Middle East Journal of Science

https://dergipark.org.tr/mejs

MEJS

e-ISSN:2618-6136

Research Article

ARCHIMEDES OPTIMIZATION ALGORITHM-BASED PITCH ANGLE CONTROL IN WIND ENERGY SYSTEMS

Hasan Bektas PERCIN *[*1], ***Abuzer CALISKAN*** [2]

[1] Firat University, Elazig, Türkiye Orcid[1]: https://orcid.org/0000-0001-8968-969X
[2] Department of Electrical and Electronics Engineering, Firat University, Elazig, Türkiye
Orcid[2]: https://orcid.org/0000-0001-8262-7912
* Corresponding author; hbpercin@firat.edu.tr

Abstract: *Variable-speed wind energy systems equipped with permanent magnet synchronous generators (PMSGs) have become a common configuration in wind energy industry. Appropriate pitch angle control is designed to limit the output power of the system by adjusting the pitch angle of the wind turbine blades at higher wind speeds. This approach reduces mechanical stress on the turbine, extends its operating speed range, and increases the overall lifespan. Intelligent control methods, such as optimization algorithms, are notable for their fast and reliable control performance; however, their use in pitch angle control applications remains relatively limited. In this study, a pitch angle control based on the Archimedes Optimization Algorithm (AOA) was developed and analyzed using MATLAB/Simulink. The proposed control system demonstrated fast and stable performance at higher wind speeds. Additionally, the control mechanism was set to deactivated at lower wind speeds to optimize energy efficiency for varying conditions. When compared to other conventional control methods, alternative approaches generally achieve an average accuracy of %75 to %80. However, the proposed control method performed a significantly faster convergence speed and achieved an accuracy rate exceeding %90.*

Keywords*: Wind energy; Archimedes optimization; Pitch angle; MATLAB/Simulink*

Received: November 28, 2024 *Accepted: December 24, 2024*

1. Introduction

In recent years, pollution problems, increasing production costs, and the fast depletion of fossil energy sources have reached an indisputable level. Above all, industrial development and an increasing population across the world will increase limited fossil energy usage and lead to more emissions of greenhouse gases, which have consequences for global climate change [1, 2]. These problems lead to a remarkable transition and increasing investments in renewable energy sources. One of these, wind energy, has become a significant source due to its safe, pollutant-free, and inexhaustible nature. According to the 2023 Global Wind Energy Council (GWEC) report, 78 GW of new wind power capacity was added globally, making it the third-highest year for capacity expansion. The total installed capacity worldwide has reached 906 GW, representing a significant year-on-year growth rate of 9%. It is anticipated to be the first year to surpass 100 GW of newly added capacity globally, with a projected year-on-year growth of 15%, as forecasted by GWEC Market Intelligence. The future outlook is optimistic, with GWEC Market Intelligence predicting a substantial increase in new capacity over the next five years (2023–2027). The forecast suggests the addition of 680 GW of new capacity during this period, averaging 136 GW per year until 2027. This signifies a significant upward trajectory in global capacity expansion in the coming years [3].

In principle, a wind energy conversion system (WECS) has three main components. The first component is the wind turbine. As the wind goes through the turbine blades, it makes the turbine shaft move, and this movement creates mechanical power. The second component is a drivetrain that transfers mechanical power to the generator. The last component is the electric generator, which converts mechanical power to electric power. Other control structures and interfaces are integrated into these main components [4, 5]. WECSs can be categorized into fixed-speed and variable-speed configurations. Variable-speed WECSs are more commonly used than fixed-speed types. The main advantages of variable-speed types are their ability to extract more energy, reduce mechanical stresses, and provide a longer working life [6]. For electrical generators, there are several types used with WECSs. Recently, the permanent magnet synchronous generator (PMSG) has gained great popularity due to its advantages, such as gearless operation, better reliability, and higher power density [7]. For WECSs, the rapid wind variations and system conditions require different control structures. Generally, there are two main controls used for WECSs. The first control is utilized for maximum power production efficiency below the rated wind speed, which provides the most efficient output power for a WECS. The second control aims to limit the instant power at higher wind speeds. This control is defined as pitch angle control [8, 9].

For pitch angle control of WECSs, various control methods have been studied in the literature. Controllers utilizing PID controllers are more convenient for small WECSs. They utilize various parameters such as wind speed, generator power, and rotor speed to derive appropriate pitch angle values through the controller [10–13]. However, PID-based controllers may not perform well due to the nonlinear characteristics of WECSs. Furthermore, the choice of controller gains can be a challenging task in response to instant wind variations. Some control methods are modified with different control structures to overcome these problems [14–16]. Due to the nonlinear system dynamics and wind speed variations, intelligent controllers have been developed. These controllers ensure flexible, fast, and autonomous control. These features have made their use widespread in all kinds of control applications. Such controllers include fuzzy logic, artificial neural networks, and various optimization algorithms. They are highly suitable techniques for stable pitch angle control of WECSs [17]. The fuzzy logic control (FLC)-based pitch control of WECSs provides many advantages, such as independence from system parameters, adaptability, and simplicity. However, fuzzy logic control (FLC) requires expert knowledge of the system to design the fuzzy interface and necessitates memory allocation [18–21]. Artificial neural networks (ANNs) are another method that emulates information processing by the neural structure of the brain. ANNs consist of neural layers, specified learning, and training algorithms. ANN-based WECS controls are commonly used for power optimization at higher wind speeds [22–25]. Recently, optimization algorithms have gained popularity in controlling nonlinear systems. They can be developed the social hierarchy of animals in the natural world or from various physical phenomena. [26]. They can be used for different control objectives and have advantages such as better adaptability, fast response, and independence from system parameters. Furthermore, they can be combined with other methods, defined as hybrid control structures. The genetic algorithm-based control method is one of the commonly used optimization algorithms [27, 28]. The particle swarm optimization (PSO) method is another metaheuristic technique that derives its operating principle from the searchability of flocks [29, 30]. Similarly, other metaheuristic algorithms (Firefly, Ant Colony, Artificial Bee, Differential Evolution algorithms, etc.) can be exemplified for different energy applications and control techniques. At present, there is a growing focus on investigating novel and creative optimization techniques, which have been demonstrated to yield more robust, efficient, and precise control performance [31–38].

In our study, Archimedes optimization algorithm (AOA) based pitch angle control is proposed. This algorithm can be controlled by requiring fewer controlling parameters and it enables different convergence phases to optimize the pitch angle controller adaptively.

The main contributions from this paper are listed in the following points:

●The usage of newly introduced algorithms is uncommon for pitch angle control. Studying these algorithms can contribute to studies related to pitch angle control. A comprehensive analysis of the performance of innovative methods for the aforementioned control will inevitably result in the implementation of more reliable and more efficient methods for the regulation of pitch angle.

●Using an activation structure enables pitch angle control at higher wind speeds. Below the rated wind speed, the control system is deactivated to enable maximum efficiency. In this way, different control structures can be used for a WECS at changing wind speeds.

The rest of this study is organized as follows. Section 2 explains basic modeling principles, operating regions of a WECS, and pitch angle control. Section 3 describes the principle of the proposed AOA and its usage for pitch angle control. Simulation results of the proposed method based on variable wind speeds are given in Section 4. The conclusions are given in the last section.

2. Materials and Methods

The main configuration for a WECS includes a wind turbine, a generator, and different types of drivetrains. In addition to these, appropriate control units are integrated into the overall system. The produced energy can be used for both standalone and grid-connected applications. The basic conversion scheme for a WECS is shown in Figure 1.

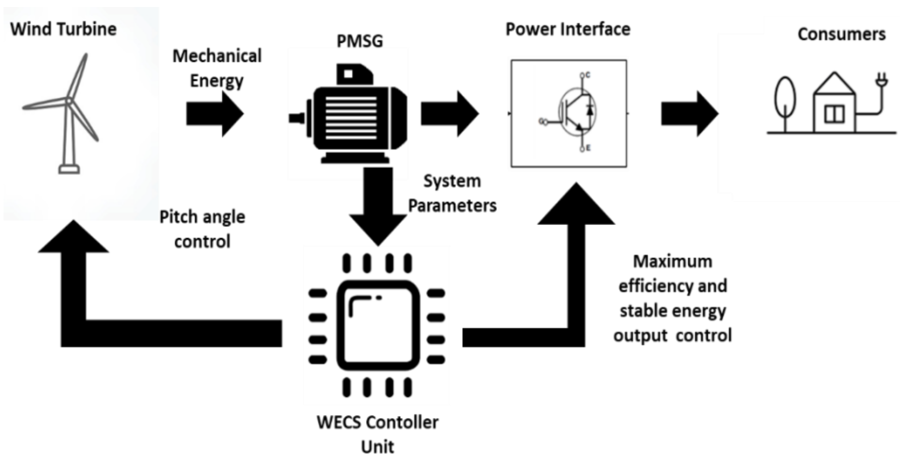

Figure 1. The conversion scheme of a WECS.

In Figure 1, the WECS converts the kinetic energy of the wind into mechanical energy via the wind turbine, and then into electrical energy through the electric generator. The power interface is responsible for the efficiency and stability controls of energy production. All these controls are implemented through this interface using different controller designs. Pitch angle control is applied to the turbine blades through hydraulic or electromechanical actuators. To understand pitch angle control, mathematical models are essential for grasping the fundamental principles of energy conversion in wind energy systems. The power captured by a wind turbine from flowing wind is expressed as shown in Equation (1).

$$P = \frac{1}{2} \times C_P \times p \times A \times V_W{}^3 \quad (1)$$

In Equation (1), P is the extracted mechanical power from the wind (W or J/s), ρ is the air density, which can be defined as a constant equal to 1.225 kg/m^3, V_W is the wind speed and A is the swept area by turbine blades (m^2), C_P (power coefficient) is defined as the energy conversion efficiency and it is a function of tip speed ratio (TSR) (λ) and pitch angle (β) defined in Equation (2).

$$C_P(\lambda,\beta) = C_1\left(\frac{C_2}{\lambda_i} - C_3 \times \beta - C_4\right)e^{-(C_5/\lambda_i)} + C_6 \times \lambda \tag{2}$$

Where $C_{(1\text{-}6)}$ are characteristic design values for wind turbines TSR (λ) and λi values can be expressed as in Equation (3).

$$\lambda = \frac{w \times R}{V_W},\ \frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \tag{3}$$

In equation (3), R is the radius of the swept area by the wind turbine and ω represents the mechanical speed of the turbine in rad/s [39]. Figure 2 shows the relationship between the C_P and the TSR for different β values.

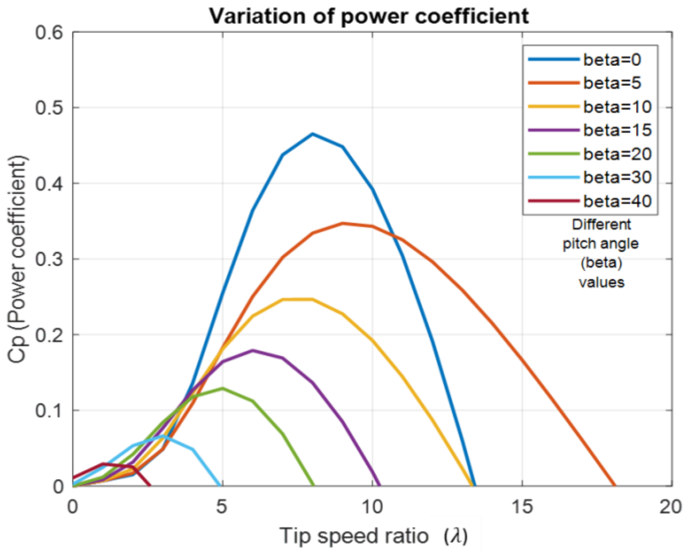

Figure 2. The variation curve of Cp with TSR and pitch angle.

In Figure 2, the relationship demonstrates that the maximum values of C_P are achieved at optimal values of TSR. These optimal values can be obtained using a speed controller for WECS, as described by Equations (2–3). In practice, C_P can reach a maximum value within the range of 0.4–0.5. This indicates that the produced mechanical power is less than 50% of the instant wind power [40]. Another feature shown in Figure 2 is that the power coefficient can be adjusted by increasing the value of the pitch angle to limit the instant power at higher wind speeds.

2.1. Pitch angle control

The pitch angle control is implemented by adjusting blade angles around their longitude axes [41]. The pitch angle controller system is a crucial and effective component for improving the efficiency of wind energy conversion systems and enhancing the stability of output power. Its variable mode of operation also helps reduce the impact of fluctuating natural conditions, which can otherwise place excessive stress on mechanical components [42]. The implementation of pitch angle variation is shown in Figure 3.

Figure 3. The implementation of pitch angle [41].

Pitch control is categorized into two types. The first is individual pitch control (IPC), which allows for independent adjustment of each blade's pitch angle. IPC utilizes an electromechanical actuator to manage the blade pitch. These systems consist of an electric motor, a gearbox, a power supply unit, and an energy storage system. The second is collective pitch control (CPC), where all blades are set to the same pitch angle and hydraulic actuators are used to control all the blades simultaneously. CPCs offer key advantages, including low complexity and safer operation. On the other hand, IPCs are more efficient and exhibit faster response times compared to hydraulic controllers. However, their power-to-mass ratio is lower. Despite this, IPCs are often preferred due to their lower maintenance and operational costs [28]. With the increasing size of wind turbines, the impact of wind shear, air density variations, and extreme wind turbulence has become more pronounced. This phenomenon intensifies the cyclic loads on turbine blades, which can lead to fatigue, reduced efficiency, and shortened system lifetime. As a result, IPC has gained significant attention, as it can mitigate cyclic loads by independently adjusting the pitch angle of each blade [43]. The IPC principle is applicable for variable-speed wind turbines. Aerodynamic stall controls, which turn the blades into the wind to induce stall, are typically applied to fixed-speed wind turbines [40, 41]. Pitch angle control principle can be explained in the operating regions of a WECS shown in Figure 4.

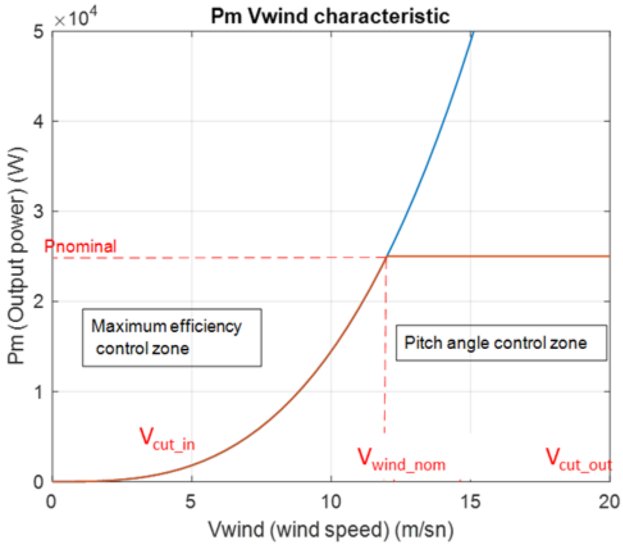

Figure 4. The operating regions of a WECS.

The captured mechanical power is proportional to the cube of the wind speed. This variation is illustrated by the blue curve in Figure 4. Three wind speed values define the boundaries of these operating regions: the cut-in wind speed (V_{cut_in}), the nominal wind speed (V_{wind_nom}), and the cut-out wind speed (V_{cut_out}). When the wind speed is lower than V_{cut_in}, the WECS is in a standstill state. Between V_{cut_in} and V_{wind_nom}, the system operates in the maximum efficiency zone, where the primary objective of the WECS control is to maximize energy efficiency for the prevailing wind speeds [44]. Above the nominal wind speed, the principal control objective shifts to limiting the output power to the rated value to ensure safe operation, improve stability, and maintain optimal power production. If the wind speed surpasses V_{cut_out}, the WECS is stopped to prevent damage [45, 46].

2.2. Archimedes optimization algorithm (AOA)

The proposed algorithm works based on the phenomenon explained by Archimedes' law of physics. This principle is concerned with an object that is either fully or partially submerged in a fluid. The fluid applies an upward force on the object which equals the magnitude of the fluid weight displaced by the object. [47, 48]. The immersed objects represent the optimization population. The AOA search process starts with the initial population. At first, each object is randomly located and has randomly assigned volumes, densities, and accelerations in fluid [47]. Like other metaheuristic algorithms, AOA updates the accelerations and positions of each object. until the termination criteria are satisfied.

AOA consists of both exploration and exploitation processes. The initialization process of all objects is defined in Equation (4).

$$O_i = l_i + rnd \times (u_i \times l_i), i = 1 \dots . n \tag{4}$$

Where l_i and u_i are the boundaries of the ith object, and n represents the object number. The volume (vol) and density of each object (den) can be expressed as shown in Equation (5).

$$den_i = rnd,\ vol_i = rnd \tag{5}$$

Where rnd represents a D-dimension vector within range [0, 1]. Each object acceleration (acc) can be expressed as in Equation (6).

$$acc_i = lb_i + rnd \times (ub_i \times lb_i) \tag{6}$$

lb_i and ub_i represent lower and upper boundaries of the search space, respectively. The object with the best position (x^{best},), the best volume (vol^{best}), the best density (den^{best}), and the best acceleration (acc^{best}) are determined based on a fitness function. Their values are recorded as best values for each iteration. Each object's density and volume can be updated as in Equation (7).

$$den_i^{t+1} = den_i^t + rnd2 \times (den^{best} \times den_i^t) \tag{7}$$
$$vol_i^{t+1} = vol_i^t + rnd2 \times (vol^{best} \times vol_i^t)$$

The current and next iterations are expressed as t and $t+1$ respectively. $rnd2$ is a randomly assigned value. In the beginning, there is a collision between the objects until the equilibrium state. This state determines the transition from the exploration stage to the exploitation stage for tracking global optimum faster. The transition operator is defined in Equation (8).

$$TF = exp\,(\frac{t-t_{max}}{t_{max}}) \tag{8}$$

Where TF is the transfer operator, t_{max} is the selected maximum iteration number. The operator value is increased gradually at each iteration until a specified unit value. The density factor (d) is another term that is utilized for improving the search process, it can be formulated as in Equation (9).

$$d^{t+1} = exp\left(\frac{t-t_{max}}{t_{max}}\right) - \left(\frac{t}{t_{max}}\right) \tag{9}$$

The d value contributes to the exploration/exploitation balance. The collision between the objects occurs in the exploration phase, the TF value could be taken as a number between 0 and 1 for the threshold value of the two stages. The acceleration of the ith object at the next iteration is updated by using a random object (ro) defined as in Equation (10).

$$acc_i^{t+1} = \left(\frac{den_{ro} + vol_{ro} \times acc_{ro}}{den_i^{t+1} \times vol_i^{t+1}}\right) \tag{10}$$

Where den_{ro}, vol_{ro}, and acc_{ro} represent density, volume, and acceleration values for the random object. When the TF value exceeds the selected number, the exploitation phase represents the equilibrium state between the objects. The acceleration of the ith object in this stage is defined as in Equation (11).

$$acc_i^{t+1} = \left(\frac{den_{best} + vol_{best} \times acc_{best}}{den_i^{t+1} \times vol_i^{t+1}}\right) \tag{11}$$

For both stages and each iteration, the acceleration process is adjusted adaptively. If the object is not close to the best solution, the acceleration change will be larger or vice versa. Furthermore, a normalization parameter prevents the local solution stagnation [47, 48]. This parameter is defined in Equation (12).

$$acc_{i-nom}^{t+1} = u \times \left(\frac{acc_i^{t+1} + min\,(acc)}{(acc) - (acc)}\right) + l \tag{12}$$

In Equation (12), l and u are the normalization edge values, they are selected within the range [0,1]. i-nom represents normalized value for the ith object at the t+1 iteration. For the exploration stage, the position of the ith object (x) is updated through the iterations as in Equation (13).

$$x_i^{t+1} = x_i^t + C1 \times rnd \times acc_{i-nom}^{t+1} \times d \times (x_{rnd} - x_i^t) \tag{13}$$

The position updating of objects in the exploitation stage is expressed in Equation (14).

$$x_i^{t+1} = x_i^t + F \times C2 \times rnd \times acc_{i-nom}^{t+1} \times d \times (T \times x_{best} \times x_i^t) \tag{14}$$

In Equations (13)-(14), $C1$ and $C2$ values are determined in the range [0,10]. T is a parameter value ($T = C3 \times TF$) based on T increasing within the range [$C3$ × 0.3, 1] and, it takes a certain percentage from the best position through the iterations. As the search process continues, the percentage of adjustment applied to the current position gradually increases. This mechanism effectively reduces the disparity between the best-known position and the current position. A constant defined as flag value (F=2), defined by user, is utilized to change the movement direction of the objects. The application flowchart of the Archimedes optimization algorithm is given in Fig. 5.

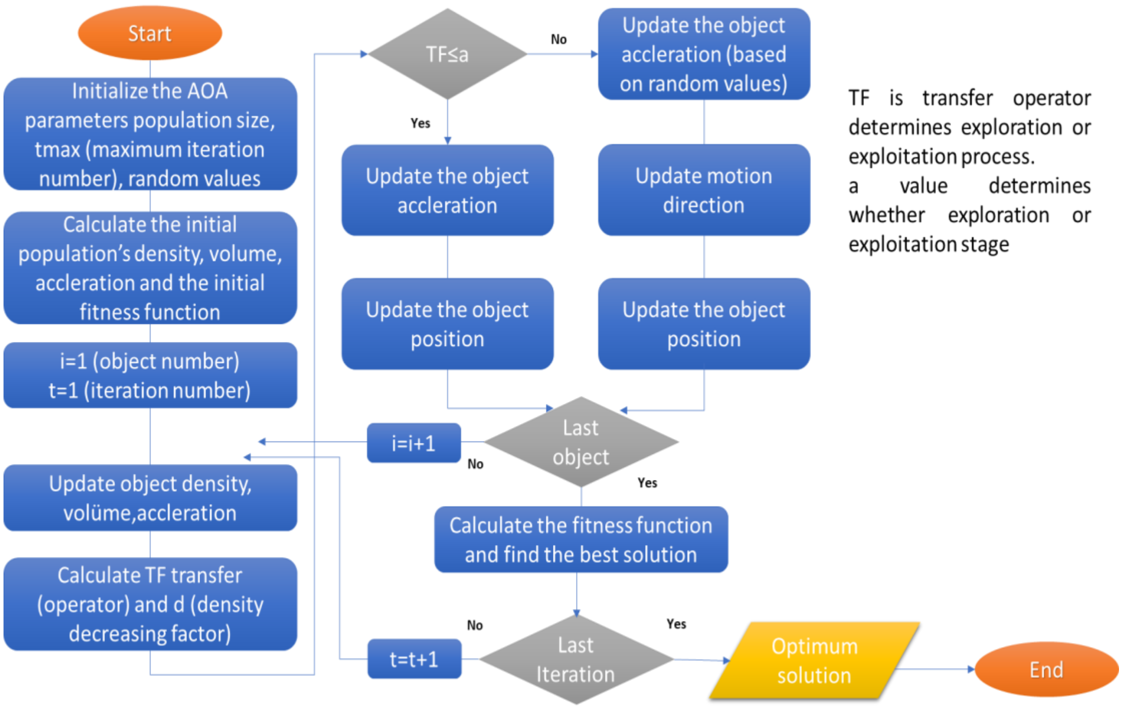

Figure 5. The flowchart of AOA.

3. Results and Discussion

Designing an AOA-based pitch angle control for a WECS is formulated as an optimization problem. The primary criterion used for evaluating the performance of the optimization method is the fitness function. The fitness function for this study aims to minimize the power error between the instant and nominal mechanical output powers. The control adjusts angle values within the range of [0°, 45°]

to limit the instant output power. These values are implemented as objects for the optimization algorithm. The control structure is activated at higher speeds than the rated wind speed. Conversely, at lower speeds, the angle values are adjusted to a minimum to maximize efficiency. The application flowchart of the AOA-based pitch angle controller is illustrated in Figure 6.

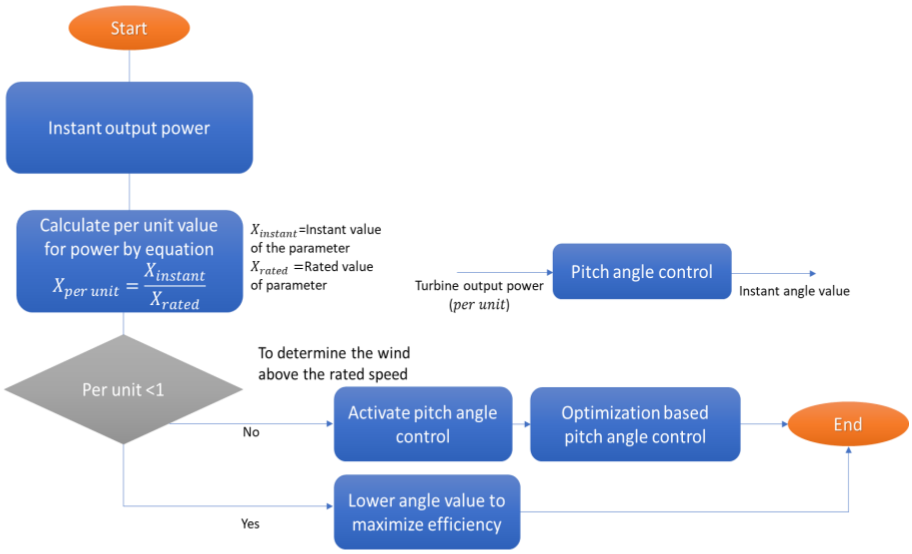

Figure 6. Application steps of pitch angle controller.

In Figure 6, the instant output power is used as an input variable in the control application. This value is calculated as a per-unit value (p.u). The calculation for $p.u$ values is calculated as in Equation (15).

$$X_{p.u.} = \left(\frac{X_{instant}}{X_{rated.}}\right) \tag{15}$$

In Equation (15), where X represents a control parameter of a WECS. This value can be electrical or mechanical parameters. In this study turbine output power was utilized. Reference power value was defined as 1 $p.u$ the utilization of per unit values simplifies the controller and controller-related calculations. The instant angle value can be applied to the wind turbine through actuators. The wind turbine simulation model through MATLAB/Simulink is shown in Figure 7.

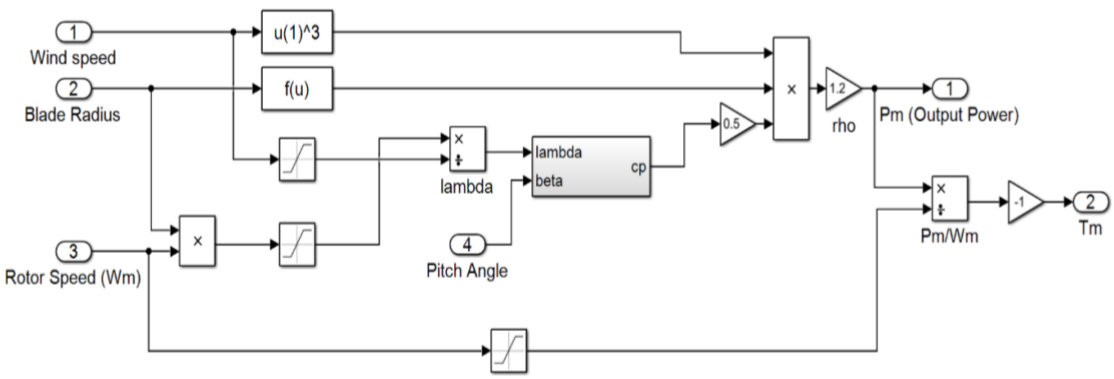

Figure 7. The Simulink model of the wind turbine.

In Figure 7, the wind turbine model was designed based on the mathematical functions of the output power, C_P, and TSR. The angle value was adjusted between 0°-45° values.

For evaluating the AOA-based controller performance, the algorithm has been designed by using a maximum number of iterations that reaches 500 iterations and the population size has been set to 50. To test the AOA-based control, simulations were carried out by using the WECS and optimization parameters, listed in Table I.

Table 1. WECS and optimization parameters

Parameters	**Values**
Rated Power ($P_{nominal}$)	25 kW
Rated Wind Speed ($V_{wind\ nominal}$)	12 m/s
The area radius by wind turbine (R)	4 m
Air density (p)	1.2 kg/m3
Population (Objects) size	20
t_{max} (Maximum iteration number)	500
a (preselected value for the algorithm)	0.5
(Constant values for optimization)	C1:2 C2:5 C3:4

The rated (nominal) wind speed was defined as 12 m/s in the simulation process. The wind speed patterns for rated and instant wind speed are given in Figure 8.

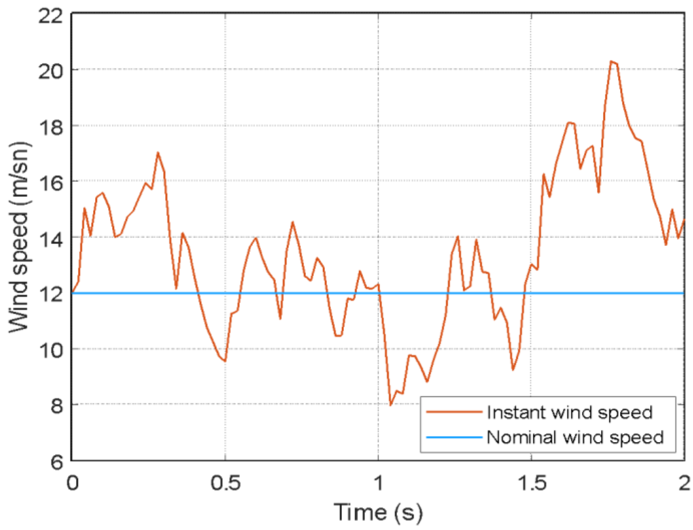

Figure 8. Wind speed patterns for simulation.

The instant wind speed (the orange curve) varies between 8 and 20 m/s in Figure 8. These wind patterns play a crucial role in simulating pitch angle control within wind energy conversion systems, ensuring adaptation to rapidly changing wind conditions. Based on the instant wind speed, the instant angle variation is shown in Figure 9.

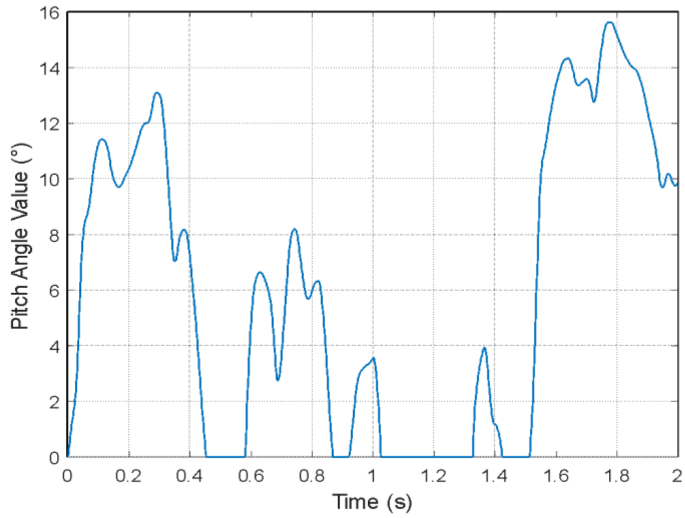

Figure 9. Pitch angle variation of the WECS.

In Figure 9, below the rated speed, the angle value is adjusted at a minimum value (0°) to keep the efficiency value (C_P) at the optimum value for maximum efficiency. When the wind speed exceeds the rated speed (12 m/s), the controller will activate the control and increase the angle value to keep the output power within the rated power limits. The angle value was adjusted by the control in the range [0°-16°]. Minimum oscillated angle variations in all wind speeds proved the remarkable performance of the AOA method. Furthermore, Fast response and compatible variation of angle values showed the high performance of the proposed controller.

The influence of pitch angle control is not illustrated only through the angle variation. The control performance can also be analyzed by assessing the other parameters of the WECS. The power coefficient (C_P) value variation is shown in Figure 10.

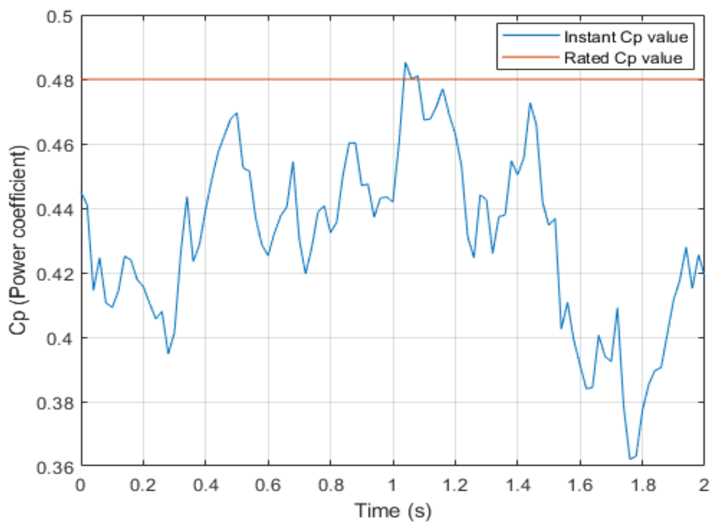

Figure 10. C_P variation of the WECS.

In Figure 10., As mentioned earlier, the obtained pitch angle value by AOA decreased the Cp value to balance the instant output power of the WECS at higher wind speed levels. The angle value was decreased to increase the power coefficient and WECS efficiency at lower wind speeds. The instant power variation of the WECS is shown in Figure 11.

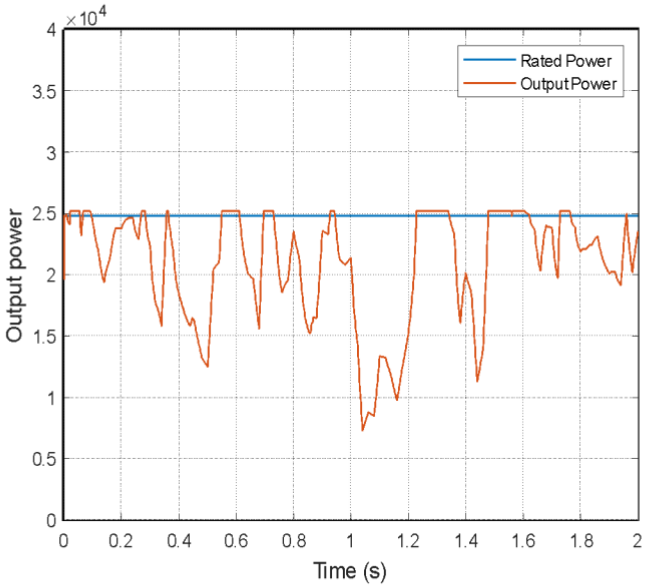

Figure 11. Output power variation of the WECS.

In Figure 11, the extracted mechanical power with AOA based algorithm tracks the rated power curve at higher wind speeds. For lower values, the output power changes in line with variations in wind speed and achieves a highly efficient performance. The proposed controller increased the capacity factor of the wind turbine by enabling it to work at rated limits for higher wind speeds Therefore it can lower the cost per kWh of electricity production.

Except for the comparison with rated values, the proposed algorithm can be compared with other conventional methods used for pitch angle control. For different studies mentioned in the literature. The comparison table for the different pitch angle controls is given in Table 2.

Table 2. The comparison table for the different methods.

Methods	**Comparison Criteria**			
	Controller efficiency	**Convergence speed**	**Complexity**	**Accuracy**
The proposed AOA method	High	High	Medium	>%90
FLC [21]	High	Medium	High	%70-%90
PID controller [15]	Low	Low	Low	<%50
P&O, INC etc. [8]	Medium	Medium	Low	%60-%80

According to Table 2, the proposed method outperformed the other methods. The metaheuristic principle provided high efficiency and fast-tracking features for the proposed method. The accuracy value reflects the stability and performance level of the controller. A higher accuracy value signifies greater stability and superior performance. The proposed method achieved higher accuracy compared to other methods Another key benefit of the proposed method is that it does not necessitate expertise in the field of expert systems., as required for the FLC method, which reduces its complexity. Conventional PID-based controllers operate based on the adjustment of controller gains. However, the proper adjustment of gains and the reliance on additional tools lower the performance and response speed of the controller, particularly during fast wind speed variations. The perturb and observe (P&O) or incremental conductance (INC) methods operate by iteratively adjusting the controller. At each iteration, the controller output is modified through constant or adaptive steps based on the variations. Although these methods are less complex, their convergence for fast variations and the magnitude and speed of controller adjustments reduce overall efficiency.

4. Conclusion

In this study, an AOA-based pitch angle control for a WECS has been proposed to limit the output power to a desirable level. The working principle of this algorithm is based on Archimedes' law. The control structure was evaluated through simulations in the MATLAB/Simulink environment. The results demonstrate that the proposed controller effectively limits the instant output power to the rated limit for wind speeds above the rated value. Faster and stable control of the pitch angle protects the WECS from higher wind speeds, ultimately increasing the system's lifespan and overall energy output. Furthermore, the control reduces the operation and maintenance expenses of WECSs. AOA-based pitch angle controllers perform well for nonlinear systems and can operate independently of system dynamics and external conditions. For the studied WECS, the proposed control provided a faster response to rapidly changing wind speeds and reduced oscillations around the rated values at higher wind speeds. For future studies, different metaheuristic algorithms can be explored to design alternative control structures for WECSs. These can then be evaluated and compared with the proposed algorithm.

Ethical statement

The author declares that this document does not require ethics committee approval or any special Permission

Acknowledgment

We would like to thank the esteemed referees and the editor for their important suggestions that improved the quality of our work.

Conflict of interest

The author declares no conflict of interest.

Authors' Contributions

H. B. Percin: Conceptualization, Methodology, Writing-original draft, Writing - review & editing
A. Caliskan: Supervision, Methodology, Writing - review & editing

References

[1] Yakob Kiros Teklehaimanot, F. K. Akingbade, B. C. Ubochi, and T. O. Ale, “A review and comparative analysis of maximum power point tracking control algorithms for wind energy conversion systems,” *International Journal of Dynamics and Control*, vol. 12, no. 9, pp. 3494–3516, May 2024.

[2] Gümüş Bilal, “Integration of Renewable Energy Sources to Power Networks and Smart Grids,” Lecture notes in energy, pp. 81–103, Jan. 2022.

[3] Alex, (2024 Nov. 11). “Global Wind Report 2023 - Global Wind Energy Council,” Global Wind Energy Council, Feb. 14, 2023. https://gwec.net/globalwindreport2023/.

[4] Kharchouf I., A. Essadki, M. Fdaili, and T. Nasser, “Comparative Study of MPPT and Pitch Angle using PI and Fuzzy Logic Controllers,” 2021 9th International Renewable and Sustainable Energy Conference (IRSEC), 2018.

[5] Nguyen H. M. and Naidu D. S., “Advanced control strategies for wind energy systems: An overview,”, 2011.

[6] Gajewski P. and Pieńkowski K., “Advanced control of direct-driven PMSG generator in wind turbine system,” *Archives of Electrical Engineering*, vol. 65, no. 4, pp. 643–656, 2016.

[7] Singh N. and Scholar M. T., “Design and Modeling of Wind Energy Conversion System Based on PMSG Using MPPT Technique,” vol. 5, no. 2, pp. 96–100, 2016.

[8] Apata O. and Oyedokun D.T.O., “An overview of control techniques for wind turbine systems,” *Scientific African*, vol. 10, pp. e00566–e00566, 2020.

[9] Elbeji O., Mouna B. hamed, and Lassaad S., “Modeling and control of a variable speed wind turbine,” 2014 5th International Renewable Energy Congress (IREC), pp. 1–5, 2014.

[10] Kumar H., Gupta A., Rupendra Kumar Pachauri, and. Chauhan Y. K, “PI/FL based blade pitch angle control for wind turbine used in wind energy conversion system,”, 2015.

[11] Wang J., Tse N., and Gao Z., “Synthesis on PI-based pitch controller of large wind turbines generator,” *Energy Conversion and Management*, vol. 52, no. 2, pp. 1288–1294, 2011.

[12] Hwas A. and Katebi R., “Wind Turbine Control Using PI Pitch Angle Controller,” IFAC Proceedings Volumes, vol. 45, no. 3, pp. 241–246, 2012.

[13] Perçin H.B. and Çalişkan A., “Modeling And Analysis Of Pitch Angle Control On Variable Speed Wind Turbines,” *European Journal of Technic*, vol. 11, no. 1, pp. 101–106, 2021.

[14] Muhando, E. B., Senjyu, T., Yona, A., Kinjo, H., & Funabashi, T., Disturbance rejection by dual pitch control and self-tuning regulator for wind turbine generator parametric uncertainty compensation. IET Control Theory and Applications, 1(5), 2007.

[15] Kim J.-S., Jeon J., and Heo H., “Design of adaptive PID for pitch control of large wind turbine generator” , 2011.

[16] Muzakkir Quamar Md, Khan K. A., Liu B., and M. Khalid, “Optimal PID and FOPID Based Pitch Angle Control of Wind Generation System,” pp. 1–6, 2023.

[17] Al-Toma, A. S., Taylor, G. A., & Abbod, M., “Intelligent pitch angle control scheme for variable speed wind generator systems”, 2017.

[18] Pachauri, R. K., Kumar, H., Gupta, A., & Chauhan, Y. K, “Pitch Angle Controlling of Wind Turbine System Using Proportional-Integral/Fuzzy Logic Controller,” *Smart innovation, systems and technologies*, pp. 55–63, 2015.

[19] Chowdhury, M. A., Hosseinzadeh, N., & Shen, W. X., “Smoothing wind power fluctuations by fuzzy logic pitch angle controller,” Renewable Energy, vol. 38, no. 1, pp. 224–233, 2011.

[20] Kamel, R. M., Chaouachi, A., & Nagasaka, K., “Enhancement of micro-grid performance during islanding mode using storage batteries and new fuzzy logic pitch angle controller”, Energy Conversion and Management, vol. 52, no. 5, pp. 2204–2216, 2011.

[21] Mousa, N. M., El-Shaer, Y. I., & El-Sebah, M. I. A. “A Proposed Controller for Pitch Angle of Wind Turbine”, Wseas Transactions On Systems And Control, 18, 527-539, 2023.

[22] Kumar, D., & Chatterjee, K., “A review of conventional and advanced MPPT algorithms for wind energy systems”, *Renewable and Sustainable Energy Reviews*, vol. 55, pp. 957–970, 2015.

[23] Tiwari, R., & N, R. B, “Comparative Analysis of Pitch Angle Controller Strategies for PMSG Based Wind Energy Conversion System”, *International Journal of Intelligent Systems and Applications*, vol. 9, no. 5, pp. 62–73, 2017.

[24] Yilmaz A. S. and Özer Z., “Pitch angle control in wind turbines above the rated wind speed by multi-layer perceptron and radial basis function neural networks”, *Expert Systems with Applications*, vol. 36, no. 6, pp. 9767–9775, 2009.

[25] Asghar A. B., Ehsan R., Naveed K., Al-Ammar E. A., Ejsmont Krzysztof, and Nejman M., “Recurrent neural network for pitch control of variable-speed wind turbine”, *Science Progress*, vol. 107, no. 2, 2024.

[26] Hannachi, M., Elbeji, O., Benhamed, M., & Sbita, L., “Comparison between ABC and ACO: Tunning of On-Off MPPT for wind systems”, *Wind Engineering*, vol. 45, no. 6, pp. 1601–1612, 2021.

[27] Burakov M., Shishlakov V., “Genetic algorithm optimization for pitch angle control of variable speed wind turbines”, MATEC Web of Conferences, vol. 113, pp. 01009–01009, 2017

[28] Tiwari, R., & Babu, N. R., “Recent developments of control strategies for wind energy conversion system”, *Renewable and Sustainable Energy Reviews*, vol. 66, pp. 268–285, 2016.

[29] Sudhakar Babu, T., Rajasekar, N., & Sangeetha, K., “Modified Particle Swarm Optimization technique based Maximum Power Point Tracking for uniform and under partial shading condition” , *Applied Soft Computing*, vol. 34, pp. 613–624, 2015.

[30] Seyedmahmoudian, M., Mekhilef, S., Rahmani, R., Yusof, R., & Asghar Shojaei, A., “Maximum power point tracking of partial shaded photovoltaic array using an evolutionary algorithm: A particle swarm optimization technique”, *Journal of Renewable and Sustainable Energy*, vol. 6, no. 2, 2014.

[31] V. da, L. P. Sampaio, and S. Augusto, “Comparative Analysis of ABC, Bat, GWO and PSO Algorithms for MPPT in PV Systems,” pp. 347–352, 2019.

[32] Mokhtari, Y., & Rekioua, D., “High performance of Maximum Power Point Tracking Using Ant Colony algorithm in wind turbine,” *Renewable Energy*, vol. 126, pp. 1055–1063, 2018.

[33] Hetmaniok, E., Słota, D., Zielonka, A., & Wituła, R., “Comparison of ABC and ACO Algorithms Applied for Solving the Inverse Heat Conduction Problem” *Lecture notes in computer science*, pp. 249–257, 2012.

[34] Rahim, A. H. M. A., & Raza, S. A., “A differential evolution based adaptive neural network pitch controller for a doubly fed wind turbine generator system”, *Research Journal of Applied Sciences, Engineering and Technology*, *6*(22). 2013.

[35] Karami-Mollaee, A., & Barambones, O., “Pitch Control of Wind Turbine Blades Using Fractional Particle Swarm Optimization,” *Axioms*, vol. 12, no. 1, p. 25, 2022.

[36] Ghefiri, K., Bouallegue, S., Haggege, J., Garrido, I., & Garrido, A. J., “Firefly algorithm based-pitch angle control of a tidal stream generator for power limitation mode”, *2018 International Conference on Advanced Systems and Electric Technologies (IC_ASET)*, pp. 387–392, 2018.

[37] Lastomo, D., Setiadi, H., & Djalal, M. R., “Optimization pitch angle controller of rocket system using improved differential evolution algorithm”, *International Journal of Advances in Intelligent Informatics*, *3*(1), 2017.

[38] Bianchi, F. D., De Battista, H., & Mantz, R. J., *Wind turbine control systems: principles, modelling and gain scheduling design*. Springer Science & Business Media, 2006.

[39] Rolan, A., Luna, A., Vazquez, G., Aguilar, D., & Azevedo, G., "Modeling of a variable speed wind turbine with a Permanent Magnet Synchronous Generator," 2009 IEEE International Symposium on Industrial Electronics, Seoul, Korea (South), , pp. 734-739, 2009.

[40] Zhou, F., & Liu, J., “Pitch Controller Design of Wind Turbine Based on Nonlinear PI/PD Control,” *Shock and Vibration*, vol. 2018, no. 1, 2018.

[41] E. José, A. M. Araújo, and S. Bouchonneau, “A review on wind turbine control and its associated methods,” *Journal of Cleaner Production*, vol. 174, pp. 945–953, 2017.

[42] Bouregba, H., Hachemi, M., Bey, M., & Hamidat, A., Stability analysis of the pitch angle control of large wind turbines using different controller strategies. *Advances in Mechanical Engineering*,*14*(11), 2022.

[43] Yamada, M., & Murakami, T., “Individual Pitch Control of Wind Turbine System by Estimating Wind Speed Using Pitching Moment”. *IEEJ Journal of Industry Applications*, *12*(5), 1008–1014, 2023.

[44] Chen, Z., & Li, H., “Overview of different wind generator systems and their comparisons,” *IET Renewable Power Generation*, vol. 2, no. 2, pp. 123–138, 2008.

[45] Ben Smida, M., & Sakly, A., “Pitch angle control for grid-connected variable-speed wind turbine system using fuzzy logic: A comparative study,” *Wind Engineering*, vol. 40, no. 6, pp. 528–539, 2016.

[46] Shehata, E. G., “A comparative study of current control schemes for a direct-driven PMSG wind energy generation system,” Electric Power Systems Research, vol. 143, pp. 197–205, 2017.

[47] Hashim, F. A., Hussain, K., Houssein, E. H., Mabrouk, M. S., & Al-Atabany, W., “Archimedes optimization algorithm: a new metaheuristic algorithm for solving optimization problems,” *Applied Intelligence*, vol. 51, no. 3, pp. 1531–1551, 2021.

[48] Fathy, A., Alharbi, A. G., Alshammari, S., & Hasanien, H. M., “Archimedes optimization algorithm based maximum power point tracker for wind energy generation system,” *Ain Shams Engineering Journal*, 2021.