Maximum Energy Harvesting Mechanism of Wind Turbine for Remote Island Electricity

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Abstract. The wind energy potential in Indonesia, according to the Ministry of Energy and Mineral Resources (ESDM), reaches 60.65 GW. The variable characteristics of the wind pose challenges in harnessing wind energy. Therefore, wind turbine systems need to be equipped with Maximum Power Point Tracking (MPPT) to enhance the output power in response to wind speed. A wind turbine system with a capacity of 3000 W, using a Permanent Magnet Synchronous Generator (PMSG) equipped with Perturb and Observe (P&O) based MPPT and a DC Boost Converter, has been presented in this paper through simulated test. The testing results shows that P&O MPPT has proven to increase the output power of the wind turbine.

Keywords: MPPT, Wind Turbine, Perturb, Observe.

1. Introduction

Indonesia, characterized by its archipelagic nature and abundant coastal regions, possesses natural conditions favorable for the advancement of renewable energy, particularly solar and wind power. According to the Ministry of Energy and Mineral Resources (ESDM), the nation possesses a considerable wind energy capacity of 60.65 GW. Through the analysis and mapping efforts of the ESDM ministry, it has been identified that regions with notable onshore wind potential encompass the southern coast of Java, South Sulawesi, Maluku, and East Nusa Tenggara.

The variable characteristics of the wind pose challenges in harnessing wind energy. With the fluctuating wind conditions, the design of an optimal and efficient wind turbine system is required. A wind turbine system equipped with Maximum Power Point Tracking (MPPT) can be a choice to maximize wind energy harvesting [1]. Maximum Power Point Tracking (MPPT) is a technique that optimizes the output power of a wind turbine in response to varying wind speed. Among the most prevalent MPPT techniques is Perturb & Observe (P&O) [2]. The harvested wind energy will be used to meet the load demand, and excess electrical energy generated by the wind turbine will be stored in the storage system, to be utilized when the load demand exceeds the generation capacity.

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Overall, there has been widespread research on Perturb & Observe (P&O) Maximum Power Point Tracking (MPPT) in wind turbine systems. However, there is a notable absence of research focused on the sensor-less MPPT mechanism for wind turbines that could enhance their power output. This study aims to fill this research gap by conducting modelling of the P&O MPPT mechanism in wind turbines.

2. System Configuration

Figure 1 shows a schematic of the wind turbine system for remote island power. The wind turbine system consists of a 3 kW PMSG which is coupled directly to the wind turbine. boost converter with mppt P&O algorithm is used to realize maximum power extraction from wind turbines.

2.1. Wind Turbine Model

Wind energy is generated as a result of the irregular distribution of solar radiation across the Earth's surface. Humans are capable of harnessing the mechanical energy of wind speed in order to satisfy their energy consumption requirements [3].

Turbines, which are also referred to as turbines, are apparatus designed to transform electrical energy from alternative sources including steam, water, and wind. Wind turbines function by converting the rotational motion of the wind into a mechanical energy source, which is subsequently utilized to power a generator. The quantity of wind energy captured by the turbine is dependent on the size of the turbine blades and the wind speed in a given region [3]. The subsequent equation can represent wind energy:

$$P_w = \frac{1}{2}\pi R^2 \rho v^3 \tag{1}$$

R denotes the radius of the wind turbine, ρ signifies air density, and v signifies wind speed within the formula. The equation can be used to express the generated mechanical power:

$$P_m = \frac{1}{2} C_p(\lambda, \beta)\, \pi R^2 \rho v_w{}^3 \tag{2}$$

Cp is the power coefficient (%)
0.57 is the utmost efficacy of a wind turbine, according to the Betz limit. where $C_p(\lambda, \beta)$ is the power coefcient function, λ is the tip speed ratio, β is the blade pitch angle. For a fixed bitch angle β=0, the power coefficient and tip speed ratio are expressed as:

The value in question is established through the interaction of the power coefficient Cp and the tip speed ratio/TSR (λ). TSR represents the ratio of turbine speed to wind speed, whereas the power coefficient represents the ratio of mechanical power to wind power [3].

$$C_p(\lambda, \beta) = C_1\left(\frac{C_2}{\lambda} - C_3\beta - C_4\right) e^{\frac{-C_5}{\lambda i}} + C_6\lambda \tag{3}$$

$$\lambda_i^{-1} = (\lambda + 0.008\,\beta)^{-1} - 0.035(1+\lambda^3)^{-1} \quad (4)$$

$$\lambda = \frac{\omega_m R}{V_w} \quad (5)$$

The maximal output power of the wind turbine is achieved when the power coefficient is adjusted to its maximum value, denoted as Cpmax, as stated in Equation (2). In the absence of wind speed exceeding the designated value, the wind turbine's pitch angle control is deactivated, resulting in a constant pitch angle (β). As a result, the power coefficient Cp can be manipulated by modifying the tip speed ratio, as indicated by Equation (3). Equation (5) additionally suggests that in order to attain the optimal tip speed ratio λ at a given wind speed, it is necessary to manipulate the rotor speed. In light of the rapid fluctuations in wind velocity, it is necessary to regulate the rotor speed in order to maintain operation at the Maximum Power Point (MPP). As a result, sophisticated controllers are required to regulate the rotor speed in order to obtain the maximum amount of power despite fluctuating wind velocities. Figure 1 presents the power-speed (P–ω) characteristic curve of the wind turbine, which visually represents varying wind velocities [4]. To achieve maximum power extraction, the corresponding values for λopt and Cp−max are determined to be 8.1 and 0.48, respectively.

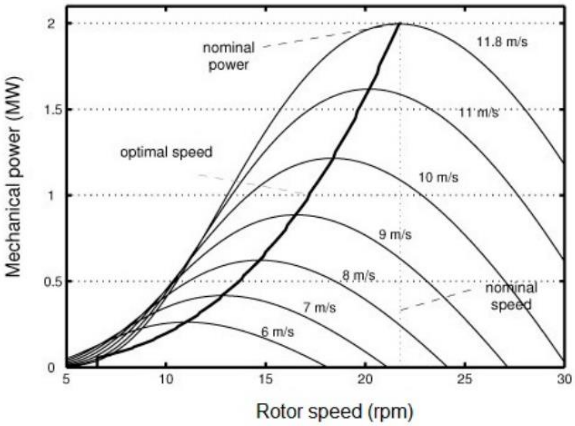

Fig 1. Wind turbine characteristics with pitch angle of 0◦ [4].

Table 1. Wind Turbine Parameters.

Parameters	Quantities and Units
Nominal mechanical output power	3000 W
Base power of the electrical generator	3000/0.9 VA
Base wind speed	12 m/d

Maximum power at base wind speed of nominal mechanical pow	1 p.u
Base rotational speed of base generator speed	1.3 p.u
Pitch angle beta to display wind turbine power characteristics	0°

2.2. Permanent Magnet Synchronous Generator (PMSG)

By means of a mechanism, the generator converts mechanical energy to electrical energy [5]. The functioning of this device entails the conversion of the torque (T) and rotor speed (ω) inputs into voltage (V) and current (I) values, respectively. The electricity generated by the Permanent Magnet Synchronous Generator (PMSG) is three-phase alternating current (AC). PMSG, which is commonly utilized in wind turbines of moderate to low power capacity, is of paramount importance in the process of electrical energy generation. The diagram below illustrates the d-axis and q-axis voltages (Vds and Vqs) of a surface-mounted PMSG in the dq reference frame [6]:

$$V_{\mathrm{ds}} = R_s \mathrm{i}_{ds} + L_d \frac{\mathrm{d}i_{ds}}{\mathrm{d}t} - \omega_s L_q \mathrm{i}_{qs} \tag{6}$$

$$V_{\mathrm{ds}} = R_s \mathrm{i}_{ds} + L_d \frac{\mathrm{d}i_{ds}}{\mathrm{d}t} - \omega_s L_d \mathrm{i}_{ds} + \omega_s \lambda_m \tag{7}$$

where Rs represents the stator resistance in ohms, ids and iqs denote the stator current along the direct and quadrature axes, Ld and Lq represent the inductances along the d–q axis, λm signifies the rotor flux linkage in weber units, and ωs signifies the electrical speed. Formatting the torque of the PMSM into the subsequent equation:

$$T = T_{em} + T_r = \frac{3}{2}.\frac{P}{2}.\mathrm{i}_{\mathrm{qs}}[\lambda_m + \left(L_d - L_q\right).\mathrm{i}_{\mathrm{ds}}] \tag{8}$$

where Tr and Tem represent, respectively, reluctance and electromagnetic torque, and P denotes the number of poles [6].

For surface-mounted PMSG, $L_{\mathrm{d}} = L_{\mathrm{q}}$. Consequently, $T_{\mathrm{r}} = 0$ and the machine torque is expressed as:

$$T = T_{em} = \frac{3}{2}.\frac{P}{2}.\mathrm{i}_{\mathrm{qs}} \lambda_m \tag{9}$$

Table 2. PMSG Parameters

Parameters	Quantities and Units
Number of phases	3
Back electro-motive force (EMF) waveform	Sinusoidal
Rotor type	Round

Parameters	Quantities and Units
Mechanical input	Torsi (Tm)
Stator phase resistance	0.4578

2.3. Rectifier

By means of a rectifier, alternating current (AC) is converted to direct current (DC). The diode is the fundamental component that forms the basis of the rectifier. When Alternating Current (AC) flows through a diode, it exhibits conduction for a portion of the wave while blocking for the remaining portion [7]. The system architecture integrates a half-wave rectifier, which utilizes a solitary diode to impede the propagation of the positive portion of the AC wave generated by the Permanent Magnet Synchronous Generator (PMSG) and allow the negative portion to pass through. Additionally, Table 3 presents the parameters utilized in this rectifier configuration.

Table 3. Rectifier Parameters.

Parameters	Quantities and Units
Number of bridge arms	3
Snubber resistance (Rs)	100000 Ω
Snubber capacitance (Cs)	Inf
Power electronic device	Diodes
Forward voltage (V_f)	0.8 V

2.4. Boost Converter

T One form of direct current converter, the boost DC-DC converter topology, operates to enhance the magnitude of the input voltage to produce an output voltage of a greater value. An inductor (L), active switching components such as an IGBT or MOSFET (Q), a diode (D) functioning as a passive switch, and a capacitor (C) comprise the boost converter. The boost converter circuit utilizes an inductor to store energy in the form of current, while the capacitor functions as a filter to diminish the fluctuation in the boost converter's output voltage [5]. Figure 2 depicts the circuit model of the boost converter. Table 4 presents the boost converter's parameters.

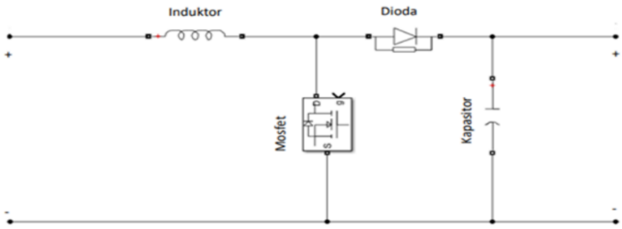

Fig 2 Boost Converter Circuit.

The relationship between the output voltage *(V_o)* and the input voltage *(V_s)* in buck mode can be expressed as Eq. (5) [5].

$$V_o = 1 - \frac{V_S}{D} \tag{10}$$

Meanwhile, the minimum inductor value *(L_{min})* and output capacitor *(C)* in the buck converter are expressed by Eq. (6) and Eq. (7).

$$L_{min} = \frac{(1-D)^2 * D * R}{2 * f} \tag{11}$$

$$C_{min} = \frac{D * Vout}{Vr * R * f} \tag{12}$$

Table 4. Boost Converter Parameters

Parameters	Quantities and Units
Frequency Switching (fs)	5000 Hz
Inductor (L)	0.0750 H
Capacitor (C)	0.46875 F

2.5. Perturb and Observe (P.O.) Algorithm

Maximum Power Point Tracking (MPPT) is a prevalent methodology utilized in the field of wind power generation with the objective of maximizing the extraction of power from renewable energy sources. By manipulating the duty cycle value in the DC converter, this method increases the power harvesting's efficacy. MPPT is employed to optimize the voltage of the generator by means of the rectifier, more precisely at the location of the boost converter [8]. Figure 2 illustrates the operational concept of the Perturb & Observe (PO) MPPT.

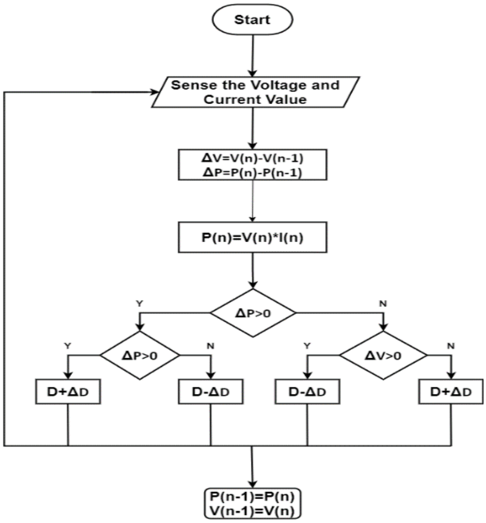

Fig 3. Flowchart Perturb and Observe (P.O.) Algorithm.

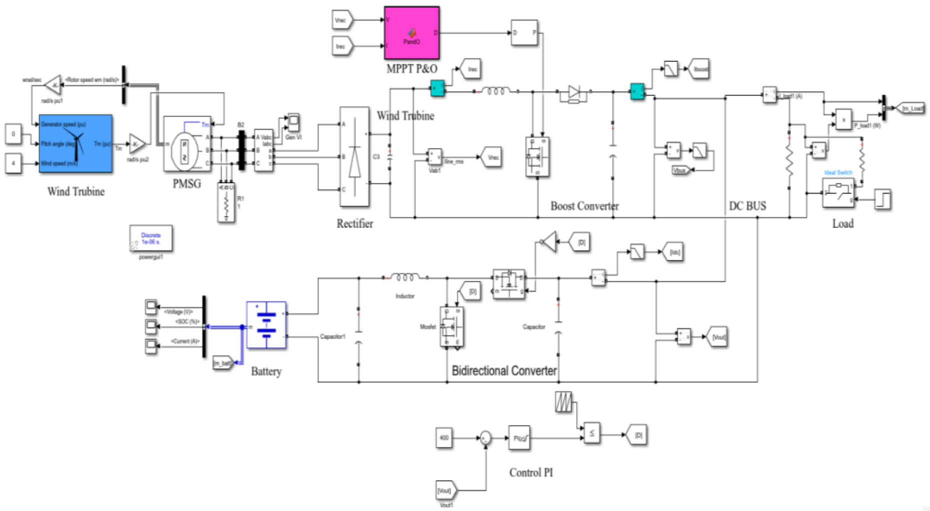

Fig 4. Circuit Model Simulation Maximum Energy Harvesting of Wind Turbine in Matlab/Simulink.

The flowchart of the MPPT Perturb and Observe (PO) algorithm is presented in Figure 2. In this context, V denotes the wind turbine's output voltage, and ΔV represents the new voltage value. P represents the wind turbine's output power, whereas ΔP denotes the new power value. The duty cycle value is denoted as D, whereas the duty cycle value modification from the previous duty cycle is represented by ΔD.

3. Simulation Result and Discussion

This section explains the Maximum Energy Harvesting Mechanism of wind turbines for power generation on remote islands. In this study, wind speeds of 12 m/s, 9 m/s, and 6 m/s were used to determine the wind energy harvesting mechanism. The mechanical output power of the wind turbine is 3000 W with a resistive load of 57 ohms. A simulation was conducted on the designed system utilizing MATLAB/Simulink for a duration of two seconds. The circuit model for simulation is illustrated in Figure 4.

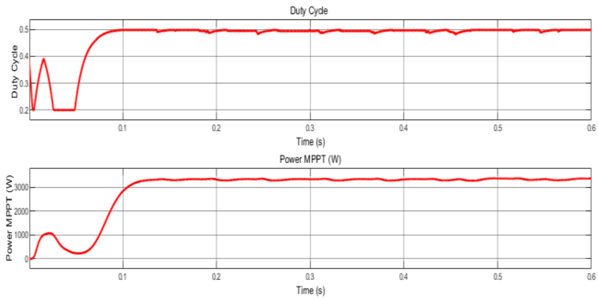

Fig 5. Duty Cycle Boost Converter and Output Power at wind speed 12 m/s.

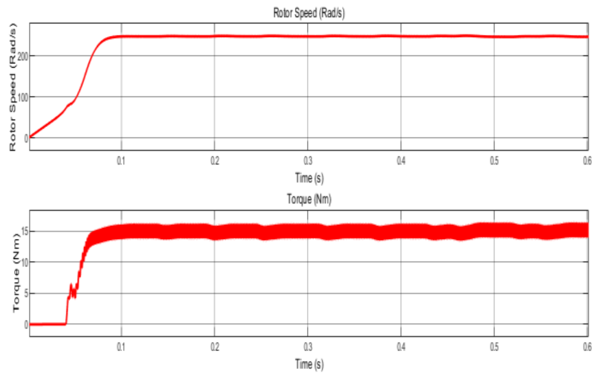

Fig 6 Rotor speed (Rad/s) and Torque (Nm) at Wind Speed 12 m/s.

Using the P&O MPPT algorithm, the output power of the wind turbine can be optimized for a wind speed of 12 m/s, as shown in Figures 6 and 7. Around 3300 W is the maximal power output of the wind turbine at a wind speed of 12 meters per second. The process of tracking the maximum power point of the wind turbine occurs from second 0 to second 0.1, during which the P&O algorithm will adjust the duty cycle, leading to changes in mechanical torque and rotor speed. This will enhance the output power of the wind turbine. From seconds 0.2 to 0.6, the turbine output power reaches the maximum point (steady state), and the duty cycle oscillates according to the P&O algorithm. The oscillating duty cycle also results in oscillations in torque, rotor speed, and output power of the wind turbine. During this steady-state condition, the torque and rotor speed values are 16 Nm and 255 rad/s, respectively, with a duty cycle of approximately 0.5.

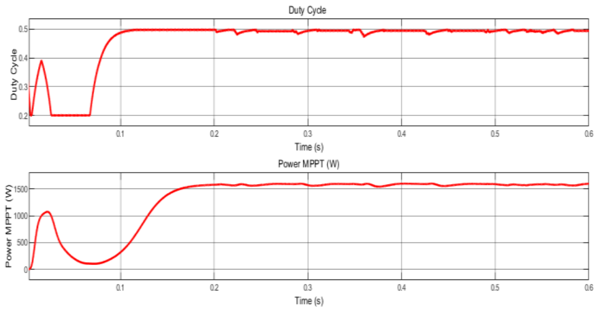

Fig 7. Duty Cycle Boost Converter and Output Power at wind speed 9 m/s.

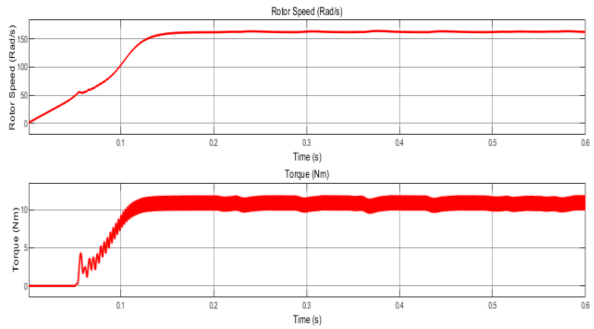

Fig 8 Rotor speed (Rad/s) and Torfuw (Nm) at Wind Speed 9 m/s.

Based on figures 7 and 8, with a wind speed of 9 m/s, the output power of the wind turbine can be maximized using the P&O MPPT algorithm. The maximum power value of the wind turbine at a wind speed of 9 m/s is around 1600 W. The process of tracking the maximum power point of the wind turbine occurs from second 0 to second 0.1, during which the P&O algorithm will adjust the duty cycle, leading to changes in mechanical torque and rotor speed. This will enhance the output power of the wind turbine. From seconds 0.2 to 0.6, the turbine output power reaches the maximum point (steady state), and the duty cycle oscillates according to the P&O algorithm. The oscillating duty cycle also results in oscillations in torque, rotor speed, and output power of the wind turbine. During this steady-state condition, the torque and rotor speed values are 12 Nm and 164 rad/s, respectively, with the duty cycle oscillating around 0.492-0.5.

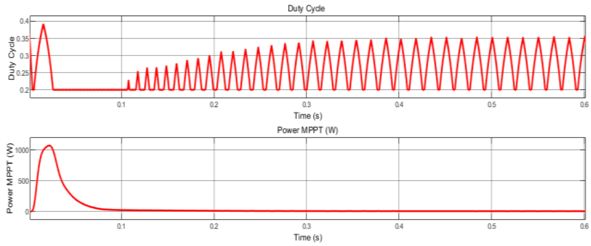

Fig 9 Duty Cycle Boost Converter and Output Power at wind speed 6 m/s.

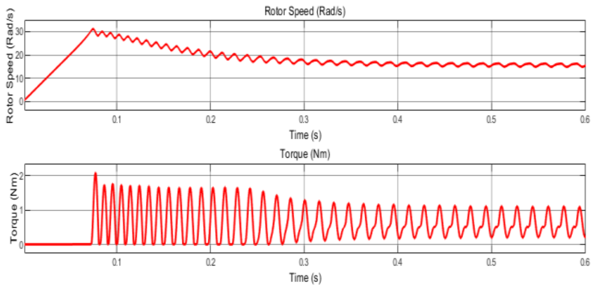

Fig 10. Rotor speed (Rad/s) and Torfuw (Nm) at Wind Speed 9 m/s.

The P&O MPPT algorithm can optimize the output power of the wind turbine at a wind speed of 6 m/s, as shown in figures 9 and 10. Around 8 W is the utmost power output of the wind turbine at a wind speed of 12 meters per second. The process of tracking the maximum power point of the wind turbine occurs from second 0 to second 0.1, during which the P&O algorithm will adjust the duty cycle, leading to changes in mechanical torque and rotor speed. This will enhance the output power of the wind turbine. From seconds 0.2 to 0.6, the turbine output power reaches the maximum point (steady state), and the duty cycle oscillates according to the P&O algorithm. The oscillating duty cycle also results in oscillations in torque, rotor speed, and output power of the wind turbine. During this steady-state condition, the torque and rotor speed values are 1 Nm and 16 rad/s, respectively, with a duty cycle ranging from approximately 0.26 to 0.35.

4. Conclusion

The results obtained from simulating the MPPT mechanism on the wind turbine using a Boost Converter with the P&O algorithm reveal its capability to effectively track the peak power point of the wind turbine output. The incorporation of P&O MPPT introduces changes in the duty cycle triggering the boost converter, subsequently affecting the output power value, torque, and rotor speed in the Permanent Magnet Synchronous Generator (PMSG). This, in turn, enables the wind turbine to achieve its maximum output power. Through systematic testing, it has been demonstrated that the implementation of P&O MPPT successfully enhances the output power of the wind turbine. For future research endeavors, addressing oscillations near the Maximum Power Point (MPP) can be achieved by modifying the P&O algorithm or exploring alternative algorithms. Additionally, to enhance the overall efficiency of the wind turbine, adjustments to parameters such as pitch angle, rotor speed, and optimization of the tip speed ratio should be considered.

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