Automatic Step Size Selection of the PO MPPT Algorithm to Improve Wind Power Generation

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ABSTRACT

Perturb and Observe (P&O) is a commonly used algorithm for Maximum Power Point Tracking (MPPT) in wind turbines. MPPT plays a critical role in enhancing wind turbine efficiency by dynamically adjusting operating parameters to adapt to fluctuating wind conditions. Although P&O is favored for its simplicity and adaptability, its performance is hindered by step size selection issues, which lead to inefficiency, oscillations, and slow convergence. To overcome these limitations, this research proposes a modified P&O algorithm that automates step size selection based on divided sectors of wind speed and normalized power in region two. Additionally, an integration of the pitch-angle control from region three was employed to maintain the optimal power output under variable wind conditions. The proposed approach reduces tracking time, minimizes perturbation errors, and ensures a stable power output. The proposed modifications enhance the efficiency and reliability of Wind Energy Conversion Systems (WECS) by addressing the shortcomings of the conventional P&O methods.

Keywords-wind turbine; modified MPPT; pitch angle

I. INTRODUCTION

The rapid advancement of wind energy technology is driven by the growing global demand for renewable energy sources, with the MPPT technology playing a crucial role in optimizing the efficiency of wind turbines. MPPT, widely recognized in Photovoltaic (PV) systems, optimizes power output by continuously tracking environmental conditions to operate at the Maximum Power Point (MPP) [1]. However, unlike the relatively stable conditions of PV systems, the application of MPPT in wind turbines is more complex due to the highly variable nature of wind speeds and directions. To maximize energy capture, MPPT systems continuously monitor wind conditions and dynamically adjust turbine parameters, such as rotor speed and generator load. Various MPPT methods, including P&O, fuzzy logic control, and neural networks, have been developed to enhance turbine performance, providing advanced solutions to ensure maximum energy extraction under fluctuating conditions. Thus, the implementation of MPPT significantly improves the power output efficiency, driving the development of wind power technology forward [2-4].

MPPT methods for wind power systems are essential for maximizing energy extraction from wind turbines by continuously adjusting the operating conditions. These methods are generally classified into two categories: direct and indirect methods [5, 6]. Direct methods use real-time measurements of the power output and adjust the turbine parameters directly to determine the optimal operating point. These methods are straightforward and adaptive, allowing a quick response to changes in wind conditions. However, they often require sensors and can be sensitive to noise, leading to potential inaccuracies. Indirect methods, on the other hand, rely on pre-established models or look-up tables that correlate specific operating conditions with optimal performance, rather than directly measuring power output. Although indirect methods reduce the need for sensors and are less affected by noise, they depend heavily on the accuracy of the models and may struggle to adapt to changing environmental conditions or turbine characteristics.

The MPPT algorithm of indirect power control for wind turbines plays a crucial role in optimizing energy capture by adjusting the turbine's operating point to its MPP [5]. A widely used method is the Power Signal Feedback (PSF), which involves implementing a predefined power curve to guide the turbine. The advantages of the PSF method include its simplicity and ease of implementation. However, its effectiveness can be reduced by changes in the wind conditions and inaccuracies in the predefined curve, making it less adaptable. Another approach is the Fuzzy Logic algorithm, which uses fuzzy rules to adjust the turbine's performance dynamically. This method is known for its adaptability and robustness in handling uncertainties, but it requires careful tuning of fuzzy rules and may be complex to implement. The Hill Climbing Search (HCS) method, on the other hand, adjusts the operating point by incrementally climbing toward the MPP. It is straightforward and easy to implement, but can be slow to converge, especially under rapidly changing wind conditions. Finally, the P&O algorithm works by perturbing the system and observing the resulting power change to determine the next step. Its simplicity and adaptability to varying wind speeds make it effective, though it may cause slight oscillations around the optimal point. In conclusion, although each method has its strengths and weaknesses, the P&O algorithm is the most effective one because of its simplicity, adaptability, and consistent performance under varying wind conditions, making it highly suitable for indirect power control in wind turbines [7, 8].

The P&O-MPPT, is the most widely deployed technique for MPPT due to its effectiveness as a sensorless mathematical optimization method, its flexibility, simplicity, and robustness, which do not require prior knowledge of wind turbine characteristics. This algorithm can track the MPP as the wind speed fluctuates, making it highly effective. However, selecting the appropriate step size remains a challenging task. A larger step size provides a faster response but causes more oscillations around the peak, reducing efficiency, whereas a smaller step size improves efficiency but slows down convergence. Several studies have explored modifications to the P&O algorithm, including Variable Step Size (VSS) [8-10], adaptive step size [11, 12], and hybrid approaches combined with other algorithms [13, 14]. Additionally, some studies have investigated enhancing MPPT performance by integrating it with Pitch Angle control when the power output reaches nominal levels [15-19]. The main challenge with this algorithm lies in selecting the appropriate step size, as it directly affects its performance, potentially leading to inefficiency, slower operation, high-speed oscillations, mechanical vibrations, and unstable electrical output. Therefore, it is still necessary to develop a new, efficient MPPT algorithm that addresses the shortcomings of current algorithms, enhances the power output efficiency, and further improves the performance of the WECS.

This study aims to introduce a new modified MPPT P&O algorithm to address the challenging task of selecting the appropriate step size under varying wind conditions and the shortcomings of the conventional P&O algorithm. The primary objective of this modification is to reduce the perturbation errors caused by the fluctuating wind conditions encountered when using the conventional P&O algorithm. To achieve this, an MPPT method is proposed that formulates an algorithm to automate step size perturbation by dividing sectors in region two based on normalized power and wind speed. Additionally, it implements pitch angle control in region two by adopting the pitch angle characteristics from region three to maintain the maximum power in each sector. The following list provides a summary of the main contributions of this study:

- This study proposes dividing the sector in region two to reduce the time tracking under significant wind speed fluctuations.
- Automation of step size selection to reduce perturb errors and shorten the time to achieve MPP.
- Due to physical constraints and safety regulations, the speed and extent of changes in the pitch angle of wind turbines are limited [20]. Therefore, this study proposes maintaining a fixed pitch angle for each sector in fluctuating wind conditions.

II. DESCRIPTION AND MODELING OF WIND TURBINE OPERATING REGIONS

A. Wind Generation System

In a WECS, the wind turbine converts the kinetic energy of the wind into mechanical energy, which is subsequently transformed into electrical energy. The factors that influence the conversion of wind energy into mechanical energy by the rotor include air density, the rotor's swept area, and wind speed. Both air density and wind speed are climatological variables that depend on the location. Therefore, wind turbines operate within a specific range of wind speeds, defined by cut-in and cut-out thresholds, to optimize the extraction of available wind power.

Wind turbine operating areas can be divided into four regions based on the cut-in cut-out wind speed.

- Region 1: There is no power generation from the wind turbine owing to the insufficient wind speed to initiate rotor rotation. The wind turbine remains idle until the wind speed exceeds the cut-in threshold.
- Region 2: The wind turbine generates power across a range of wind speeds but not at nominal power levels. This region starts from the cut-in speed and continues until the rated speed is reached.
- Region 3: The wind turbine generates power exceeding the nominal power level until the wind speed exceeds the cut-out threshold.
- Region 4: There is no power generation and illustrates distinct regions of operation for a wind turbine system.

The wind turbine operates in region 2 and region 3 when the wind speed exceeds the cut-in speed up to the rated speed. In region 2, the wind speeds have not yet reached the nominal rated speed. To optimize the power generation under these conditions, MPPT algorithms are required.

To handle the mechanical stresses experienced by wind turbine blades at high wind speeds, pitch angle controllers are required when operating in region 3 [21]. These controllers significantly adjust the angle of attack on the wind turbine blades. This adjustment is essential to prevent damage to the wind turbine, especially during unexpected wind gusts, and the reference pitch angle (β_{ref}) is continuously adapted, as stated by the following mathematical expression:

$$\beta_{ref} = \begin{cases} \beta_0 = 0, 0 < \omega_k < \omega_{rated} \\ \frac{\Delta\beta}{\Delta\omega_k}(\omega_k - \omega_{rated}) + \beta_0, \omega_k > \omega_{rated} \end{cases} \quad (1)$$

where β_{ref} is the reference pitch angle control, ω_k is the rotor speed in (rad/s), and ω_{rated} is the rated speed.

B. Model of Conventional-P&O Algorithm

Among the various MPPT algorithms, the P&O method is widely used to adjust the control variables during wind speed fluctuations. The P&O algorithm is a sensorless mathematical optimization technique that effectively searches for the MPP by providing a clear tracking process among the control variables. This conventional P&O algorithm observes the changes in power following each perturbation at the reference speed. If the system's harvested power increases, the rotor speed is adjusted in the same direction. Conversely, if the power decreases, the speed changes in the opposite direction. The tracking direction is determined by the sign of ΔP, and the analysis of this algorithm allows for the identification of the following operational rules:

- If $\Delta P_k > 0$, the speed set-point is added by $\Delta\Omega$ steps.
- If $\Delta P_k < 0$, the speed setpoint is reduced by $\Delta\Omega$ steps.

This process of perturbation and observation is repeated quickly and continuously. The goal is to reach and maintain the operating point at which the power produced by the wind turbine reaches its maximum. The iteration model can be described by [13]:

$$V_{k+1} = V_k + \alpha \,.\, \Delta V \quad (2)$$

where V_{k+1} is the predicted voltage, V_k is the measured voltage, and α is the duty cycle.

After applying perturbation, the generated power is:

$$P_{k+1} = Power\ Function\ at\ V_{k+1} \quad (3)$$

This value is compared with the previous value to determine the correct direction of the perturbation. The perturbation direction needs to be correct otherwise it is necessary to change.

C. Normalized Mechanical Power

The normalized mechanical power (P_k^N) is defined according to (4) and (5). Additionally, P_{max}^l represents the maximum power within each sector [15].

$$P_k^N = \frac{P_k}{P_k^{max}} x100 \quad (4)$$

$$\begin{cases} P_{max}^l = \beta_l . P_k^{max} \\ \Delta\omega_k^{ref} = \alpha_1 x \omega_k^{nom} \\ Where\ \omega_k^{nom} = \frac{\lambda_{opt} x V_k}{R} \end{cases} \quad (5)$$

where β_l is the pitch angle in each sector, l=1…L is the indicated index of the sector, λ_{opt} is the tip speed ratio, and R is the radius of the turbine.

III. PROPOSED METHOD

A. Automatic Selecting Step Size of P&O based on Sector in Region Two

The Automate selecting Step Size (ASS) P&O MPPT Technique enhances the algorithm's responsiveness and accuracy, ensuring more reliable and efficient power tracking under diverse wind conditions. This can be achieved by formulating an algorithm that automates the step size perturbation by dividing the sectors in region two based on the normalized power and wind speed.

This approach can eliminate errors that may occur in the CPO algorithm by implementing pitch angle control in region two by adopting the pitch angle characteristics in region three based on (1). Pitch angle control is used to maintain maximum power in each sector.

Sector (l1-4) in Table I represent the range of rotor speed and mechanical power, categorized based on the normalized power. The power normalization is divided into several sectors, with l1 acting as the delimiter. Each sector is indexed by L, where L spans from 1 to L the total number of sectors.

Overall, the MPPT algorithm can be defined as shown in Figure 1.

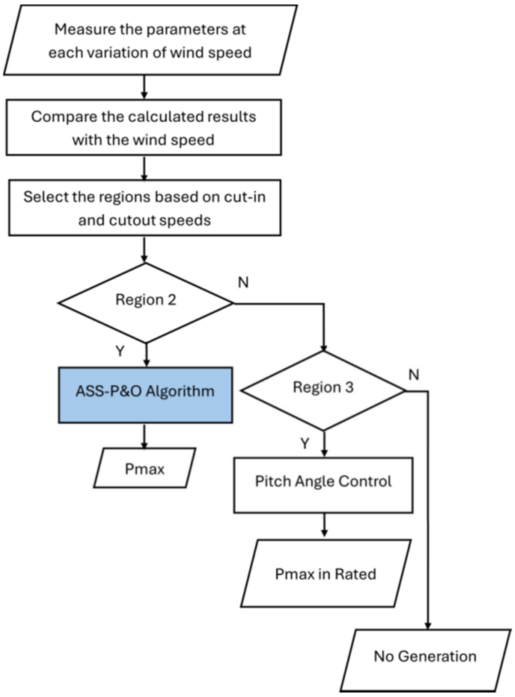

Fig. 1. Desrciption of the MPPT technique.

B. Model ASS-P&O Algorithm

The ASS-P&O algorithm is derived using (1), (4), (5), with its functionality succinctly described by (6):

$$\begin{cases} MPP_{k+1} < MPP_k \\ \omega_{k+1} > \omega_k^{nom} \end{cases} where\ \beta_l \times MPP_k^{max} \quad (6)$$

Where, MPP_k^{max} is the MPP in each sector.

The steps of the ASS-PO MPPT algorithm are:

- Identify sector regions based on normalized wind speed: Normalize the wind speed data and divide them into different sectors. Each sector represents a range of wind speeds, helping in targeted optimization strategies for different wind conditions.
- Determine parameter β for each sector: Calculate the specific parameter β for each sector. This parameter is key to optimizing the MPPT for different wind speed ranges, ensuring maximum efficiency.
- Compare power outputs (P_{k+1} and (P_k): Continuously compare the current power output (P_k) with the next predicted power output (P_{k+1}). This comparison helps in making real-time adjustments to maintain the optimal power generation.
- Adjust direction based on power comparison: If the next predicted power output (P_{k+1}) is greater than the current power output (P_k), the adjustment direction is correct, and the MPP is within that sector.
- Optimize parameter β for sector transition: If the next predicted power output (P_{k+1}) is less than the current power output (P_k) and the next wind speed (ω_{k+1}) is greater than the current wind speed (ω_k), the system adjusts parameter β to ensure that at the new wind speed (ω_{k+1}), the maximum power (P_{max}) can be achieved in the next sector ($l+1$).

IV. RESULTS AND DISCUSSION

The configurations of the wind turbine and MPPT were simulated using MATLAB/Simulink software. The main goal of this simulation is to validate the results of the existing P&O MPPT method and compare them with those of the proposed ASS-PO MPPT method. The simulation aims to demonstrate the efficiency of MPPT development, particularly in terms of the effectiveness of step size selection and the time required to track the MPP. By comparing these methods, the simulation seeks to highlight improvements in the system performance, focusing on faster response times and enhanced tracking stability toward the MPP.

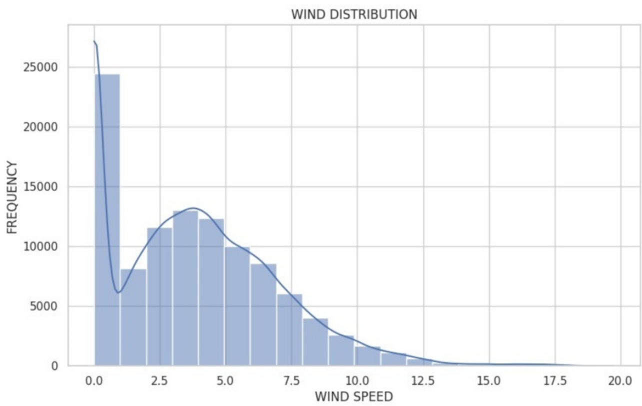

Fig. 2. Normal distribution of wind speed.

A. Sector Division And Pitch Angle Value

Based on the normal distribution of wind speed throughout the year (Figure 2), region two was divided into four sectors, as depicted in Table I. The pitch angle values for each sector are listed in Table I based on (6).

TABLE I. SECTOR DIVISION AND PITCH ANGLE VALUE

Sector (l)	Wind Speed (m/s)	Pitch Angle
1	2.5-4	0
2	4.1-5	0.01
3	4.1-6	0.3
4	6.1-8	0.6

B. Simulation Results

The parameters of the wind turbine with Permanent Magnet Synchronous Generator (PMSG) used in the simulation can be found in Tables II and III. Figure 3 displays the performance of the ASS-PO MPPT with varying wind speeds ranging from 3 m/s to 5 m/s, which falls within sector one of region two. The ASS-PO MPPT can respond to changes in the wind speed and automatically adjust the step size, allowing it to reach the MPP in a relatively short time.

TABLE II. PMSG PARAMETERS

Parameters	Symbol	Value
Radius of turbine	R	2 m
Air density	ρ	1.225 kg/m^3
Pitch angle	β	Variable value
Optimal tip speed	λ_{opt}	8.1
Coefficient of maximum power	CP_{max}	0.48

TABLE III. WIND TURBINE PARAMETERS

Parameters	Symbol	Value
Nominal power	P	12 kW
Stator resistance	Rs	0.485 Ohm
Direct and quadrature inductance	$Ld = Lq$	3.95 mH
Field flux	Ψ_{fl}	0.119 wb
Number of pole pairs	np	12
Inertia	Jt	0.027 kg m^2
Friction	f	0.0016 Nm

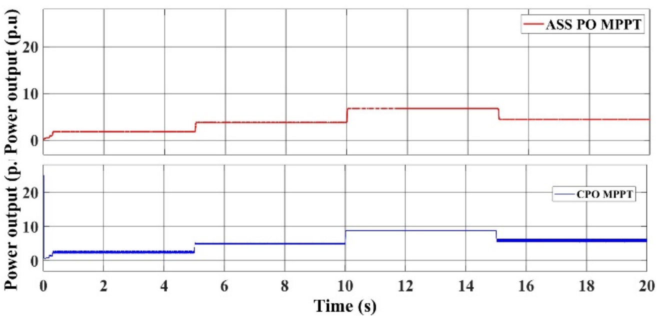

Fig. 3. Performance of ASS-PO MPPT.

Based on the simulation results outlined in Figure 3, the MPPT results over 20 s, with 5-second intervals, show that during the first 5 s, the proposed MPP curve closely aligns with the theoretical MPP curve. This occurs because the MPP value corresponds to that sector. However, during the third 5-second interval, the difference between the proposed MPP and the theoretical MPP becomes more pronounced, as the pitch angle does not change within that sector. This is because the goal of the modified MPPT is to optimize the energy efficiency of the wind turbine.

C. Validation of ASS-PO MPPT with the Existing MPPT Methods

A comparison study including the reaching time and efficiency of the proposed ASS-PO MPPT, Conventional P&O (CP&O), and VSS P&O algorithms is provided and listed in Table IV. The proposed ASS-PO MPPT algorithm exhibited a faster response, as shown in Figure 4. Moreover, the proposed ASS-MPPT algorithm was able to reach maximum power within 33 ms for a wind speed of 8 m/s. ASS-P&O MPPT has zero oscillations because of the effective tracking approach.

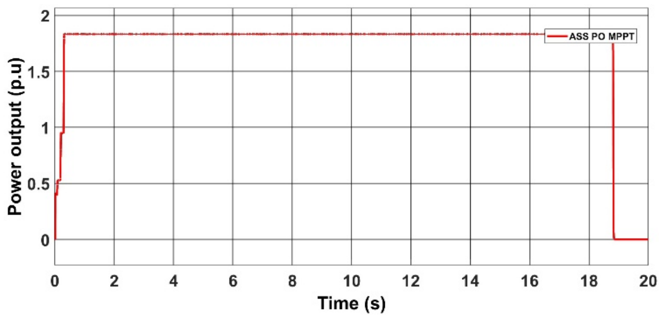

Fig. 4. Performance of the ASS-PO MPPT at a wind speed of 8 m/s.

TABLE IV. COMPARISON OF ASS-P&O MPPT AND OTHER P&O MPPT

MPPT Algorithm	Step Size (p.u)	Reaching time (ms)	Efficiency
Small SS-P&O MPPT [4]	0.005	520	93.05 %
Big SS-P&O MPPT [4]	0.05	55	92.31 %
VSSP-&OMPPT [4]	0.01~0.03	170	93.96 %
Proposed ASS-P&O MPPT	$\Delta\omega$	33	94.12 %

V. CONCLUSIONS

Given the inherent variability in wind power, it is essential to maintain optimal performance in wind turbine systems. This study emphasizes the effectiveness of the Perturb and Observe Maximum Power Point Tracking (P&O-MPPT) method as a straightforward solution by employing adaptive step sizes. Key contributions include a novel sector-based division in the working region 2 to enhance tracking performance under significant wind speed fluctuations, and automating step size selection to minimize perturbation errors while accelerating convergence to the MPP. Moreover, the study implemented pitch angle control in region 2, adopting the pitch angle characteristics from region 3 to sustain the maximum power output in each sector. Owing to the physical constraints on pitch angle adjustments, the study also recommends maintaining a fixed pitch angle for each sector during fluctuating wind conditions, offering a practical solution for real-world applications in fluctuating wind environments.

Compared with the previous P&O MPPT method, the proposed Automate selecting Step Size (ASS)-MPPT algorithm achieves Maximum Power Point (MPP) within 33 ms at a wind speed of 8 m/s, showing a significant response time improvement over the conventional approach. The ASS – P&O MPPT is slightly more efficient than the previous P&O MPPT.

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