

# Wind Energy Control Technologies for Power Quality Improvement on a Microgrid-A Review

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DOI: <https://doi.org/10.30880/emait.2024.05.02.003>

## Article Info

Received: 12 December 2024  
Accepted: 30 December 2024  
Available online: 31 December 2024

## Keywords

Wind energy control, hybrid energy system, wind turbine controllers, efficiency, energy industries

## Abstract

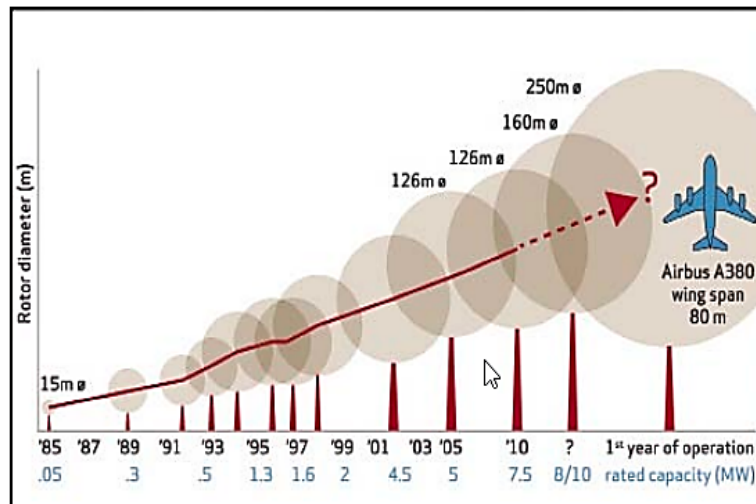
This paper focuses on the development of wind energy control technologies in hybrid energy systems, highlighting their crucial role in integrating renewable energy sources on a microgrid. It examines the wind turbine curve, a fundamental framework for wind turbine operation, and the challenges and possibilities of integrating wind power into renewable energy systems, various methods to improve the efficiency and stability of wind turbines, with wind turbine control methods as the cornerstone. The study also examines the qualities of advanced wind turbine controllers, highlighting their efficiency in using wind energy resources and investigates wind energy conversion systems (WECSs) electrical generators, highlighting current developments that promise increased energy production and system dependability. The aim is to contribute to the ongoing discussion on wind energy control technologies by utilizing various cutting-edge studies. The study aims to offer insights and perspectives guiding the energy industry towards sustainability and environmental friendliness through a comprehensive assessment of these crucial components.

## 1. Introduction

As wind energy becomes increasingly central to global renewable energy strategies, the development of advanced control technologies is critical for addressing the power quality challenges in microgrid applications. Wind energy offers a sustainable alternative to conventional power sources, with significant potential for growth as it becomes more cost-competitive [1-3]. However, wind energy faces unique challenges, including intermittency, voltage fluctuations, and frequency instability, which can compromise power quality and reliability. Addressing these issues is essential for the seamless integration of wind energy into the microgrid. This will ensure stable operation and enhance reliability, standards for power quality, and sustainable energy systems [4-5].

To meet these demands, modern wind energy systems require robust control systems designed to manage pitch control, generator speed, and overall turbine stability, particularly as the industry shifts toward larger turbines, particularly in offshore settings [6-7], as shown in Fig. 1. The deployment of larger wind turbines has been economically advantageous, yet presents engineering challenges related to high temperatures and efficiency across broader wind regimes [8-9]. Additionally, compliance with grid code requirements for frequency and

voltage stability is critical for wind energy control operators, who must adapt to evolving industry standards and competitive pressures [10-11].



**Fig. 1** Evolution of standard rotor diameters [5]

Appropriate control systems are essential for large wind turbines to ensure machinery protection, human safety, and power quality [12]. These systems, which include pitch control, generator speed governing, and turbine control elements, play crucial roles in maintaining performance and structural integrity, enabling turbines to convert wind energy into mechanical and electrical power for grid supply [13-14]. Power control strategies, such as physical models, statistical methods, artificial intelligence, and hybrid techniques have been implemented in wind farms to support consistent and efficient energy delivery [15-16]. In addition, wind forecast systems help operators anticipate fluctuations in power generation. This will enable timely adjustments in the controls [17] of key design parameters, such as the angle of attack, turbine speed, and wind velocity, to stabilize and maximize power delivery [18-19].

Simultaneously, the advancement of effective control systems in wind energy applications is crucial for enhancing the power quality [20]. The anticipated doubling of the wind energy capacity from 95 GW in 2020 to 190 GW by 2030 is primarily driven by technological advancements, cost reductions, supportive policies, increased investment, and ambitious clean energy targets. Innovations in wind control technologies are pivotal for maximizing the energy output and enabling more efficient energy capture and utilization. Moreover, the expansion of offshore wind projects, enhanced grid integration, and implementation of energy storage solutions have addressed limitations that hinder growth. Fig. 2 illustrates the renewable production of wind energy, showing its projected increase from 95 GW in 2020 to 190 GW by 2030.

Control systems play a crucial role in enhancing operational stability, optimizing performance, and ensuring smooth grid integration [22]. Modern control techniques have been designed to optimize the performance and efficiency of wind turbines.

This review critically evaluates current wind energy control technologies, identifying key advancements and challenges in improving the power quality of microgrids. It also explores the integration of wind turbines with various control technologies to ensure an efficient power supply and assesses the effectiveness of diverse control mechanisms in optimizing energy capture to ensure safety by maintaining a stable power output, frequency, and facilitating grid integration. To achieve these objectives, a comprehensive literature review was conducted focusing on peer-reviewed articles, conference proceedings, and technical reports from the past decade. The selection criteria emphasize studies addressing wind turbine control systems, their integration with power grids, and their impact on energy efficiency. The selected studies were analyzed by comparing different control strategies, their applications, and outcomes across various wind energy scenarios.

Given the increasing deployment of wind energy owing to environmental concerns, this study underscores the need for effective control strategies to ensure reliable and efficient power generation. These findings will contribute to the ongoing efforts to enhance wind energy systems and their integration into the global energy landscape. Although existing studies have examined different types of control strategies for wind turbines, there remains a gap in research regarding the in-depth integration of hybrid control methods to optimize energy efficiency under varying environmental conditions. This study aims to address this gap by exploring these under-researched techniques and their potential for enhancing the adaptability, reliability, and efficiency of different wind turbine controls



Fig. 2 Cumulative global installation of wind turbine [21]

## 1.1 Description Wind Energy System

A wind turbine is a mechanical structure that is used in the generation of electrical power from wind; hence, it comprises several interrelated subsystems [23-24]. The process begins with the aerodynamic rotor being used to trap the kinetic energy of the wind and mechanically transform it into useful energy [25]. Mechanical energy is then converted into electrical energy by the generator, which supplies electricity to the power grid.

Introduced as a critical feature of renewable energy solutions, contemporary wind power technologies encompass several features, whereby each component occupies its respective position in the functionality and regulation of the overall setup, as illustrated in Fig. 3. The components of the wind energy system are as follows:

- **Aerodynamic Rotors:** The major role of aerodynamic rotors is to intercept wind energy and convert the intercepted energy into mechanical energy, which sets up the energy conversion process. Turbine characteristics and design, including horizontal- and vertical-axis rotors, play a major role in turbine efficiency [26].
- **Gearbox Systems:** A gearbox system is used to control the number of rotations of the rotor with the aim of increasing the efficiency of the generator. These systems can be different with choices, such as planetary and helical gearing, which influence the efficiency and durability of the vehicle.
- **Generators:** While generators are also an important part of the invention, they convert the mechanical energy provided by the rotor to electrical energy to supply electricity to the power grid.
- **Power Electronic Interfaces:** These interfaces control the amount of electricity transferred to or from the turbine and, in particular, regulate the power quality and compatibility of electricity with the standards set by the power grid.
- **Control Systems:** These include pitch and yaw adjustments, both of which are essential for regulating turbine operations, thereby maximizing overall efficiency and operational stability.
- **Yaw Control:** Yaw control mechanisms enable the turbine to rotate and align itself with the prevailing wind direction and optimize energy capture.
- **Brakes:** The braking system is crucial for ensuring safety by halting turbine operations during emergencies or maintenance activities, thereby protecting both the equipment and personnel

The interplay between these components is essential for maintaining optimal performance and power quality [27]. Fig. 4 illustrates a block diagram of the wind turbine system, highlighting the interconnected subsystems: aerodynamic, mechanical, generator, and driving dynamics. These subsystems function in concert to control various aspects of the turbine operation, including pitch adjustment [28].

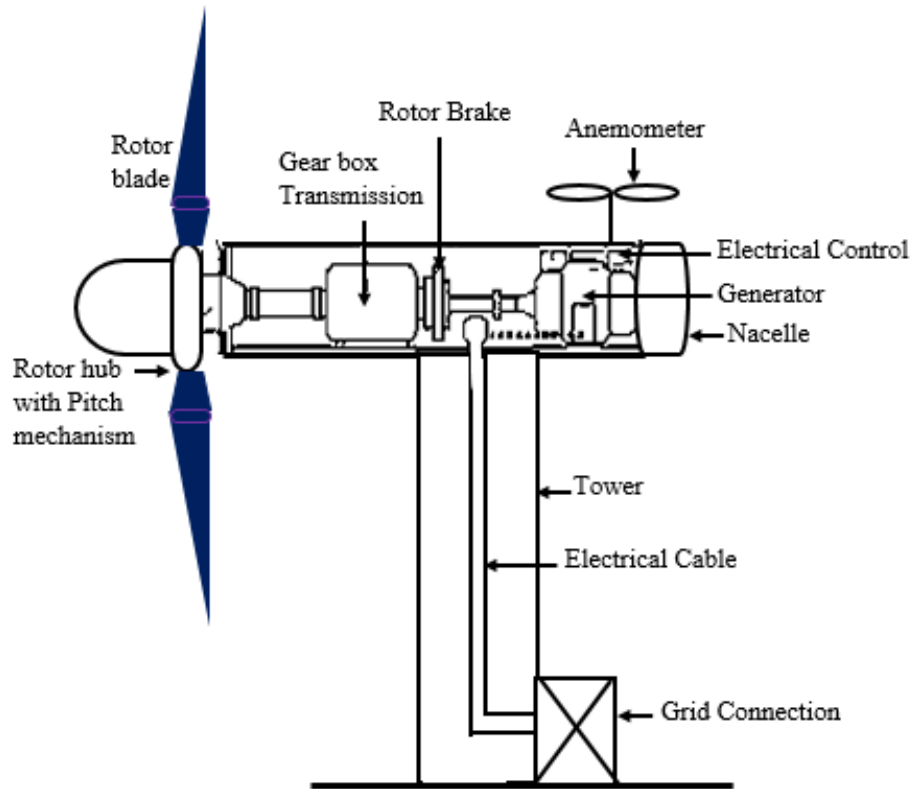


Fig. 3 Description of a wind turbine system [26]

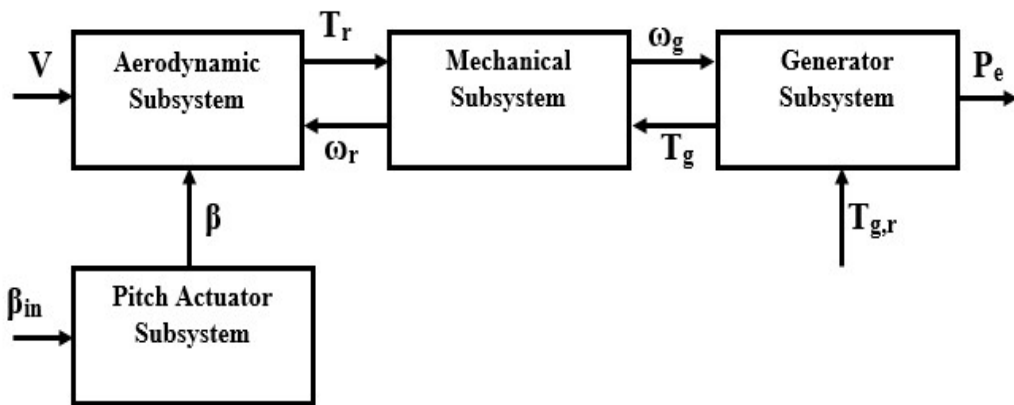


Fig. 4 Block diagram of wind turbine system [28]

The conversion of wind energy to electrical power involves several critical factors that affect the control efficiency and stability of the system [29]. For example, the gearbox ratio plays a vital role in determining the perceived rotational speed and the division of the generator. In addition, the hub serves as a crucial link between the low-speed shaft and servos, facilitating the transfer of mechanical energy. By examining the interdependencies between these components and their collective impact on power quality improvement, we can gain a more comprehensive understanding of the complexities involved in wind-turbine control and operation.

### 1.2 Power Curve and Control Technologies in Wind Turbine Operation

Fig. 5 presents the power curve based on wind speed, illustrating the power properties of a wind turbine measured using the IEC61400-12 standard. The curve includes three critical wind-speed parameters: cut-in, rated, and cut-out speeds [30].

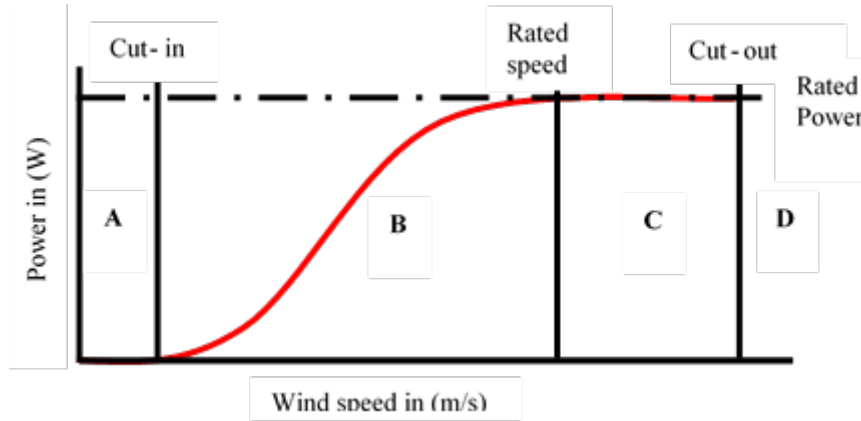


Fig. 5 Wind turbine power curve

- **Cut-in Speed:** This wind speed at which the turbine begins to generate power.
- **Rated Speed:** At wind speed, the turbine operates at its highest efficiency, with power generation following a cubic function of wind speed.
- **Cut-out Speed:** This maximum wind speed at which a turbine can operate safely. Beyond this threshold, the turbine was shut down to prevent further damage.

The need for variable-speed operation and control arises from different wind-speed ranges [31]. Aerodynamic power management strategies are employed to maintain the power output at the rated value as the wind speed increases. Specifically, control technologies dynamically adjust the pitch and yaw of turbine blades to optimize energy capture while ensuring safe operation. If the wind speed exceeds the cut-out threshold, the turbine is programmed to automatically shut off to mitigate risks [32-33].

Building on the understanding of wind turbine operation and the significance of power curves, it is essential to delve into the importance of the power and efficiency of wind control systems. This exploration will illuminate how effective control strategies not only optimize energy capture but also enhance the overall performance and reliability of wind energy systems.

### 1.3 Power and Efficiency of Wind Control System

Power and efficiency are critical concepts in wind-energy generation. Power is defined as energy per unit time [34-35], whereas efficiency refers to the capacity and effectiveness of a system or its components. According to [36], efficiency is quantified as the ratio of useful output to required input. In the context of the power curve of an operational turbine, the regulation of the turbine performance in relation to the wind is primarily achieved by balancing its rotational speed against the wind velocity. The tip speed ratio (TSR) is essential for maintaining this balance, as expressed in Eq. 1:

$$\lambda = \frac{2\pi fl}{v_1} \quad (1)$$

where  $f$  is the frequency of the blade rotation (Hz),  $l$  is the length of the blade (m), and  $v$  is the velocity ( $\text{m/s}^2$ ). The efficiency of a wind turbine is known as the power coefficient ( $C_p$  as shown in Eq. 2. where  $\rho$  is the air density normally  $1.29 \text{ kg/m}^3$  and  $A$  is the area of the blade (in meters).

$$C_p = \frac{P_{actual}}{P_{ideal}} = \frac{0.25\rho A(v_1^2 - v_2^2)(v_1 + v_2)}{0.5\rho Av_1^3} \quad (2)$$

Particular control technologies, such as pitch control systems and variable-speed drives, are essential for improving power efficiency and quality. Pitch control systems modify the blade angle to enhance energy capture throughout fluctuating wind speeds, thereby increasing the power coefficient and ensuring that the turbine functions efficiently within its design parameters. Variable-speed drives enable turbines to adjust to varying wind conditions, sustain an appropriate tip speed ratio, and diminish mechanical strain on turbine construction. Collectively, these technologies not only augment energy production but also substantially enhance the reliability and quality of the power sent to the grid.

## 2. Wind Integration in Renewable Energy System

The integration of control technologies with wind turbine systems is essential for achieving safe and cost-effective electricity production from wind energy [37]. This involves establishing operational constraints on torque and power, reducing fatigue life degradation owing to changing wind directions, variable wind speeds, turbulence, frequent start-stop cycles, and optimizing energy output [38]. This study focused on pitch-controlled wind turbines operating at variable speeds, leveraging advanced sensors and real-time control mechanisms to manage structural loads and stabilize power generation [39]. Additional investigations of turbine configurations can reveal alternative control approaches with similar functional benefits to solve the energy crisis.

With problems such as the deepening global energy crisis and environmental degradation, the incorporation of wind energy into renewable systems is even more important. According to Blaabjerg et al. [40], electronic converters, such as voltage source converters, VSCs, and PWM systems, are ESVPs because of their responsibility to bolster renewable energy integration against common problems such as voltage, harmonics, and reactive power issues. These converters, typically assembled with the Flexibility of AC Transmission System (FACTS), show a better quality of power and control voltage and make the grid compatible. Gorel and Fadhil [41] and Zanib et al. [42] supported the above concern by pointing at skills in the utilization of these electronic converters in careers while maintaining a high standard of output.

It was found that the integration of wind and PV systems was effective in meeting the overall renewable energy generation objectives and minimizing CO<sub>2</sub> emissions. According to Ghadiali and Xydis [43], the integration of wind and PV sources is a better solution because the intermittency of one source can be balanced with the other. Other accessories, such as battery energy storage systems (BESS), are incorporated in these arrangements to control power volatility, whereby captured power during the energy production period is stored for use during low wind incidents to maintain stable power output and healthy grid performance.

Recent studies on the optimization of hybrid wind farm design systems have focused on the aspects of energy storage and control methodologies. Ali et al. [44] also studied small hybrid wind-solar systems in Iraq and established that such systems improve the reliability of the electricity supply and decrease the vulnerability to fossil fuels. Yousif et al. [45] simulated the supply and storage system for large-scale wind and solar energy integration with the main grid to determine how pumped hydro-storage and lithium-ion batteries can sustain energy flow. These storage devices and control technologies address wind energy fluctuations.

Several control technologies are crucial and utilized to control wind farms and their integration into the utility grid. For instance, the supervisory control and data acquisition (SCADA) reported by Balasubramanian et al. [46] facilitates ongoing surveillance of the operation of wind turbines, thereby allowing real-time control to avoid voltage fluctuations and other quality issues in power. SCADA systems act on changes in wind conditions that are necessary and crucial for stabilizing the output under different conditions. Another type of direct current (DC), referred to as high-voltage direct current (HVDC) transmission, is highly useful for long-distance transmission of wind energy from offshore wind farms owing to its minimal energy losses and stable grid connection, as noted by Jain et al. [47]. Second, other techniques in voltage regulation, as discussed by Olanite et al. [48], guarantee constant voltage given wind fluctuations, address compliance with the voltage grid, and improve stability.

These control and integration technologies play a critical role in addressing key issues related to power quality, wind variability, and grid reliability, enabling wind energy to serve as a dependable resource within renewable energy systems. Expanding beyond wind energy to other renewable sources, Al-Shahri et al. [49] examined optimization strategies for solar energy systems to enhance power quality, whereas Alhousni et al. [50] highlighted the potential of solar energy as a sustainable alternative in regions such as Dhofar and Oman, emphasizing the viability of renewable energy in diverse climates. Similarly, Ebrahimi et al. [51] demonstrated the benefits of hybrid renewable systems by integrating geothermal and photovoltaic power, achieving CO<sub>2</sub> emission, and improving power quality. Incorporating the flexibility of renewable energy supply, Almajali et al. [52] have further improved solar distillation, driving 83.5% thermal efficiency and 19Lm<sup>-2</sup> per day. These improvements show the possibilities of using solar distillation to increase the quality and effectiveness of power and renewable energy. Combined, this signify that the renewable energy systems have great potential in enhancing quality of power in many applications in a way that enhances reliability, efficiency, and sustainable development within energy systems.

Consequently, to understand the role of control technologies to improve the reliability and integration of wind energy, it is crucial to analyse procedures addressing operation of the wind turbine systems. These mechanisms regulate speed and power output of turbine and structural loading to manage generation quality and integrity. Further research efforts should be directed to improving these mechanisms with the help of modern technologies, such as machine learning and others. The subsequent section discusses crucial approaches including pitch control, yaw control, and generator speed control that enhance the turbines' efficiency and uphold the requirements of the energy system.

### 3. Control Mechanisms Used in Wind Energy Systems

Control mechanisms should be well adopted in wind energy systems to achieve higher performance and reliability, and play a significant role in enhancing the efficiency of the power system. These mechanisms respond to several more critical parameters: the effect of the controller on power generation [53], balancing the asymmetric load and fatigue, and the characteristics of the control system [54]. These control strategies, including pitch and yaw controls, have a significant positive influence on the wind turbine response to varying wind conditions from the bearing load cycles of the blade [55]. A strong control effort is required to reduce these stresses and avoid such failures [56-57]. However, this type of configuration may make the analysis of the dynamic properties of a control system less straightforward and requires systematic approaches to the analysis and design. Therefore, the application of grid standards is imperative for integrating these control mechanisms to enable efficient energy delivery and coordination with the wind energy generation and requirements from the grid. Fig. 6 illustrates the various types of control mechanisms employed in modern wind turbine controllers.

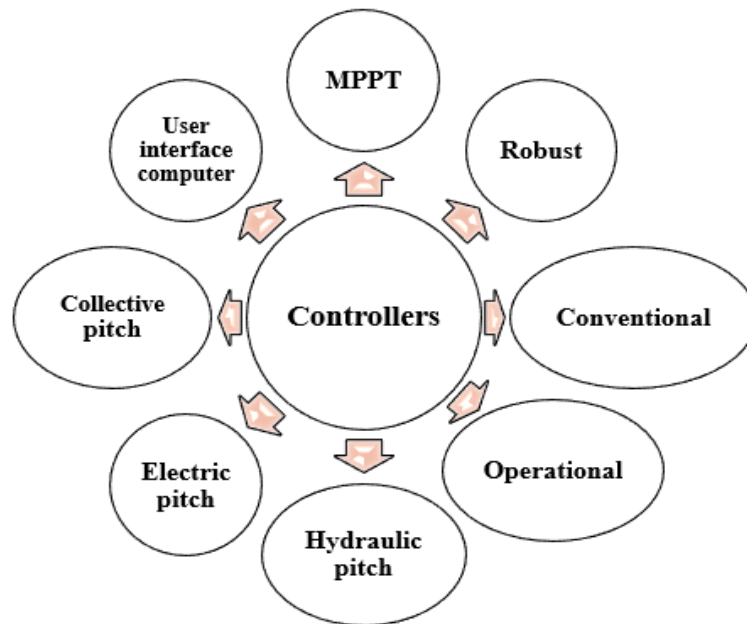


Fig. 6 Different types of wind energy controllers [37]

#### 3.1 Pitch Control Mechanisms in Wind Turbines

Pitch control is an essential mechanism in wind turbines that optimizes the blade angles and rotor speeds to achieve specific power outputs [58]. By adjusting the rotor blade angles relative to the wind, the pitch system controls the rotor speed to maximize the power capture and reduce the structural loads, which decreases the fatigue of the turbine components [59-60]. Pitch control systems are classified into Individual Pitch Control (IPC) and Collective Pitch Control (CPC). IPC independently adjusts each blade angle, enhances energy capture, and mitigates load imbalances caused by turbulence or non-uniform wind [61-62]. In contrast, CPC adjusts all blade angles simultaneously, ensuring coordinated operation across the rotor [63]. Both pitch control types are crucial for managing the torque in fixed-speed turbines and optimizing the energy conversion in variable-speed turbines. Additionally, taller turbine towers improve the wind capture. Overall, pitch control enhances safe operation, increases energy capture, and reduces mechanical stress, thereby extending turbine lifespan [64].

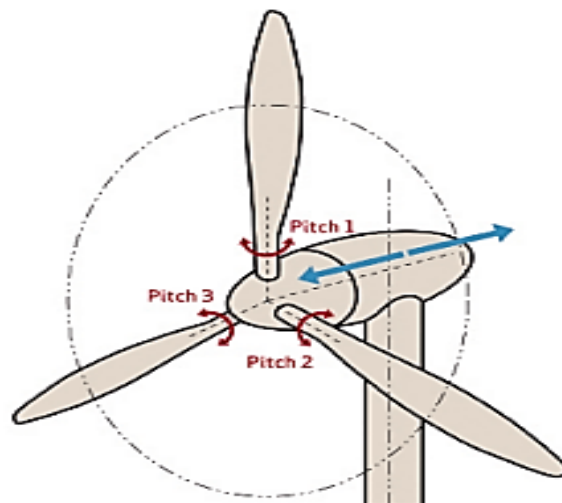
Numerous studies have developed pitch control technologies to improve wind turbine performance, reliability, and stability. Almihat and Kahn enhanced pitch angle control stability through feedback, feed-forward, and sliding-mode control techniques [37]. Mousa et al. introduced a Simple Optimal Intelligent PID Controller (SOI-PID), which demonstrated faster response times and improved rise and settling times compared with traditional PID, Fuzzy Logic, and Fuzzy-Adaptive-PID controllers [65]. Venkaiah et al. proposed a sliding mode controller based on an exponential rate-reaching law with stability verified through Lyapunov analysis, which showed superior performance and stability [66]. Bouregba et al. integrated Maximum Power Point Tracking (MPPT) into pitch control and found that the PI-NFLC controller is highly effective for large turbines [67]. Kalpana and Ansari's Fractional-Order Fuzzy PID controller, paired with a Superconducting Magnetic Energy Storage Unit (SMES), outperformed conventional controllers in a wind-diesel system [68]. Lüy and Metin utilized the Particle

Swarm Optimization (PSO) and Ziegler-Nichols methods to tune PID controllers, achieving reduced oscillation and improved energy conversion efficiency in renewable systems [39].

Pitch control mechanisms significantly enhance power quality within microgrids, particularly through IPC systems that dynamically respond to the stochastic nature of wind, delivering a steadier output that is critical for microgrid stability. Advanced controllers such as SOI-PID and Fractional-Order Fuzzy PID reduce the settling time, increase robustness, and ensure a stable energy supply to the microgrid. These control strategies are instrumental in boosting the efficiency and reliability of microgrids that increasingly rely on renewable sources, thus supporting grid stability and integrity as the energy transition progresses.

### 3.1.1 Individual Pitch Control (IPC)

PC are vital for wind turbine control systems. It reduces unequal mechanical loads on turbine blades, extends their lifespan, and improves performance. While controlling the turbine speed and power output, the IPC compensates for the stresses and fatigue on the turbine structures. Brake and modify the rotor blade angle [69-70]. Wind turbine technology has advanced to allow variable-speed turbines to respond to wind conditions. The pitch control system in these turbines adjusts the rotor blade angle to between  $0^\circ$  and  $90^\circ$ , as shown in Fig. 7. The pitch was set to  $0^\circ$  when the wind speed was below the rated power and was steadily increased to  $90^\circ$  [41]. The turbine stopped electricity production by turning the blades  $90^\circ$  when the wind speed reached 28 m/s.



**Fig. 7** IPC individually adjusts the pitch of each rotor blade [5]

Wind turbine lifetimes are being improved through economic and technical advancements [71]. The IPC system, which consists of multiple controllers, sensors, and calculation units, optimizes the blade pitch angles based on mechanical load values, operation values, and weight factors, as shown in Fig. 8. This minimizes the loads and maximizes the energy output while limiting the power output of the turbine as the wind speed increases [72].

Numerous studies have been conducted to augment the load mitigation efficiency and optimize the wind energy conversion efficiency via individual pitch control (IPC) techniques. Aktan and Bottasso [70] concentrated on IPC utilizing a diminished actuator duty cycle, employing a nonlinear PI formulation, and numerical optimizations guided by a fatigue-oriented cost function. This study seeks to enhance load mitigation efficiency under realistic inflow conditions. Routray et al. [73] compared various IPC methodologies, including model predictive control (MPC), H-infinity ( $H_\infty$ ), and PI-based IPC.  $H_\infty$ -based IPC proved to be the most efficacious in load reduction, especially when combined with collective pitch control. Yamada and Murakami [74] devised an IPC system for wind turbines that improved wind energy conversion efficiency. Their approach employs a pitching moment estimate and reaction force observer (RFOB) to regulate the individual pitch. This novel method enhances the efficiency of wind-energy conversion. Gambier [75] redefined IPC methodologies as transfer matrices to enhance systemic comprehension. They underscored the significance of proportional-resonant controllers in the dynamics of IPC and highlighted the necessity of reformulating IPC methodologies.

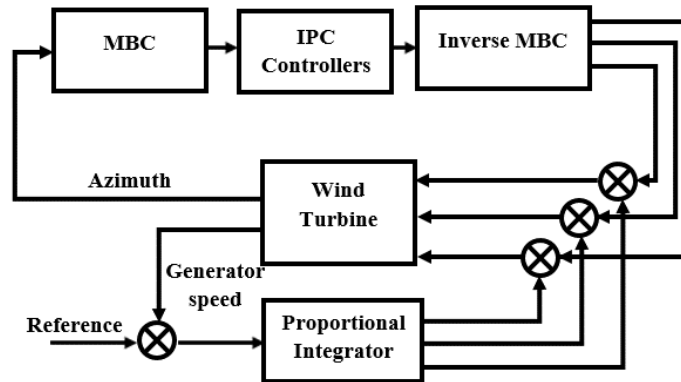


Fig. 8 Individual pitch controller in wind turbine [73]

### 3.1.2 Collective Pitch Control (CPC)

Collective Pitch Control (CPC) is a mechanism used in wind turbines to simultaneously adjust the pitch angle of all rotor blades, as shown in Fig. 9. It ensures coordinated blade movement, optimizes energy capture, and maintains safe operation [5]. CPC systems are simple, reliable, and cost-effective compared with Individual Pitch Control (IPC) systems. CPC is rather simple, but ensures a high level of reliability and efficiency of energy capture for turbines with fixed-speed generators. In addition, owing to the complicated dynamics and uncertainty of the application of wind turbine pitch control, several control algorithms, such as AI and fuzzy logic controllers, exhibit characteristics of environmental flexibility [76]. Sliding mode controllers, proportional-integral controllers, and sliding-mode observers are a combination of control system techniques used to increase the conversion of power and provide stable output power in variable-speed wind turbines. Jáuregui et al. [77] indicated that it is vital to use particle swarm optimization and other types of evolutionary algorithms to enhance the control system parameters of a pitch angle controller. The CPC plays an important role in the enhancement of wind in turbines with reference to the unpredictability of wind conditions. This is an efficient and economical means of energy generation; however, it is ineffective for the variation and turbulence of micro-winds. Artificial intelligence, fuzzy logic, particle swarm optimization, and control algorithm techniques enhance the capabilities of wind turbines. Kipchirchir and Söffker [70] developed an independent pitch-based robust disturbance-accommodating controller (IPC-RDAC) for wind turbines that offers an alternative to traditional collective pitch control (CPC) systems. The IPC-RDAC utilizes a proportional-integral controller derived from the ROSCO-GSP model to improve the load mitigation and speed regulation in wind energy systems.

In another study, Mohsin et al. [78] proposed torque control approaches with the use of collective pitch control (CPC) and individual pitch control (IPC) in order to achieve better results and decrease loads. They employed a non-linear CRAFTS simulator for the control design, implementation, and assessment. Effective methods of pitch control for horizontal-axis wind turbines were investigated by Goyal et al. [79], with special reference to collective pitch control and hybrid-related control schemes. Joshi et al. [80] proposed studies on enhanced pitch control using an AI controller and compared them with conventional PID controllers for set-point jobs and load frequency control based on Betz's law.

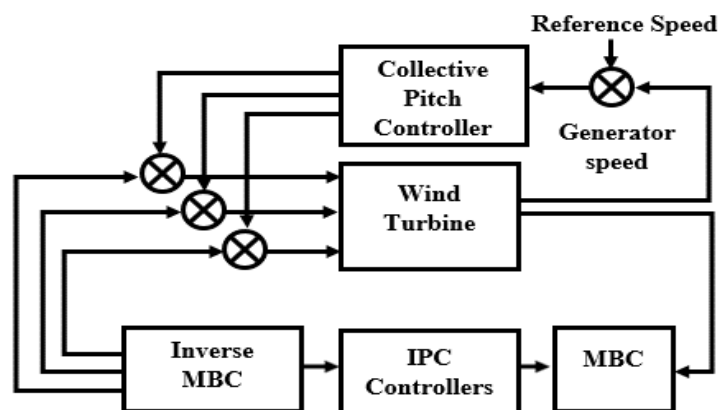


Fig. 9 Collective pitch controller in wind turbine [77]

### 3.1.3 Hydraulic Pitch Controller

In the field of wind turbine technology, hydraulic pitch controllers are crucial for regulating the pitch angle of turbine blades to optimize power production and ensure safe operation as shown in Fig. 10. Substantial evidence has been acquired through literature analysis to develop and optimize such controllers with reference to their performance. One way to enhance hydraulic pitch control is to use digital hydraulics because of its high response rate, good power/weight ratio, and good durability. Another method for controlling the hydraulic cylinder velocity involves deriving the flow gain from the cylinder velocity, and then holding it to set the position of the cylinder as controlled by the pitch controller. The goals of these techniques are to improve the power control and minimize pitch control faults to improve the general functioning of the pitch control system [81]. Venkaiah and Sarkar [82] proposed a model-free fuzzy feed-forward PID controller for the pitch control of a wind turbine. This controller provides maximum power tracking and wind gust peaking protection.

Yin et al. [83] proposed an electro-hydraulic servo pitch system that helps precisely control the pitch angle while easing the variation in the power supply. Other hydraulic pitch control systems employed in wind turbines were discussed by Pelin et al. [84], including load shielding, enhanced aerodynamicity, and proper power capture. Various control methods have been described, including passive stall control and collective and individual blade control, which have issues such as slow feedback, rigidity leakage, and air-borne product transmission problems but are reliable in operation.

Recent studies have focused on dynamic analysis, effective control, and establishment of a model for hydraulic pitch controllers. These investigations have demonstrated that hydraulic pitch adjustments reduce torque fluctuations to a negligible level, thus retaining wind turbine output power. In addition, fault compensation solutions for solving problems, identifying faults, and fixing them in real time were presented in [37]. Alemu and Ayenew [85] investigated the optimal regulation of electrohydraulic actuators in wind turbines using genetic algorithm-based fractional-order proportional integral derivative (GA-FOPID) controllers. They outperformed conventional proportional-integral-derivative (PID) controllers and conducted performance evaluations at various wind velocities. Korkos et al. [86] investigated the utilization of deep-learning methodologies, specifically autoencoders, to detect issues in the hydraulic pitch systems of wind turbines. Compared to other dimensionality reduction algorithms, the deep autoencoder demonstrated the most impressive performance, achieving a 95.5% F1-score.

Lakshmi and Ramakrishnan [87] investigated the optimization of a digital hydraulic pitch actuator for large-scale wind turbines using a model-based design. Their sophisticated controller overcame conventional controllers, thereby improving the efficiency of the power generation and pitch control systems. In [88], Roh introduced a pitch controller based on deep learning. The controller enhanced the average power generation by 5% and reduced the pitch motion by 5% by employing a deep-learning approach to mitigate hydraulic actuator delays. Wang et al. [89] developed an H-robust control methodology for hydraulic variable pitch systems in wind turbines. Their approach employed mixed sensitivity optimization to reduce steady-state errors and improve the robustness of the system.

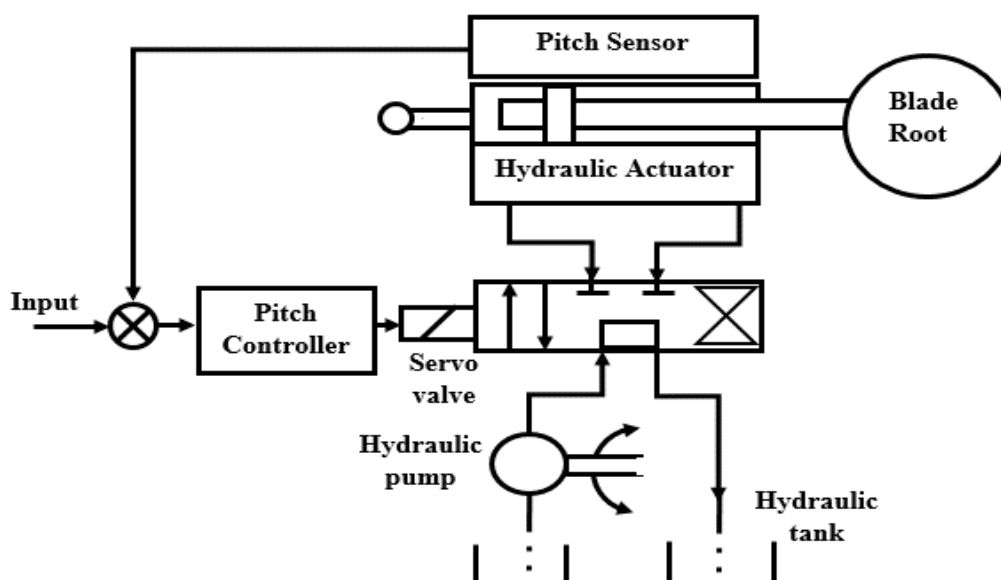


Fig. 10 Hydraulic pitch controller in wind turbine system [80]

### 3.1.4 Electric Pitch Controller

Electric pitch controllers are essential for wind turbines because they adjust the blade angles to adapt to changing wind conditions and to ensure safe operation. They play a crucial role in maximizing energy extraction from varying wind speeds and topographical conditions, ultimately improving the overall performance of wind turbines, as shown in Fig. 11 [90]. Conventional pitch control controllers, such as PID controllers, are used to address uncertainties and nonlinearities. However, there is growing interest in AI-based controllers, such as fuzzy logic controllers, which can enhance performance by adjusting blade positions in response to wind surges. Digital pitch controllers incorporating machine learning techniques have also demonstrated superior power control and pitch control tracking performance.

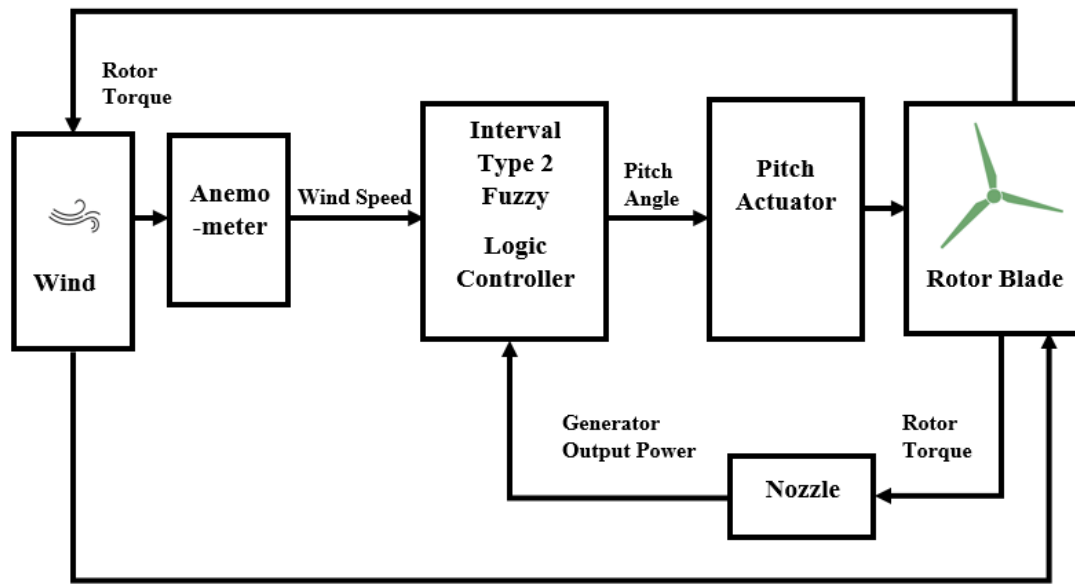


Fig. 11 Electric pitch controller [80]

### 3.1.5 Challenges of Pitch Control Method

Wind variability is a fundamental characteristic of wind energy resources and affects wind power generation by changing temporal and spatial variations [91]. Turbulent airflow near the ground causes rapid fluctuations in the wind speed, impacting the turbine performance and structural loads. Wind shear, which is the vertical gradient of wind speed with height, affects the turbine efficiency. Wake effects, caused by the rotor-intercepting wind of one turbine, affect neighboring turbines [92]. Intermittent wind energy production requires energy storage systems or grid integration strategies to balance the supply and demand. Load reduction is crucial in wind turbine pitch control systems for addressing mechanical fatigue, optimal energy capture, fast response to turbulence, individual blade control, and structural integrity [93]. Rapid pitch adjustments are essential for avoiding overshooting or oscillations. Individual blade control is crucial for optimizing the load distribution in multiblade turbines. Advanced control algorithms and robust sensors are essential to address these challenges.

Actuator faults are other issues that affect reliability and robustness. Consequently, fault tolerance is a major concern in pitch control systems of wind turbines. They include fault-tolerant control, which aims to mitigate these faults and maintain overall system performance. To sustain and control the power generation at the global level, pitch system control is mandatory. These advanced techniques have been efficiently used to estimate the pitch system state, faults, and other uncertainties that aid in fault detection and subsequent compensation [94]. The topics related to fault tolerance are sophisticated and primarily involve fault control and diagnosis. Estimating the pitch angle in wind turbines is challenging and critical because of its association with aerodynamic torque and rotor overspeed. Good stability enables the singer to control the pitch and, hence, performs very well. The authors analyzed strain gauges and sensors for blade loads to determine pitch improvements and cutting-off cyclic loads. More recent developments include the use of a reaction force observer to estimate pitching moments and wind speeds.

Blade-load interaction is a considerable problem for pitch control systems, which modify the blade position to decrease wind turbine loads during turbulence. These loads were controlled using individual pitch control methods including a multiblade coordinate transform. Optimal ind. pitch control simulations have demonstrated

that incorporating azimuth offset can decrease blade FL for fear of actuator exertion [95]. Factors such as wind shear impose difficulties in wind energy utilization; they influence turbine characteristics and strength. Other control approaches are being studied, such as individual pitch control, to handle wind shear and simultaneously maximize the power coefficient while minimizing structural loads. Wind shear also presents a pitch control system with another problem because the pitch changes continuously owing to the varying wind conditions. There are also main ideas that are very important when designing and tuning the pitch control system: they must have high sensitivity to wind variations and be susceptible to rapid changes in the wind [96-97].

### 3.2 Maximum Power Point Tracking (MPPT) Controller

Maximum power point tracking (MPPT) is an essential control strategy used in wind turbines, where wind speed, blade pitch angle, and generator speed are measured, as shown in Fig 12. It employs anemometers to measure wind velocity and direction, blade pitch to achieve maximum power capture, and synchronous generator speed to rotor speed [98]. MPPT controllers work in such a way that they permanently check the power rating and change the parameters of the turbines to benefit from optimal power generation, particularly in regions encountering fluctuating wind behavior. It is an electronic apparatus that converts direct current from wind turbines (WT) or solar panels and validates the power exchange with the battery bank or utility grid [99]. Some characteristics of MPPT controllers include voltage control, efficiency, operational flexibility, and battery charging control [100]. Conventional methods include IPC and DPC to manipulate the generator torque and boost power points. Intelligent types of MPPT include FOIM and FLC, which are less oscillatory than earlier types [101].

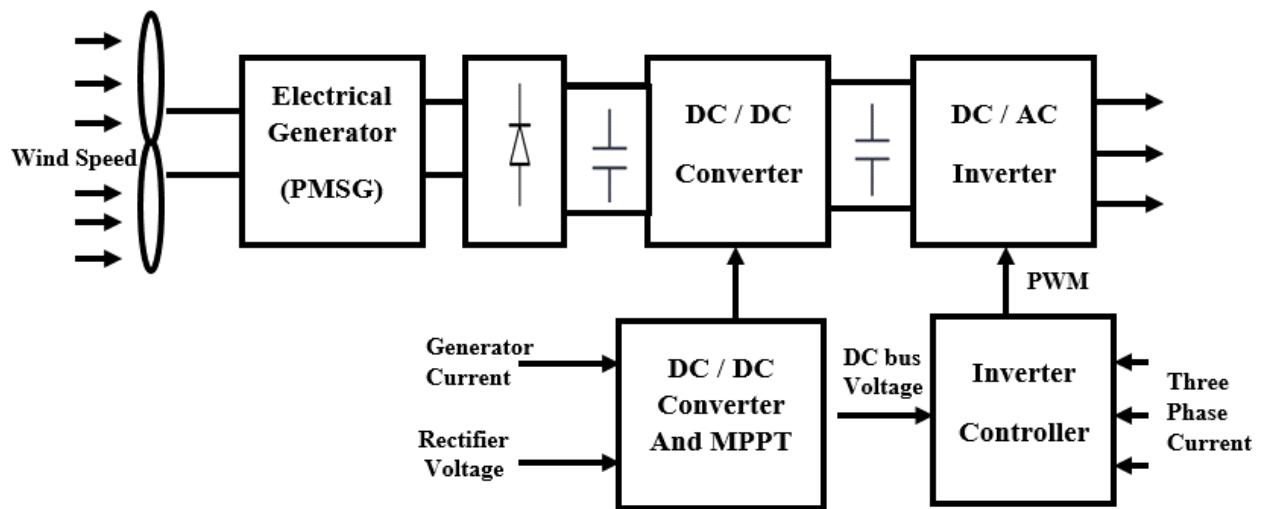


Fig. 12 Maximum Power Point Tracking (MPPT) Controller [102]

Wind-generated power systems require control methods that enable them to produce the maximum power while regulating the power system. In MPPT charge controllers, the current output is regulated to deliver the correct amount of current to the load and achieve maximum power voltage with only a small loss. Some advanced algorithms have been developed with a close focus on MPPT techniques: mechanical sensors have been developed, new tracking speed techniques have been developed, and dynamic and steady-state performances have been upgraded. Yousra and Tahar [103] developed a deep Q-network technique to control the MPPT of a PMSG connected to a wind turbine. Arianborna et al. [104] and Shuvo et al. [105] proposed an MPPT method for wind energy generation that employed deep reinforcement-learning-based adaptive speed management and a prediction model for turbine speed and output power optimization [106]. In summary, MPPT control techniques are essential for optimizing wind energy harvesting in wind turbine systems, as illustrated in Fig. 5.

### 3.3 Conventional Algorithms

Conventional algorithms are widely used and established techniques employed for various applications, including wind energy systems, based on proven mathematical principles and have been extensively studied, refined, and widely adopted in the industry. The MPPT controllers in wind energy systems are based on conventional algorithms such as Perturb and Observe (P&O) and incremental conductance) [107].

### 3.3.1 Perturb and Observe (P&O)

P&O is a widely used technique for extracting the maximum power from wind turbine generators with the goal of searching for and maintaining the optimum operating point [108] and functions through measurement, power calculation, observation, perturbation, and adjustment. The P&O algorithm is easy to implement, flexible, and robust against perturbations. But it also has some drawbacks like oscillations, slow tracking rate, and accurateness problems for overcoming these problems, some advanced techniques like FLC and IC have been introduced that makes the MPPT system much more efficient, with faster tracking rate, accuracy, and stable in wind energy applications [109].

### 3.3.2 Incremental Conductance

Another MPPT algorithm is incremental conductance (IC), which is used in wind energy systems. In its operation, it is relatively similar to P&O, but has several differences from this company. It measures the voltage and current of the wind turbine generator, calculates its power output, conducts conductor calculations, compares it with an instantaneous conductor, and reconfigures the generator voltage or current to correspond to the comparison before continually tracking the MPP [110]. The benefits of implementing IC consist in the increase of the tracking accuracy, in the fact that the tracking action under the conditions of the fluctuations of the wind velocity is considerably faster, the capacity to track the MPP even in the case of partial shading or other disruptive change, and stable functioning without constant oscillation round the MPP [111].

### 3.3.3 Fractional Open-Circuit Voltage

The FOCV is a basic algorithm for the MPPT widely implemented in WE systems, which is as follows: It works continuously by tuning power and voltage in the wind turbine Generator's open circuit to scale it, adjust it and control for Maximum Power Point [112]. The constant factor (k) varied from 0.7 to 0.8: This was arrived at, majoring in the fact that the MPP voltage in Wind Turbine Generators ranges from 70-80 percent of its open-circuit voltage. The FOCV algorithm has several advantages, such as a low computational cost and the requirement of fewer sensors. The dynamic response of the FOCV algorithm to different system parameters, such as wind speed, may not be very appealing because it requires the system to perform several additional operational measurements [112].

Moreover, the Fractional Short-Circuit Current (FSCC), which assumes the maximum power point current of the solar panel, is proportional to the short-circuit current of the panel. The controller periodically measures the short-circuit current and calculates the maximum power point current as a fraction of the short-circuit current. The FOCV method is widely employed for small-scale or low-cost wind energy systems, owing to its simplicity and low processing requirements. Advanced MPPT algorithms, such as P&O or IC, may be more suitable for complex or high-performance wind energy systems [113].

## 3.4 Indirect Power Control (IPC)

One of these techniques can be employed in conjunction with MPPT controllers. The DC MPPT controllers control the voltage or current of the PV system to operate at the MPP. However, such direct control may suffer from certain challenges, particularly under fluctuating environmental conditions [114]. Among the advantages of their usage, the tracking accuracy is increased, stability is enhanced, and control algorithms are simplified. IPC can track the maximum power point with far greater precision and respond far more quickly to fluctuations in the panel's output [115]. It can also be used when the load is resistive, inductive, or capacitive in nature or for almost any other type of load. When using MPC with MPPT controllers, PV systems can produce an overall higher performance, high energy-collection efficiency, and higher reliability under varying climate conditions. There may be slight differences in how IPC is integrated into an MPPT, depending on the MPPT controller, system design, type of power converter, and control algorithm [115].

## 3.5 Direct Power Control (DPC)

Direct Power Control (DPC) is a method for controlling the power output of a photovoltaic (PV) system, unlike Maximum Power Point Tracking (MPPT). In MPPT, either the voltage or current generated by the PV system is varied to create a P-V curve [116]. However, DPC focuses directly on controlling the power output rather than just the voltage or current. DPC has several advantages over MPPT, including direct power control, voltage or current regulation, simpler control architecture, and improved accuracy and stability. It such as controlling a switch connected between the PV panel and the load, enabling the power converter to switch on and off for a certain time. The DPC algorithm design is less challenging than MPPT because it does not require the establishment of voltage or current control loops [117]. It also provides better stability and precise control of power and provides stability at the maximum power point compared with direct voltage or current control. The decision on whether to use

DPC or MPPT largely depends on the PV system characteristics, available computing power and speed controls, tracking precision, and system stability requirements [118].

### 3.6 Intelligent MPPT Algorithms

Advanced MPPT algorithms enhance the efficacy and capacity of Wind Energy Converters (WECs) by considering specific components and parameters. Key techniques include wind speed estimation, turbine characteristic modeling, adaptive control methods, fuzzy logic and neural networks, multi-objective optimization, and hybrid approaches [119]. Estimating wind speed allows for the prediction of available wind power and the adjustment of system settings accordingly. Turbine characteristic modeling, described mathematically or through machine learning, provides a precise understanding of the nonlinear power-to-rotational speed ( $P-\omega$ ) relationship. This enables computers to predict the Maximum Power Point (MPP) more accurately and adapt to changes in wind conditions [120].

Appropriate self-tuning control methodologies tune the values in parallel synthesis to monitor tracking precision and eradicate further speed. FL and ANN demonstrated higher suitability in dealing with the complex nonlinear correlations among the turbine parameters than conventional methodologies, improving the adaptive MPPT proficiency. When the wind speed estimator is integrated with advanced control schemes or fuzzy logic with neural networks, MPPT efficiency is enhanced. There are different types of further subdivisions based on Intelligent MPPT algorithms, some of which are fractional order intelligent MPPT and Fuzzy Logic Controller (FLC) MPPT[121].

#### 3.6.1 Fractional-Order Intelligent MPPT Algorithm

The intelligent MPPT algorithm is an advanced control method that integrates fractional-order calculus with intelligent techniques to enhance MPPT performance in wind energy conversion systems. By extending integer-order derivatives and integrals to the fractional-order, this approach provides greater flexibility and a faster transient response than traditional integer-order controls [122]. The algorithm uses fuzzy logic or neural networks to optimize key relationships among wind turbine factors, such as wind speed, rotor speed, and power output, enabling the system to adapt to changes in wind conditions and system characteristics. This adaptation ensures high-performance and efficient power generation across different scenarios.

This fractional-order intelligent MPPT algorithm presents an enhancement in the tracking precision, dynamic behavior, stability, flexibility, and multiple optima. Its main strength is that it can be balanced under different wind conditions and configurations in terms of control [123]. However, this algorithm cannot be implemented without complex processing power and specialized control equipment, which in turn adds complexity and cost. Nevertheless, it can substantially enhance the efficiency of wind energy systems

#### 3.6.2 Fuzzy Logic Controller (FLC)

A Fuzzy Logic Controller (FLC) is a widely used approach to MPPT in wind energy systems and is applicable in this study. This technique addresses the imprecise and non-linear effects of various system factors in wind energy conversion systems [124]. In an FLC-based MPPT algorithm, the wind speed is represented in the fuzzy domain, whereas the output power is represented in the membership domain. The proposed SPC-IFA (Self-Proposed Controller with Intelligent Fuzzy Algorithm) includes a fuzzy rule base derived from either expert knowledge or empirical data on wind turbine performance and MPPT. This rule base allows adaptive input-to-action control. The FLC-based MPPT algorithm is flexible, capable of handling the nonlinearities typical in wind energy systems, integrates expert insights, and can accommodate multiobjective tasks [125-126].

Fuzzy logic reduces uneven changes in characteristics, such as wind speed, rotor speed, and power generated by the turbine [127]. However, the use of the FLC-based MPPT algorithm is highly sensitive to membership functions, rule-based settings, and parameters controlling the fuzzification process. It is also important to understand that FLC-based MPPT may be characterized by higher computational complexities as compared to other types of MPPT systems, which can cause difficulties in cost-effective implementation. MPPT based on a fixed point is also typical in wind power systems because it can handle mathematical nonlinearity and system complexity to achieve multiple objectives [127].

### 3.7 User Interface Computer Controller

In the design of a wind turbine system, a user interface computer controller [128] provides a means for users to monitor and control turbine operations. This interface includes a controller for routing the instructions and information to and from the main system controller. A built-in processor interprets the received commands and data and generates output signals in an appropriate format. To enhance the ease of use, the interface device includes a speech recognition feature that can convert spoken commands into signals processed by the processor

of the system. This feature may involve a microsensor to capture voice input and an output device with an intuitive display to relay the processed commands and data.

Furthermore, environmental changes have been effectively incorporated into systems using AI techniques [37]. FLCs are advantageous because of their adaptability and simplicity in improving the microgrid capabilities of wind energy systems. Other pitch angle controllers that are based on metaheuristics help lead to even more stable system outcomes during medium wind velocity, and Artificial Neural Networks (ANNs) assist with the control of mechanical nonlinearities of the wind turbine.

### 3.8 Robust Controller

Robust controllers play a crucial role in wind turbine systems by handling nonlinearity, interference, and disturbances, as illustrated in Fig. 13. These controllers reduce oscillations and fluctuations in speed and power output, thus enhancing system stability and performance. Common types include sliding mode, damping, and  $H_\infty$  controllers.

In [129], researchers proposed a closed-loop control strategy to address the uncertainty characteristics of wind turbine systems, effectively regulating generator speed. The performance of this controller was compared with that of a model order reduction technique, showing promising results. Similarly, Ba et al. [130] introduced a robust damping controller for a double-fed induction generator (DFIG)-based wind turbine. This controller improved reliability by mitigating unpredictable operating conditions and system oscillations and reducing frequency deviations in both experimental and simulation studies.

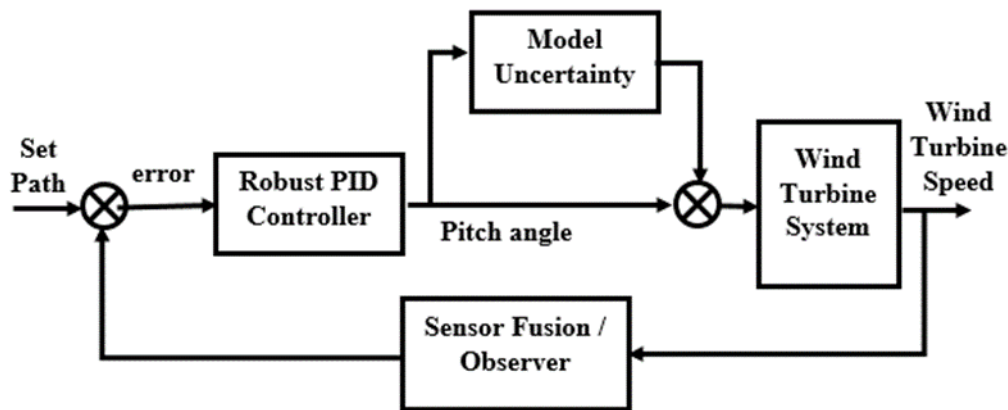


Fig. 12 Robust controller [129]

### 3.9 Conventional Controller

Small wind energy systems typically use conventional controllers, such as PID/PI controllers, to regulate rotor speed and power output, as shown in Fig. 14 [37]. While these controllers are widely researched and effective for small turbines, they often face challenges such as difficulties in accurate wind-speed measurements and slower response times. The primary factors influencing the system performance and reliability are rotor speed and generator power. Gain scheduling is one way by which nonlinear dynamics showing undesirable behaviour can be manipulated in order to conform to the desired standards. This approach minimizes the effect of the aerodynamic thrust to pitch angle by fine tuning the controller gain. The trade-off of the system sensitivity and gain yields designs with better robustness than the basic controllers that do not incorporate gain scheduling.

PID and PI controllers are prevalently employed to address the rotor speed and output power problems and are suitable for small-scale systems. Still, getting the scale right for the wind speed turns out to be most problematic. The approach of gain scheduling allows for these systems to be more robust against changes in aerodynamic torque, and therefore more credible.

## 4. Conclusion

The integration of wind energy into modern power systems offers significant opportunities, but also presents challenges that demand robust control technologies to ensure efficient, reliable, and sustainable energy generation. Wind turbines rely on interconnected components, such as aerodynamic rotors, gear systems, generators, power electronics, and advanced control systems that work together to optimize energy output and maintain power quality.

Control mechanisms, such as pitch control of the blade and yaw control, are vital to ensure good performance of the turbine while operating under varying wind conditions. These technologies are becoming relevant in the face of mounting demand for renewable energy sources and the growing problems of voltage instability, harmonic distortions, and power quality deterioration. These studies indicate the need for further advancements in electronic converters and integration of the Wind-PV hybrid system into the grid. Furthermore, the deployment of new forms of control is necessary to increase RES integration, decrease the demand for fossil fuels, and overcome global problems, such as climate change. As we address the problems of wind variability, quality of power, and integration of wind energy, the future of wind energy is made secure.

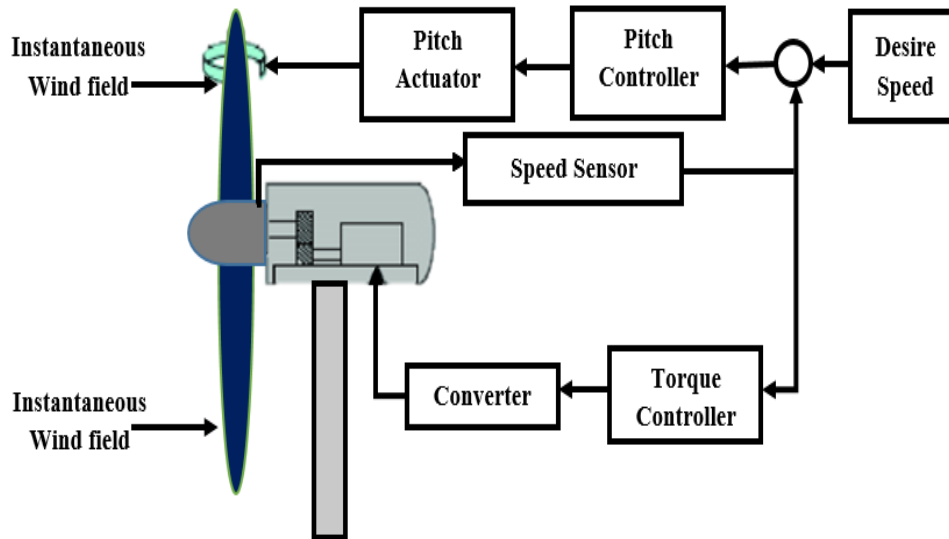


Fig. 12 Conventional controller in wind turbine system [45]

## 5. Future Work All figures

Potential future research areas include the application of machine learning, as well as the combination of hybrid control techniques that could be employed to improve the flexibility, dependability, and performance of wind turbine control systems. Scientific advancements in various types of energy storage and their interconnection with wind and photovoltaic systems can provide more reliable output and mitigate the fluctuation characteristics of renewable resources.

Research into the scalability and economic viability of these technologies is also crucial to ensure that developments in wind energy remain competitive and can be effectively implemented in diverse settings. Collaboration among academia, industry, and regulatory bodies is essential to drive these advancements, ultimately contributing to the enhancement of wind energy systems and their integration into the broader renewable energy framework.

## Acknowledgement

We acknowledge the support of TETFUND and the management of Federal Polytechnic Ede, Osun State, Nigeria, for the finance, conducive environment, and time required to perform this research.

## Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

## Author Contribution

The authors confirm contribution to the paper as follows: **study conception and design:** Titus O. Ajewole, Kabiru A. Hassan, Mutiu K. Agboola; **data collection:** Titus O. Ajewole, Kabiru A. Hassan, Mutiu K. Agboola; **analysis and interpretation of results:** Titus O. Ajewole, Kabiru A. Hassan, Mutiu K. Agboola, Olakunle Olukayode; **draft manuscript preparation:** Kabiru A. Hassan. All authors reviewed the results and approved the final version of the manuscript.

## Funding

This research is funded by TETFUND, Federal Polytechnic, Ede. Osun State, Nigeria.

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