	200.23
4	9	51.26	9.16	469.54
6	10	51.35	11.12	571.01
8	8	51.24	7.29	373.53

3.2. Performance analysis of wind power plants with MPPT perturb and observe (P&O)

This section presents the simulation results of the wind power plants system using the MPPT P&O algorithm, which gradually adjusts the reference voltage to track the maximum power point (MPP). The analysis includes voltage, current, and power output, comparing performance with and without MPPT. The algorithm's response to wind speed variations is also evaluated.

Table 2 shows that the P&O MPPT significantly increases the output power. At 7 m/s, the power reaches 441.17 W, compared to 284.17 W without the MPPT, with a peak of 847.83 W at 10 m/s, demonstrating its effectiveness for parameter variations over time. Table 2 shows that the P&O MPPT system maintains a stable voltage (51.15 V – 51.54 V), demonstrating its effectiveness in handling wind variations. Table 2 shows a significant increase in the output current, reaching 16.45 A at 10 m/s, compared to 11.12 A without the MPPT, resulting in a higher power output, and the power output with the P&O MPPT is significantly higher. At 6 m/s, the power reaches 299.74 W, compared to 200.23 W without the MPPT. At 10 m/s, the power peaks at 847.83 W, far exceeding the 571.01 W without MPPT.

Table 2. Output parameter values of wind power plant with MPPT P&O

Time (s)	Wind speed (m/s)	Voltage (V)	Current (A)	Power (W)
0	7	51.18	8.62	441.17
2	6	51.15	5.86	299.7
4	9	51.39	12.66	650.59
6	10	51.54	16.45	847.83
8	8	51.38	10.42	535.37

3.3. Performance of MPPT incremental conductance (INC)

This section presents the simulation results of the MPPT TSR algorithm, which optimizes power output by maintaining the optimal blade tip speed ratio. The results, including voltage, current, and power output, are compared with other MPPT methods. Table 3 shows the voltage, current, and power of the MPPT INC.

Table 3 shows that the INC MPPT system maintains a stable voltage (51.10 V – 51.42 V), demonstrating its effectiveness in handling wind variations. Table 3 shows that the output current increases to 13.66 A at 10 m/s, compared to 11.12 A without MPPT, resulting in a higher output power. As the wind speed increases, the output current and power also increase significantly, demonstrating the algorithm's effectiveness in maximizing power extraction. At 6 m/s, the output power reaches 247.32 W; at 10 m/s, the power increases to 702.40 W. Although the P&O MPPT produces higher power, the INC remains an efficient alternative, offering a stable voltage and better output power compared to the system without MPPT.

Table 3. Output parameter values of wind power plant with INC

Time (s)	Wind speed (m/s)	Voltage (V)	Current (A)	Power (W)
0	7	51.14	6.45	329.85
2	6	51.1	4.84	247.32
4	9	51.32	10.87	557.84
6	10	51.42	13.66	702.39
8	8	51.38	8.69	446.49

3.4. Performance of MPPT tip speed ratio (TSR)

This section presents the simulation results of the MPPT TSR algorithm, which optimizes power output by maintaining the optimal blade tip speed ratio. The results, including voltage, current, and power output, are compared with other MPPT methods. As shown in Table 4, the TSR MPPT system maintains a stable voltage (~51 V) but produces lower output current and power than the P&O and INC MPPTs. At 10 m/s, the power reaches 324.35 W, much lower than other MPPT methods. This indicates that TSR is effective in stabilizing the voltage, but its effect on the output current and power is limited. The output current increases with wind speed but remains lower than other MPPT methods. Table 4 shows that at 6 m/s, the current is 2.35 A, reaching 6.34 A at 10 m/s. In contrast, the P&O and INC MPPTs produce much higher currents, resulting in higher output power, and the power reaches 119.85 W, increasing to 324.35 W at 10 m/s. Compared with the P&O (847.83 W) and INC (702.39 W) MPPTs at the same speed, TSR is less effective in maximizing energy extraction.

Table 4. Output parameter values of wind power plant with TSR

Time (s)	Wind speed (m/s)	Voltage (V)	Current (A)	Power (W)
0	7	51.03	3.29	167.88
2	6	51	2.35	119.85
4	9	51.12	5.34	272.98
6	10	51.16	6.34	324.35
8	8	51.1	4.29	219.21

3.5. Comparison of wind power output results

The comparison of output voltage between systems without MPPT, MPPT P&O, MPPT INC, and MPPT TSR reveals significant differences in stability and optimization, as shown in Figure 6. MPPT P&O consistently delivers the highest voltage stability, followed by MPPT INC. MPPT TSR produces the lowest voltage output, indicating it is the least effective in improving voltage levels. The output current comparison examines how each method manages the power generated by the wind turbine. Similar to voltage behavior, a system without MPPT exhibits fluctuating current. MPPT algorithms dynamically adjust the system to maintain stable current despite varying wind speeds. This evaluation highlights each method's effectiveness in stabilizing output current and improving energy conversion efficiency. For the current over time, refer to Figure 7. The results, illustrated in Figure 7, show that MPPT P&O and MPPT INC significantly improve current output compared to a system without MPPT, while MPPT TSR performs the worst. MPPT P&O delivers the highest current values across all wind speeds, followed by MPPT INC. MPPT TSR consistently performs the worst, generating the lowest current values.

This section compares the output power of each tested method, as power output is the primary indicator of wind power system efficiency. MPPT algorithms are expected to generate higher power than a system without MPPT. The results are presented in graphs and tables to provide a clear understanding of each method's performance. For power over time, refer to Figure 8. As shown in Figure 8, MPPT P&O consistently delivers the highest power output, followed by MPPT INC. Meanwhile, MPPT TSR performs the worst in power optimization. MPPT P&O provides the highest power gains across all wind speeds, making it the most effective method. MPPT INC also improves power output but is slightly less efficient than P&O. The system without MPPT generates moderate power, while MPPT TSR consistently performs the worst.

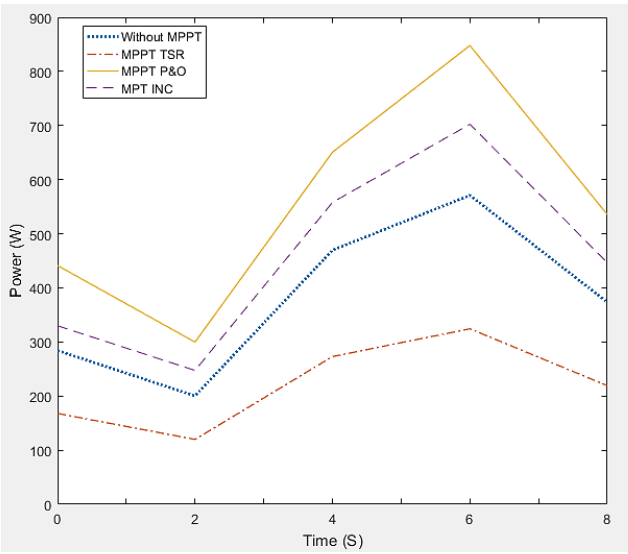


Figure 6. Voltage output comparison of wind power systems without MPPT and different MPPT methods

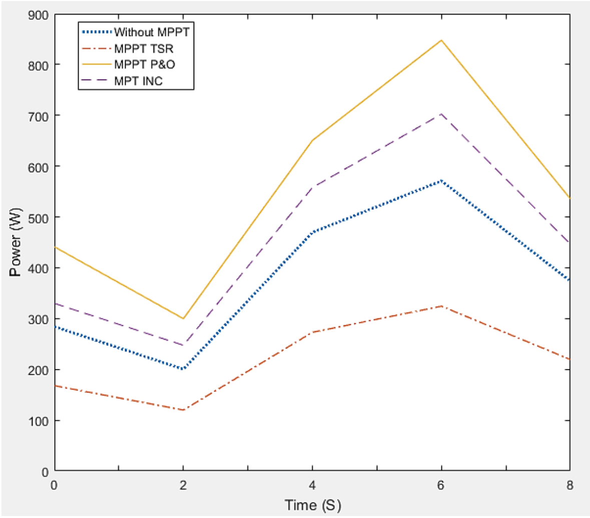


Figure 7. Current output comparison of wind power systems without MPPT and different MPPT methods

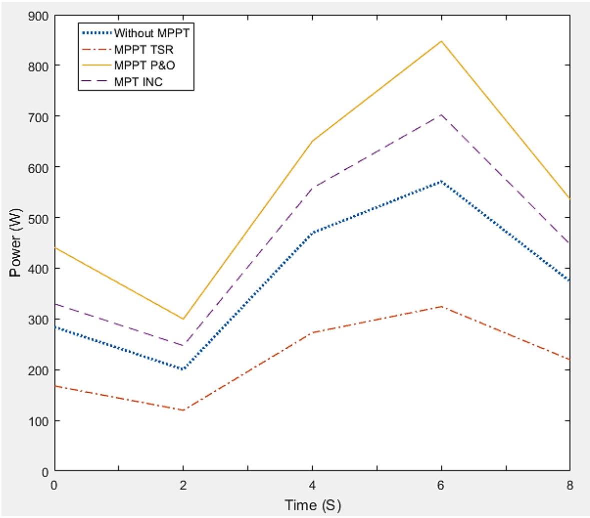


Figure 8. Power output comparison of wind power systems without MPPT and different MPPT methods

From Tables 5-7, it can be seen that the P&O method has the highest output value of the other two methods. This is because the P&O method tends to have a faster tracking speed compared to several other MPPT methods. The P&O algorithm is relatively simple and easy to implement in a control system, this method does not require in-depth knowledge of the physical parameters of the wind turbine, such as series or parallel resistance to operate. Meanwhile, the INC Incremental Conductance Algorithm method is more complex compared to other methods such as Perturb and Observe, so it requires a deeper understanding and greater computing resources and TSR Although adaptive, this method can be less effective in very turbulent or rapidly changing wind conditions because it requires time for adjustment and The performance of this method is highly dependent on the accuracy of the turbine performance modeling, which can be difficult to obtain precisely, especially for newly developed wind turbines or in varying operational conditions. The following are the overall test results for the three MPPT methods.

Table 5. Voltage output table of all methods

Time (s)	Wind speed (m/s)	Voltage (V) without MPPT	Voltage (V) P&O	Voltage (V) INC	Voltage (V) TSR
0	7	51.11	51.18	51.14	51.03
2	6	51.08	51.15	51.1	51
4	9	51.26	51.39	51.32	51.12
6	10	51.35	51.54	51.42	51.16
8	8	51.24	51.38	51.38	51.1

Table 6. Current output table of all methods

Time (s)	Wind speed (m/s)	Current (A) without MPPT	Current (A) P&O	Current (A) INC	Current (A) TSR
0	7	5.56	8.62	6.45	3.29
2	6	3.92	5.86	4.84	2.35
4	9	9.16	12.66	10.87	5.34
6	10	11.12	16.45	13.66	6.34
8	8	7.29	10.42	8.69	4.29

Table 7. Power output table of all methods

Time (s)	Wind speed (m/s)	Power (W) without MPPT	Power (W) P&O	Power (W) INC	Power (W) TSR
0	7	284.17	441.17	329.85	167.88
2	6	200.23	299.7	247.32	119.85
4	9	469.54	650.59	557.84	272.98
6	10	571.01	847.83	702.39	324.35
8	8	373.53	535.37	446.49	219.21

4. CONCLUSION

This study reveals significant wind energy potential in Indonesia, particularly in Southeast Aceh. Its location along the equator and mountainous landscape create favorable wind conditions. Show that the P&O MPPT method produced the highest power output at various wind speeds. At 7 m/s, this method produced 441.17 W, significantly higher than the 329.85 W obtained from the INC method and the 167.89 W obtained from the TSR method. Similarly, at 10 m/s, P&O produced the highest power output of 847.83 W, compared to 702.40 W INC and 324.35 W TSR. The output current followed a similar trend, with P&O producing the highest current value. For example, at 9 m/s, P&O produced 12.66 A, surpassing INC (10.87 A) and TSR (5.34 A). These results conclude that the P&O MPPT method is the most effective in optimizing wind turbine power output under various wind conditions. Although the INC method also performed well, its efficiency remained slightly lower than that of P&O. Conversely, the TSR method demonstrated the lowest efficiency in maximizing power generation. Therefore, for wind energy utilization in Southeast Aceh, the P&O MPPT method is recommended as the most optimal strategy for maximizing wind power conversion. Future researchers are advised to conduct further testing and analysis related to wind energy utilization, taking into account other factors that can affect wind turbine performance, such as wind direction, temperature variations, and humidity. Furthermore, further research can be conducted by developing a more adaptive control system that can adapt to changing environmental conditions in real time using artificial intelligence (AI) technology, thereby maximizing wind energy potential. Research on the use of more complex MPPT systems or a combination of several MPPT methods can also be carried out to test their efficiency under more extreme wind conditions.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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Maksum Pinem	✓		✓	✓	✓	✓		✓		✓	✓	✓	✓	

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
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

Authors state no conflict of interest.

DATA AVAILABILITY

The data that support the findings of this study will be available in https://power.larc.nasa.gov/data-access-viewer/. The derivative data that support the findings of this study are available from the corresponding author, [MAD], upon request.

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