Wind Energy Conversion Technologies and Control Strategies: A Review

Abdelfattah Dani*‡, Mohamed Benlamlih*, Zineb Mekrini*, Mhamed El Mrabet*, Mohammed Boulaala*

*Industrial Systems Engineering and Energy Conversion Team, FSTT, Abdelmalek Essaadi University, Tetouan, Morocco

(dani.a.fattah@gmail.com, benlamlih@gmail.com, zineb.mekrini@gmail.com, m.elmrabet@gmail.com, m.boulaala@gmail.com)

‡ Corresponding Author; Abdelfattah Dani, FSTT, BP: 416, Tangier, Morocco, Tel: +212 539 393954, dani.a.fattah@gmail.com

Received: 05.06.2023 Accepted:02.07.2023

Abstract- Renewable energy sources are becoming increasingly popular, especially wind power. According to many criteria, the Wind Energy Conversion System (WECS) can be categorized into various types. As part of their application, in the small and standalone Horizontal Axis Wind Turbine (HAWT), most of the generators utilized in these technologies are Permanent Magnet Synchronous Generators (PMSGs) because of their low weight and high efficiency regarding their cost. This study compares and presents the advantages and limitations of various Wind Turbine (WT) types. In addition, a comparison between the PMSG and doubly fed induction generator has been presented. On the other hand, this paper reviews and analyzed the main control strategies applied in WECS. Based on the available studies in the literature, maximum power point tracking control strategies are widely used to harvest the maximum power from wind energy. This control is divided into indirect power control and direct power control. While the pitch angle control strategies can be classified as traditional collective pitch angle control and individual pitch angle control, which is applied to adjust the rotation speed of WT blades. Nevertheless, machine-side converter and grid-side converter control strategies are among the widely used methods for improving power quality. The conventional control strategies reveal many drawbacks and challenges. However, to reduce and even overcome this issue, combining conventional with robust and intelligent controllers may be a good solution.

Keywords Wind Turbine; Doubly Fed Induction Generator; Permanent Magnet Synchronous Generator; Pitch Angle Control; Maximum Power Point Tracking; Machine-Side Converter and Grid-Side Converter control.

1. Introduction

With the tangible environmental problems, the request of renewable energy production is becoming increasingly high. Meanwhile, air pollution from fossil fuel-based generating appears to be a serious issue these days. Wind energy is a natural, renewable, and sustainable energy source. At the same time, it is an effective solution for reducing the global warming impacts and the energy gap between supply and demand [1]. Wind energy has seen rapid expansion in the world. In 2021, the newly installed wind power capacity totalled 93.6 GW, as mentioned by the global wind energy council in 2022 report. This growth brings the total installed wind capacity to 837 GW, representing an increase of 12,4% from 2020 [2]. Power electronics device advancements enable wind energy generation and ensure electricity quality. However, it is necessary to continue research on various types of electric generators to satisfy the future needs for the wind energy industry [3]. In the same context, Doubly Fed Induction Generators (DFIG) and Permanent Magnet Synchronous Generators (PMSG) are becoming increasingly popular in variable-speed wind system technologies [4,5,6]. Several commercial-technical features of Wind Energy Conversion Systems (WECS) have been the focus of several studies in the literature review [7,8,9]. Moreover, significant developments in wind energy technology have driven research efforts in this field intending to develop more advanced components and robust control strategies, to optimize the wind energy generation and its transmission to the grid [10]. It is observed in the literature studies that several control strategies are suggested to accomplish this objective [11]. Pitch angle control is a technique applied to adjust both the angle of blades and turbine rotation [12], [13]. In order to improve the performance of pitch angle control many solutions are proposed: Fuzzy logic control in the case of the nonlinearity of the system parameters [14], model predictive control is an efficient method in terms of extracting the maximum output power [15], Feedforward/ Feedback control which is an adaptive technique adjusts the response to wind speed fluctuations [16], and sliding mode control which is a robust control can compensate the WT model uncertainties [17]. Maximum Power Point Tracking (MPPT) is another method implemented to adjust the rotor speed to specific values aims to extract the maximum available power from the wind [18]. Indirect power control is a simple and efficient algorithm, it has a quick response, but it requires prior knowledge of the system and also the measurement of the wind speed [19,20]. However, no prior system knowledge and wind speed measurement are required in direct power control, which is a simple and moderate efficiency MPPT algorithm [21,22,23,24]. In addition, MPPT algorithms based on artificial intelligence, such as fuzzy logic control [25] and neural networks control [26] are highly efficient and complex methods, which require prior knowledge of the system, as well as wind speed measurements. Furthermore, Machine-Side Converter and Grid-Side Converter (MSC–GSC) controls deal with the optimal production and quality of extracted power [27]. Field-oriented control and direct torque control are the two conventional MSC, while voltage-oriented control and direct power control are the two conventional GSC [20,28,29]. In addition, backstepping is an efficient MSC-GSC strategy for nonlinear control that can be useful for nonlinear systems [30].

This present study is a comparative review of generators and control strategies applied in WECS. It is intended to provide a general overview of wind energy systems and to serve as a general reference in this topic. The present paper is divided into five main sections structured as follows: Section 2 is a short comprehensive paragraph, in which we present the primary constituents of a WECS, and the types of wind turbine systems according to various criteria. Section 3 presents a brief review of the types of generators. Moreover, this section discusses separately and also compares PMSG versus DFIG. Section 4 covers the control strategies applied to the Wind Turbines (WTs). Finally, the last section provides a conclusion, where we summarize the paper.

2. Wind Energy Conversion System

2.1. Typical Structure of WECS

The wind turbine blades, a gearbox (which can be avoided in some other systems), an electric generator, a power electronic system used as a converter, and an electrical transformer linked to the grid are the primary parts utilized in a conventional WECS as represented in Fig.1 [31,32]. The WT blades harvest and convert kinetic energy from the wind into mechanical energy. Then, that mechanical energy generates electricity through rotating a generator.

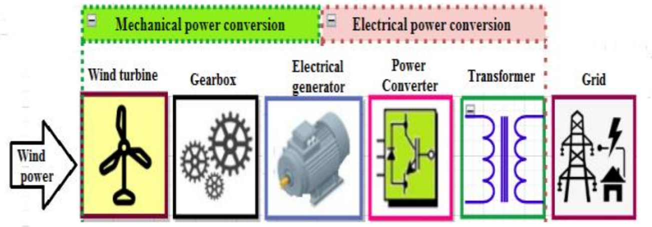

Fig.1. The typical configuration of a conventional WECS**.**

2.2. Classification of WECS

Wind power system technologies can be classified into several sections, according to different criteria as depicted in Fig.2: Based on the rotational speed of the electrical generator, there are a Variable-Speed Wind Turbine (VSWT) and a Fixed-Speed Wind Turbine (FSWT) [32,33]. Depending on the electrical power produced, there are small (50W-15kW), medium (100W-1MW), and (1MW-3MW) large wind turbines [34,35,36]. Regarding how to exploit wind power, it can be categorized into three categories: stand-alone system which is a WT that can be used for generating electrical energy in rural areas [37,38,39]. The hybrid system means a renewable energy system consisting of more than one renewable energy source instead of just one, such as a photovoltaic-wind energy system and wind farm [40,41], which is a collection of WTs that are assembled and placed together in one place known as a wind park. In which the WTs are used to produce electricity collectively [5,42,43]. By the position of the rotational axis, WTs are categorized into two groups as represented in Fig.3. The first one a Horizontal Axis Wind Turbine (HAWT), which is usually consists a gearbox, an electric generator, power electronics, and control systems are arranged in the nacelle, which is placed on top of a large tower [44,45]. The second one is known as the Vertical Axis Wind Turbine (VAWT), in general except for the blades, all its devices are fixed at the ground [46,47,48]. The VAWT-based power system can be further subdivided into three forms (Darrieus model, Savonius model, and H-rotor) [34,44]. In addition to these classifications, there are onshore, nearshore, and offshore wind systems. When the turbines are installed on land, they are referred to as onshore wind systems. Unlike offshore wind systems [49], which are located on the seas and oceans, thus making them difficult to build and maintain. While nearshore wind systems refer to those built in an area considered close to the coast [50]. Furthermore, due to the increasing demand for higher towers holding more oversized rotors, it is crucial to investigate and develop the design of the WT tower foundations [51].

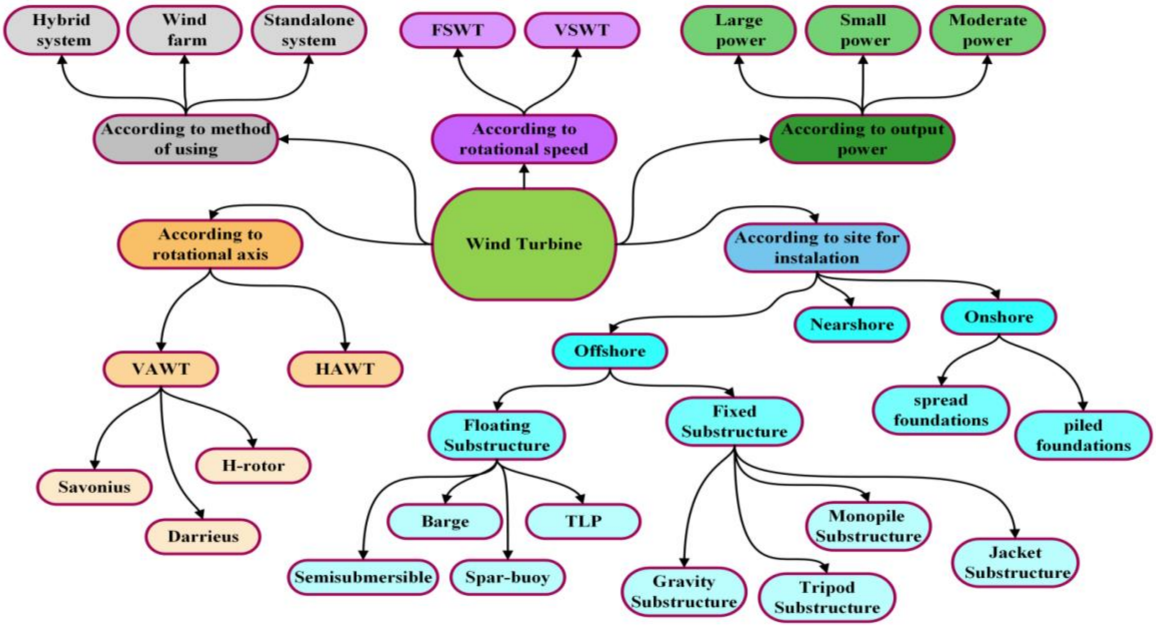

Fig.2. Classification of WECS.

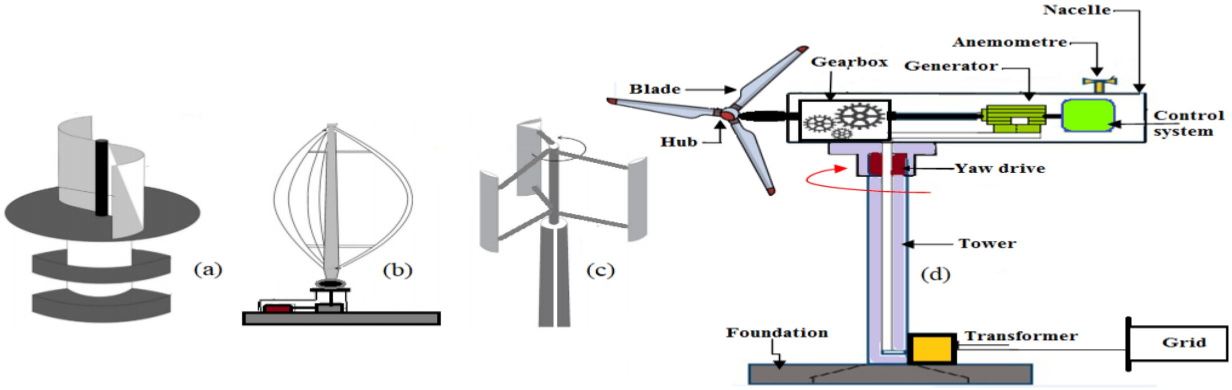

Fig.3. Shematic diagram of different types WT:
(a) Savonius; (b) Darrieus; (c) H-Rotor; (d) HAWT [44].

The foundations of WTs are the support structures and units on which the turbines are built and which ensure their strength. There are various kinds forms of foundations for onshore wind turbines. While the supports structures for offshore WTs can be classified into two basics forms. The floating substructures, which are appropriate for deep water locations in the seas and particular geological seafloor conditions [45,52]. In addition, the fixed substructures which are applicable in shallow water, as well as offshore place with adequate geological conditions [45,49,53]. There are also several specific shapes for both floating and fixed turbine foundations, which are illustrate in Fig 4.

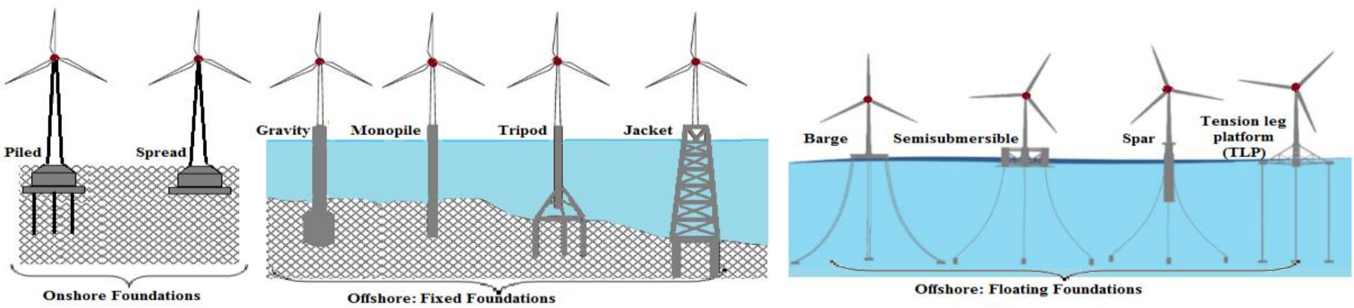

Fig.4. Wind turbine foundation technologies [52,53,54,55].

2.3. Comparison of Different WECS Types

Table 1 provides a concise overview of the primary benefits and limitations of the different kinds of WECS, based on various features: FSWT versus VSWT, VAWT versus HAWT, and onshore versus offshore. Considering the control strategy development, variable speed HAWT is more suitable for onshore and offshore WECS due to its major advantages, such as efficiency and power quality. But on the other hand, it has some challenges to overcome, such as high maintenance costs and design complexity. Furthermore, despite their difficulty and maintenance costs, offshore wind farms are becoming competitive technologies compared to onshore wind farms. Thus due to less impact on humans, the large installation area, and more constant wind speed.

Table 1. A comparison of various kinds of WECS [32,44,45,47,48,53].

Wind turbine types	Advantages	Drawbacks
FSWT	- Simple structure, usually reliable. - Low maintenance/ installation costs.	- Low power extraction capability. - Fatigue loads problem. - Low quality of electricity.
VSWT	- High efficiency. - More stable and high-quality electricity. - Minimal mechanical fatigue loading.	-High cost due to converter systems. - Complex control.
VAWT	- Installation in urban areas. - All wind directions are available. - Less space requirement. - Relatively simple design. Low noise and low cut-in wind speed level. - Easy, safe, and low cost of maintenance/ construction.	- Lower power coefficient. - Fatigue loads problem. - Not economically attractive.
HAWT	-Higher power coefficient. - Widely used in wind farms (onshore/offshore). - Most economical.	- Difficult, unsafe, and high cost of maintenance/ construction - Problem of noise level. - Design complexity. Visual effect. - Need yaw mechanism.
Onshore WT	- Proximity to power grid. - Low cost of maintenance and construction. - Simple foundation construction.	- Loss of biodiversity, bird deaths. - Landscape encroachment. - Problem of noise level. - Human intervention
Offshore WT	- More efficiently (20% -40% more than onshore WT). - Less impact to humans. - Huge wind farms. - More constant and higher wind speed.	- Difficult, unsafe, and high cost of maintenance/ construction. - Stability problems due of high center of gravity. - Induce big waves, negative impact for fisheries. - Grid connection complexity. - Loss of biodiversity, bird deaths

3. Generator Structures

The essential objective of the continuous advancements in WECS is to provide effective methods for reducing the cost of electrical energy generation. In this order, the main contribution of the electrical generator, as one of the components of the WTs, is manifested in transforming the mechanical input power of the blades into electric output power, hence lowering the cost of electricity [56]. The FSWT with a Squirrel Cage Induction Generators (SCIG) and multistage gearbox has been the first type of WECS directly linked to the electrical grid [57]. Depending on the generator design, WT can be classified into several types. Figure 5 depicts the most common generator configurations used in WECS.

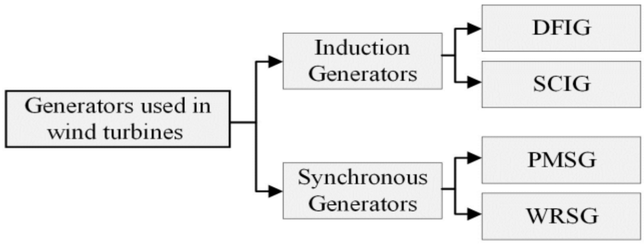

Fig.5. Classification of generator structures used in WECS.

3.1. Induction Generators

Induction generators are distinguished by their highly developed technology, minimal maintenance requirements, cheap operating expenses, and simple control and operation. They are very robustly built and offer natural short-circuit protection [58]. In addition to SCIG, Doubly Fed Induction Generators are induction generators used in WECS. They both have the same operating principle. Typically, SCIG has a squirrel-cage rotor and the DFIG rotor includes windings like the stator transfer power between the shaft and the electrical system. The most popular generator used in wind generation power systems with variable speeds is DFIG. In contrast to the rotor windings, which are linked to the grid via an electrical converter, the stator and the electrical network are connected directly via a transformer, thus avoiding any electrical power converter [59] as illustrate in Fig.6.

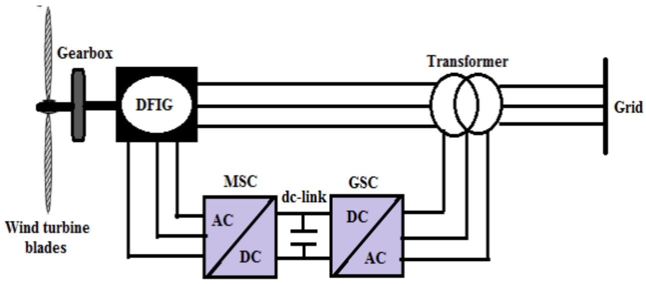

Fig.6. DFIG - based wind turbine.

3.2. Synchronous Generators

Direct-drive wind energy conversion systems are typically synchronous generator-based systems. In this case, the generators stators sections have three-phase windings; depending on the model, they either feature a rotor winding powered by direct current from another electrical circuit, this type known as Wound Rotor Synchronous Generator (WRSG), or permanents magnets fixed in the rotor and this type known as a permanent magnet synchronous generator. The rotor of the turbine blades drives these machines directly. As a result, they can be linked to the turbine without using a gearbox [60]. Day by day, besides DFIG the PMSG is increasingly used, particularly in systems involving small wind turbines, because of their high efficiency, high torque, and low maintenance cost [9,61]. PMSG is considered a brushless self-excited synchronous generator. Generally, such machines can be divided into two categories according to how used the permanent magnets of the rotor [58]: The first category is surface mount permanent magnets, that is, the magnets are affixed to the rotor surface. To avoid any possibility of magnet separation at high speeds, this category is suggested for low-speed WTs. The second is the PMSG with built-in magnets, which are suitable for high-speed wind turbines; in this instance, the magnets are inserted into the rotor body. A typical PMSG-based WECS is coupled to the electrical grid through an AC-DC power electronic converter, followed by a DC-AC power conversion system, and also a transformer [9], as represented in the block diagram in Fig.7.

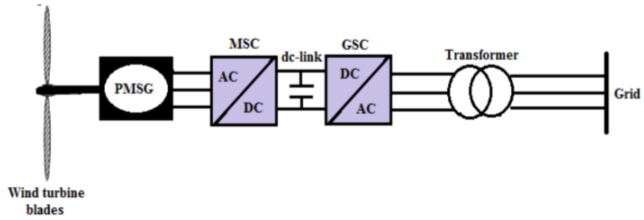

Fig.7. PMSG - based wind turbine.

3.3. *Comparison Between PMSG and DFIG*

Considering the characteristics of the PMSG and DFIG, as shown in Table 2, PMSG is often the favoured choice for standalone and small WECS because of its reliability and high efficiency. Alternatively, it is directly linked to the turbine, eliminating the need for a gearbox. This configuration offers the benefits of reducing system size, complexity, and maintenance expenses.

Table 2. Features comparison of PMSG versus DFIG [56,57,58,59,60,61].

Generator	DFIG	PMSG
Advantages	- Variable speed. - Low construction cost - Medium- High efficiency. - High robustness and stable response - Complete control of reactive/active power	- High efficiency and reliability. - Full speed range - Brushless self-excited SG - No winding in rotor - Gearless generator - Low Maintenance. - Complete control of reactive/active power
Drawbacks	- Brushes and slip rings problems. - Gearbox problems. - High Maintenance.	- Cost of permanent magnet. - Demagnetization of the PM. - Cogging torque effect.

4. Control strategies applied for WECS

Day by day, besides the materials developed in the field of wind power, researchers are working to identify and develop different control strategies to enhance the performance of the wind energy conversion process: such as Pitch Angle Control (PAC), MPPT control, sensorless control, and MSC–GSC control. In the following chart illustrates in Fig.8, we regroup control strategies as categories that may serve for future research in WECS.

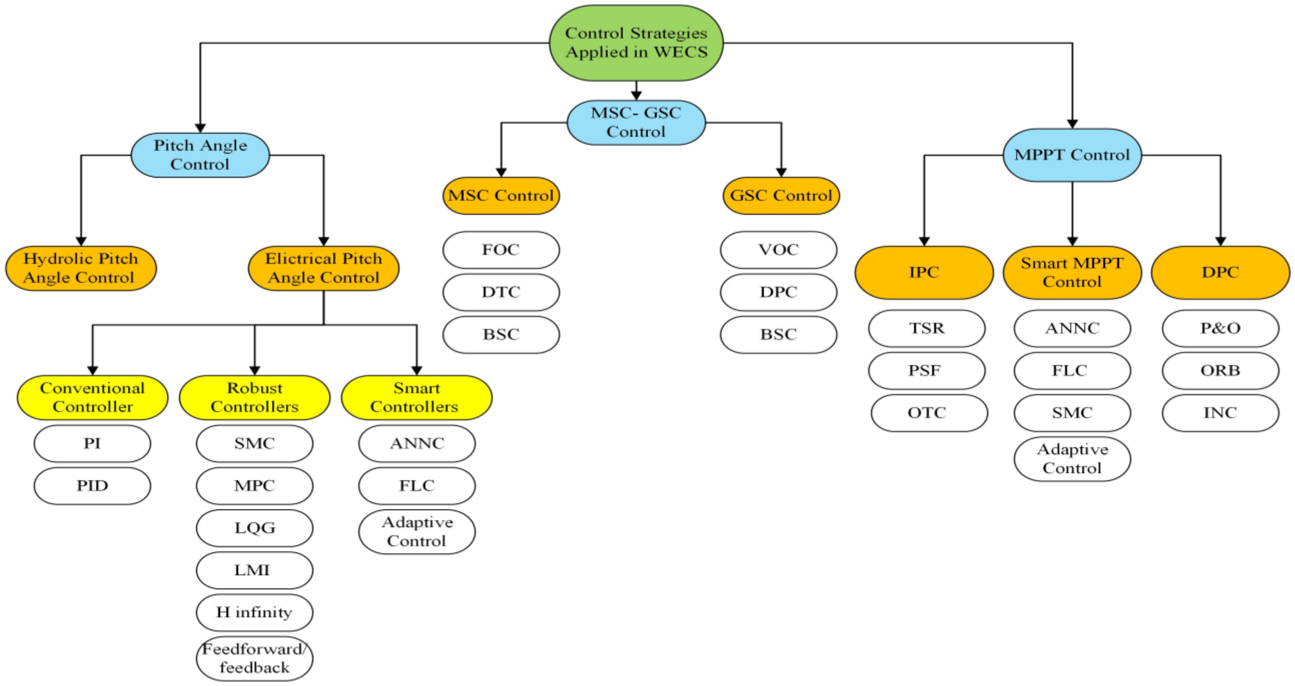

Fig.8. Classification of control strategies applied in WECS.

4.1. Pitch Angle Control (PAC)

The blade pitch actuator is a subsystem of the WT system; it is utilized to adjust the blade pitch in order to rotate it around its own longitudinal axis according to requirement. The actuator acts as a safety brake for the entire system, which can slow down or stop the turbine in case of strong wind or malfunction [62]. In order to overcome the need for pitch angle control, many researchers are proposing and developing different pitch angle control strategies. These strategies reduce the mechanical stress on the WT while providing optimal power in high wind conditions. Individual Pitch Control (IPC) and Collective Pitch Control (CPC) are the two pitch control approaches adopted for wind turbines [62]. Each of these two control techniques can be achieved through an electric or hydraulic control system [63]. CPC is the traditional technique of pitch control. It is widely applied in commercial turbines. WT blades get the required pitch collectively, meanwhile implementing the same control action in each blade [62,64]. As the name indicates, IPC regulates each WT blade independently by utilizing extra sensors. This strategy is the most significant advance in PAC, which has been extensively studied in recent years but has not yet been completely integrated into commercial WTs. The results of ongoing research in this area are expected to be validated primarily in future WTs with large and much more flexible blades [62,65].

4.1.1. Conventional PI/PID Control

The conventional control strategies used for adjusting the blade pitch angle are usually grouped according to the following three input values [63]:

- The Wind speed, as presented in Fig.9(a). The pitch angle reference can be determined from the pitch angle versus the wind speed curve. In this instance, it allows measuring the wind speed directly. However, it is not an appropriate technique because of the difficulty to tracking the wind speed precisely.
- The generator speed, as indicated in Fig.9(b). There are contrasts between the reference and regulating rotor speeds. Thus the PI controller first receives the error signal before producing the pitch angle reference value.
- The Generator power, as illustrated in Fig.9(c). After receiving the generator power error signal, a proportional integral controller creates the reference pitch angle.

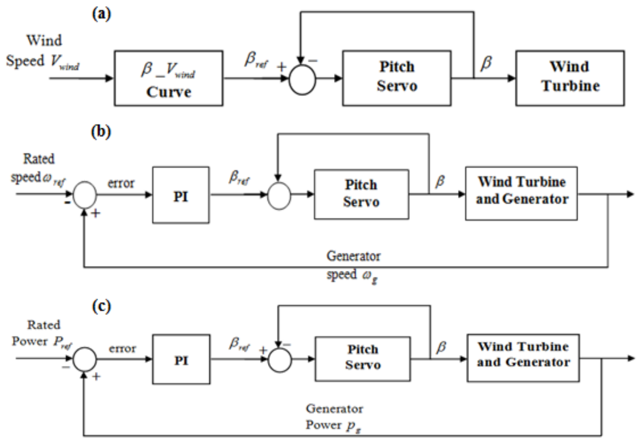

Fig.9. Block diagram of pitch control [63]: (a) wind speed as input value; (b) generator speed as input value; (c) generator power as input value.

4.1.2. *Control Based on the Lookup Table Technique*

A way of controlling the PMSG-based WECS that is based on speed reduction instead of mechanical torque has been established in the reference [66] to minimize mechanical stress under a variety of wind speeds. The lookup table-based suggested control can prevent an unexpected cut-off from the electrical network during strong wind conditions. Moreover, the WECS can continue to produce energy even if the area is a subject of typhoons, but the wind speeds should be limited to 35 m\s.

4.1.3. Sliding Mode Control

To regulate and fix the rotor speed at its nominal value; in the presence of various uncertainties in the WT model, a sliding mode control approach is proposed in reference [17,67]. Using an approximation of the power coefficient, the WT model has been rendered affine concerning the pitch angle.

4.1.4. *Model Predictive Control*

In order to mitigate the loading effects on the WTs, the study in reference [15] suggests a robust fuzzy-based model predictive controller, to limit the rotor speed and power output to its nominal value. In this method, the predictive and the fuzzy controllers are each given input data as a power output and a rotor speed.

4.1.5. *Fuzzy Logic Control*

The authors of the work in reference [14] combine fuzzy logic with the Proportional-Integral-Derivative (PID) controller to develop a specific type of pitch angle control for small-size WTS. This approach is suggested to compensate for the nonlinearity of the pitch blade angle and the wind velocity.

4.1.6. LMI-Based Control

A robust pitch controller is proposed in reference [68] to adjust the generator speed when the wind system operates in zone 3. On the one hand, the Linear Matrix Inequality (LMI) technique is used to design a collective pitch controller to obtain the rated electrical power. However, this controller is combined with an individual pitch controller, to reduce mechanical fatigue loads. Furthermore, the performance of the proposed controller is compared to that of the traditional collective pitch PI controller.

4.1.7. H∞ Based Control

To develop a robust control strategy in which the performance of the IPC system with multiple inputs and outputs is designed by using H∞ norms in reference [69]. This is a proposed robust control method to reduce the effect of periodic loads under all wind conditions in region 3. Thus, the influence of wind disturbances on the blade flap loads is reduced. The objective of using the CPC is to control the generator speed, which generates the collective signal, while the primary purpose of using IPC is to mitigate the periodic loads. As illustrate in Fig.10, using the Multi-Blade Coordinate Transformation (MBC), the blade root moments (M1, M2, and M3) in the fixed frame are converted into yaw and tilt moments (M,yaw and M,tilt). The yaw and pitch angles (β,yaw and β,tilt), which are direct outputs of the IPC, are then converted back into the rotating frame. The individual pitch signal is then added to the collective pitch signal to regulate the pitch actuators.

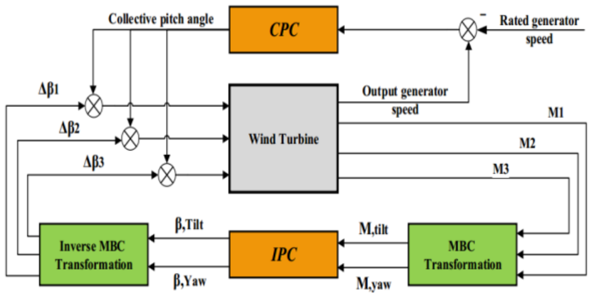

Fig. 10. The block diagram of CPC and IPC [69].

4.1.8. *Artificial Neural Network Control*

In the study [70], the authors use a neural network fitting tool of Matlab to identify the relationship between the actuator input angle and the exact pitch angle. It is a method for developing a system that controls the pitch angle of small WTs at wind speeds above its rated speed.

4.1.9. Feedforward/Feedback Control

In order to mitigate the fluctuation of generator speed and blade root load of a wind turbine, an intelligent pitch control method based on Linear Active Disturbance Rejection controller (LADRC) and Light detection and ranging (LIDAR) is developed in reference [16]. The feedforward technique using LIDAR-based wind measurement can intelligently and adaptively adjust the response to wind speed fluctuations. In addition, it can reduce the blade root loading moment. As represented in Fig.11, the relationship between the pitch angle and the observation bandwidth of the extended state observer is derived by evaluating the pole and zero distribution of the closed-loop transfer function for various wind speeds, which improves the adaptability of the LADRC feedback controller.

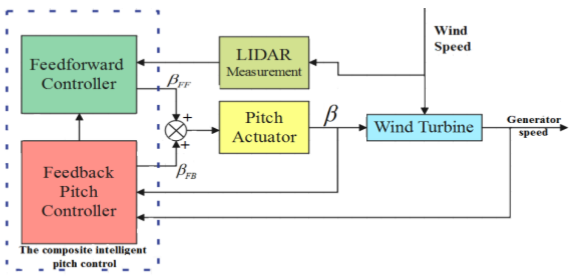

Fig.11. The composite method to intelligent pitch control [16].

4.1.10. *Features of different PAC techniques*

Table 3 presents and illustrates the results of our study on pitch angle controls and groups them according to references. These results show that the selection of the suitable PAC strategy for a given WT power system is not only related to what is required of it but also depends on the input parameter. Furthermore, the selected PAC method to achieve maximum power must be coupled with the protection of the turbine from the effects of loads.

Table 3. Summary of the different pitch angle controls.

Reference	Year	Control Methodology	Software/ Validation tool	Input parameter	Results
[63]	2014	PI Control	Matlab/ Simulink	-Wind speed -Rotor speed -Generator power	The case in which generator power used as input parameter: -Rapid pitch angle response. -Minimal power ripples.
[66]	2017	Rotational speed based pitch control	MATLAB/SimPower Systems	wind velocity	In zone 4, although the wind speed is above 25 m/s, the power generation remains continuous through the proposed method.
[17]	2019	Sliding mode control	FAST	pitch angle	Better performance with regard to tracking nominal power in the case of several uncertainties in the WT model.
[15]	2020	Fuzzy based predictive control	MATLAB/ Simulink	- Output power - rotor speed	-Adjusted and limited rotor speed and power output to their nominal values. -Efficiency in terms of extracting the maximum output power.
[14]	2020	Fuzzy-PID control	MATLAB/ Simulink	-Wind speed -Generator power	- Less oscillation. - Even at low wind speeds, the power output remains stable.
[70]	2021	Neural network fitting function based pitch control	Arduino Mega board MATLAB/ Simulink	-wind velocity - pitch angle	The neural network fitting function offers an appropriate and efficient control action.
[68]	2012	LMI based pitch control	FAST	-wind velocity	- Decreased fatigue load fluctuation - Improved speed regulation.
[69]	2019	H∞ based pitch control	MATLAB/ Simulink FAST	-Tilt pitch angle - Yaw pitch angle	- Significant mitigation of the effects of periodic load. - Reduction of fatigue over a wide operating range.
[16]	2021	Feedforward/ Feedback Control	MATLAB/ Simulink FAST	-Wind speed -Generator power - Rated speed	-Reduction of the pitch angle overshoots -Remarkable reduction of the power and generator speed fluctuation. -The pitch angle rapidly follows the stable-target value.

4.2. MPPT Controller for WECS

According to wind speed, the WT operation is divided into four zones [71], as shown in Fig.12: In the first one, which is known as the low-speed region the WT stops and disconnects from the electrical grid to avoid being operated by the generator instead the wind velocity. In addition, the second zone is characterized by a moderate wind speed. In this case, the turbine starts to operate at the cut-in speed to produce the rated power when the wind reaches its rated speed. In order to accomplish this goal and extract the available power from wind energy, MPPT control strategies have been applied to WECS. Moreover, when the wind speed exceeds its nominal value (zone 3), the wind turbine is controlled with a pitch regulator to restrict mechanical energy production. In zone 4, to avoid damage and protect against structural overloads, the WT is stopped above the cut-off speed. The main objective of using MPPT algorithms in WECS during the operating range is to track and extract the maximum power from the wind power generation [72]. At the same time, the power coefficient referred to as Cp must be maintained at its maximum value Cpmax for any wind speed within the operating zone. While Cp is a nonlinear function that depends on the tip speed ratio and the blade pitch angle [73]. MPPT algorithms are widely implemented in WECS, which can be divided as Direct Power Controllers (DPC), Indirect Power Controllers (IPC), sensorless controllers, and soft computing programs known as intelligent MPPT controllers, which can be used in combination with other controllers to improve their robustness and performance.

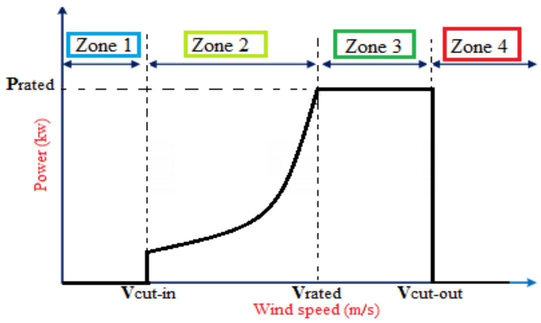

Fig.12. Power curve of a VSWT [71].

4.2.1. Conventional IPC- Based MPPT Controls

➢ Tip Speed Ratio (TSR) control

This method seeks to control the generator rotor speed ωg such that TSR remains constant at the optimal value independently of wind speed to ensure maximum harvested power by the WT [19]. Fig.13 depicts the TSR control block diagram, which compares the optimal TSR with the actual value and transmits the difference to the controller. To reduce this error, this control adjusts the value of ωg. After identifying theoretically or empirically the optimal value of TSR, it is saved as a reference.

➢ Optimal Torque Control (OTC)

The OTC is an indirect control strategy widely implemented in commercial WTs. The purpose of this control is to adjust the generator torque following a reference torque where the WT provides the maximum power at a given wind speed [20]. As illustrated in Fig.14, an error signal is created and delivered to the controller when the reference and actual torques are compared in order to maintain the optimum torque value.

➢ Power Signal Feedback (PSF) Control

Instead of applying the torque directly, PSF employs a power control loop. In this MPPT strategy, it is essential to know the reference optimum power curve that can be determined through the experimental results [19]. The maximum power values with the corresponding WT speed are listed in a lookup table. An error signal is generated and transmitted to the controller after comparing the optimum and the actual powers, as represented in Fig.15.

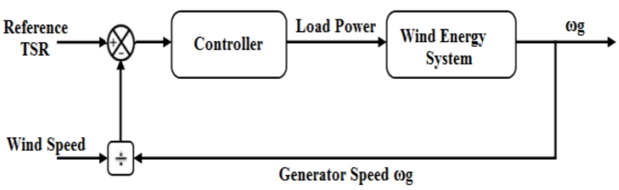

Fig.13. Block diagram of TSR-based MPPT control [19].

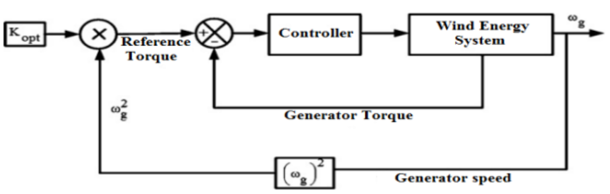

Fig.14. Block diagram of OTC-based MPPT control [19].

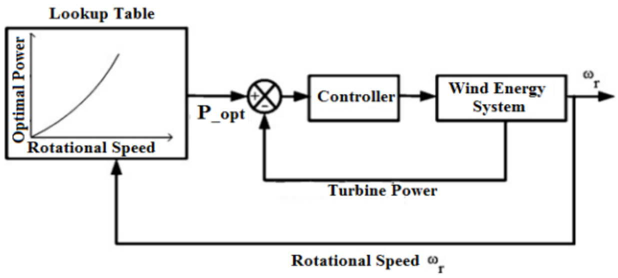

Fig.15. Block diagram of PSF-based MPPT control [19].

4.2.2. Conventional DPC-Based MPPT Controls

➢ Incremental Conductance Control (INC)

The purpose of the INC-based MPPT control strategy is to locate the maximum power point by considering the output power variation. In this case, the turbine output power can be expressed as a function of DC-link voltage [21]. It can determine the optimum DC-link voltage so as the maximum generator output power by analyzing the DC-link voltage and current changes. Figure 16 represents the block diagram scheme of this method. This sensorless method eliminates requirements on wind turbine and generator specifications, which results in a decrease in the cost with improving the system reliability [24].

➢ Optimal Relation-Based Control (ORB)

The ORB control is a sensorless method that depends on the pre-obtained optimum relationship between different WECS parameters [21], such as wind speed versus turbine rotor power, electromagnetic torque versus power [22], power versus dc-link voltage, and current versus voltage of dc-link [20,28]. Additionally, this MPPT control strategy is simple to implement due to using the DC voltage, current, and power as inputs [74]. This control is widely utilized in commercial wind power installation systems, because of their simple operation and reasonable cost. However, the need for high memory space is a big challenge [28]. Figure 17 illustrates the scheme of ORB-based MPPT control.

➢ Perturb and Observe-Based Algorithm (P&O)

A common numerical optimization technique in WECS is the P&O MPPT algorithm. Several control variables, including DC-link circuit voltage and rotor speed, are perturbed using the P&O algorithm in order to look for the most suitable point position that optimizes the power extracted [19,75]. The scheme of this MPPT control is shown in Fig18. The main objective of the conventional perturb and observe (CPO) MPPT algorithm is to observe the resulting variations in the power generation as a small-step disturbed control variable. As shown in Fig.19, the CPO controller increases the value of the rotor reference speed to move the operating point toward the MPP when it is located to the left of the peak point, and conversely when it is located to the right of the peak point [76].

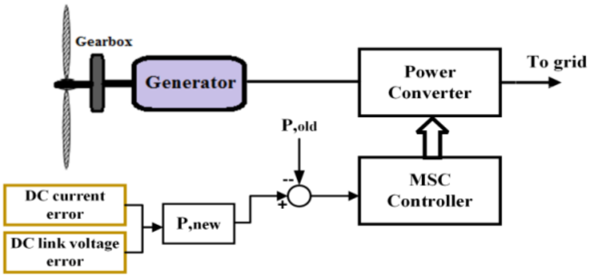

Fig.16. INC-based MPPT control [24].

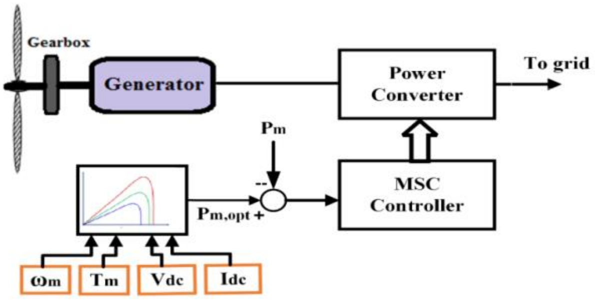

Fig.17. ORB-based MPPT control [24].

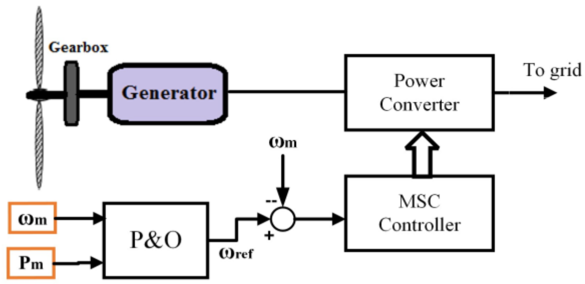

Fig.18. P&O-based MPPT control [24].

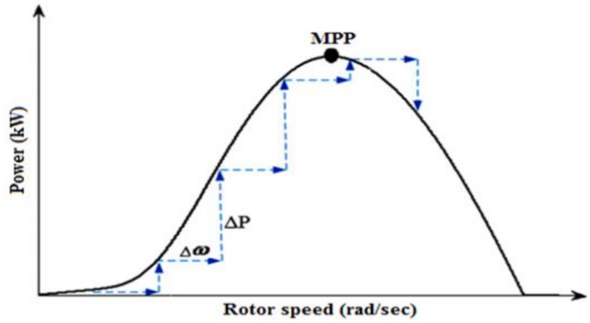

Fig.19. P&O-based MPPT algorithm with fixed step-size [19].

4.2.3. *Artificial Intelligence Controls*

Many limitations and obstacles appear when controlling wind power systems using MPPT control strategies based on DPC or IPC approaches. To overcome these problems, several methods have been proposed as soft computing methods: Fuzzy Logic Controller (FLC) [25], Artificial Neural Network Controller(ANNC) [26], and hybrid controller that combine two or more techniques by exploiting the advantages of each of them to minimize their disadvantages [20].

4.2.4. *Comparison of Different MPPT Controllers*

Table 4 can provide insights into the different MPPT approaches with their various features used to improve the power output of WECS. This knowledge can help to determine the most appropriate strategy for a particular application.

Table 4. Comparison of different features MPPT algorithms [19,20,21,24].

MPPT techniques	Cost	Efficiency	Complexity	Memory requirement	Sensitivity	Convergence speed	Tolerance to rapid variation	Anemometer	Prior knowledge
TSR	Very high	Very high	Simple	Not Required	No	Fast	Moderate - high	Required	Required
PSF	Moderate	Moderate	Simple	Required	Yes	Fast	Moderate	Required	Required
OTC	Moderate	Moderate-high	Simple	Not Required	Yes	Fast	Moderate - high	Not Required	Required
INC	Moderate	Low	Simple	Not Required	No	Low	Moderate	Not Required	Not Required
ORB	Moderate-high	Moderate	Simple	Required	Yes	Medium	Moderate	Not Required	Not Required
P&O	Moderate	Low	Simple	Not Required	No	Low	Moderate	Not Required	Not Required
FLC	High	High	High	Required	Depends	Medium	Very high	Depends	Required
ANNC	High	High	High	Required	Depends	Medium	Very high	Depends	Required
Hybrid	Moderate	Very high	Medium	Not Required	No	Fast	Moderate	No	Not Required

4.3. MSC-GSC Control

Wind turbine connection with grid power systems creates significant challenges to the stability and quality of the electrical power grid system because of wind fluctuation [28]. Regarding power quality, it is important to take into consideration the voltage variation of short duration (the flicker) in the electrical grid. In addition, maintaining the electrical network's nominal frequency despite changes in the demand for electrical load is necessary for power stability [77]. The MSC control acts on the angular speed of the rotor to maintain the optimum value. Thus, it leads to achieving maximum energy and also ensures the stability of the system [78]. Field-Oriented Control (FOC) and Direct Torque Control (DTC) are the two conventional techniques used in this control strategy. The first method consists of dual loop regulators; an outer loop control needs continuous information on the rotor speed and position to produce reference current. Moreover, a synchronous or natural reference frame is used for the inner loop control [28]. By using the minimum amount of stator current in this technique, the electromagnetic torque achieves its maximum value. FOC controls the electromagnetic torque through the quadrature axis stator current component, while the direct axis stator current should be forced to zero [20]. Conversely, in the second method, DTC controls the electromagnetic torque and power independently and directly. This solution cancels the use of a dual loop by eliminating the transition between the reference frames and also removing the inner control loop [29]. The GSC control aims to stabilize the DC-side bus voltage and also guarantee the system's ability to deliver high-quality power to the grid [79]. Voltage-Oriented Control (VOC) and Direct Power Control (DPC) are two groups of GSC control strategies. On the same approach as FOC, the VOC method comprises two control loops: the inner control loop, which is utilized to inject active power to the grid at the Unity Power Factor (UPF), and the outer control loop, which is utilized to maintain the DC link voltage at its reference value [80]. UPF operation in VOC is achievable by setting the q-axis current reference to zero. Following a similar idea as DTC, by using a Switching Table (ST), a conventional DPC strategy for GSC directly controls the active and reactive powers [29]. In this case, both a PWM modulator block and an inner current control loop are removed. The UPF operation is achieved by setting the reactive-power reference to zero [20].

Many researchers have recently become attracted by the recursive methods used to design controllers for nonlinear systems. Backstepping can be related to a general class of complex systems, making it a useful and efficient strategy for nonlinear control plans [30,81,82].

An overview of the foremost prevalent BSC enhancement techniques for controlling the PMSG-based WECS was presented in reference [30]. The goal of backstepping is to convert the overall nonlinear system into small linear subsystems. In which case, the outputs of each subsystem act as control inputs for the subsequent subsystem [81]. During the design of the controller, the Lyapunov theory was used to improve the stability of the system [30].

4.3.1. Backstepping Control for the MSC

Due to the coupling between the generator speed and the electric currents, the PMSG model is strongly nonlinear. Consequently, it requires controlling the nonlinear system through two separate successive steps in order to obtain an optimum electromagnetic torque and adjust the generator speed [82]. The first step is backstepping speed controller; aim to conceal the speed tracking error by using the Lyapunov function. The second step is backstepping the electrical current controller, in which quadratic and direct current components act as virtual inputs of the subsystem. The primary goal of this step is to maintain system stability by using the Lyapunov function [82].

4.3.2. Backstepping Control for the GSC

The main idea for controlling the GSC is maintaining the DC-bus tension and ensuring that the generated power is transmitted to the electrical network with high efficiency [81]. Backstepping control (BSC) is one of the various control strategies that can achieve these objectives. Moreover, at the grid level, power is related to both the direct and quadrature components of the grid current in the coupled form [82]. In this case, the following steps can be used to design the backstepping controller: Initially, defining the grid current errors in the (d, q) reference frame, then expressing the current-error dynamics. According to the grid current errors, the Lyapunov function can be defined to ensure system stability by making this Lyapunov derivative function negative. As a result, it must select reference voltages [82]. By setting the direct component of reference-current to zero, it can ensure that the system operates with UPF. However, the quadrature reference-current component is determined based on the bus regulator [81].

4.3.3. Comparison of Different MSC-GSC Controls

Concerning response time, robustness, and tracking error, the results summarized in Table 5 indicate that the appropriate method for MSC and GSC is the backstepping control.

Table 5. Advantages and drawbacks of different MSC-GSC controls.

Control Methodology	Reference	Year	Controlled Parameter	Advantages	Drawbacks
FOC	[29] [28] [20]	2014 2015 2016	-Electromagnetic torque and stator current	- High efficiency - Better power quality - Less tracking error - Less current / torque ripples	- Long response time - Rotor position sensor requirement - Complex implementation
DTC	[29] [28] [20]	2014 2015 2016	- Electromagnetic torque and stator flux	- Simple implementation - Fast response time - No rotor position sensor	- High torque/flux / current ripples - Poor power quality - High tracking error
VOC	[29] [28] [20]	2014 2015 2016	Active and reactive power	- Better power quality - Less tracking error -Less power/current torque ripples - Less voltage dc-Link ripple	- Long response time - Complex implementation
DPC	[29] [28] [20]	2014 2015 2016	Active and reactive power	- Simple implementation - Fast response time	- High voltage dc-Link ripple - High power / current ripples - Poor power quality - High tracking error
BSC	[81] [82] [30]	2016 2020 2022	- Stator current - Active and reactive power	- Perfect tracking error - High robustness - Short response time - Insensitivity to parametric variations	- Explosion of terms - Limited applicability

5. Conclusion

This paper compares and discusses the different types of wind turbine technologies, focusing on their characteristics, advantages, and difficulties. In addition, we also present the main components used in a typical HAWT, and the most common configurations of generators used in WECS, highlighting the main advantages and disadvantages of PMSG over DFIG. This study reveals that PMSG is mainly preferred for stand-alone and small-scale WECS applications. As compared to other generators, this preference can be justified by its reliability and high efficiency, also which is a brushless self-exiting synchronous generator that is directly linked to the turbine without a gearbox. As a result, it reduces the entire system's maintenance costs, complexity, and size. This paper also presents and explores three different control strategies applied to the wind system, namely pitch angle control, MPPT algorithms, and MSC-GSC control. This review paper reveals many limitations and difficulties associated with these current techniques. However, these problems can be reduced and solved by combining a conventional controller with intelligent controllers such as FLC and ANN or with robust controllers such as sliding mode control. Therefore, this study aims to help as a general reference for future research, especially on WTs features and different control strategies for WECS.

References

[1] R. Tiwari and N. Ramesh Babu, “Artificial neural network-based control strategies for PMSG-based grid connected wind energy conversion system,” Int. J. Mater. Prod. Technol., vol. 58, no. 4, pp. 323–341, 2019.

[2] GWEC. Global Wind Report 2022; Global Wind Energy Council: Brussels, Belgium, 2022. (accessed 22 May 2022). https://gwec.net/global-wind-report-2022/

[3] M. M. Hossain and M. H. Ali, “Future research directions for the wind turbine generator system,” Renew. Sustain. Energy Rev., vol. 49, pp. 481–489, 2015.

[4] Y. Barradi, K. Zazi, M. Zazi, and N. Khaldi, “Control of pmsg based variable speed wind energy conversion system connected to the grid with PI and ADRC approach,” *Int. J. Power Electron. Drive Syst.*, vol. 11, no. 2, pp. 953–968, 2020.

[5] J. Yao, J. Pei, D. Xu, R. Liu, X. Wang, C. Wang, and Y. Li, “Coordinated control of a hybrid wind farm with DFIG-based and PMSG-based wind power generation systems under asymmetrical grid faults,” Renew. Energy, vol. 127, pp. 613–629, Nov. 2018.

[6] H. Chojaa, A. Derouich, S. E. Chehaidia, O. Zamzoum, M. Taoussi, and H. Elouatouat, “Integral sliding mode

control for DFIG based WECS with MPPT based on artificial neural network under a real wind profile," Energy Reports, vol. 7, pp. 4809–4824, Nov. 2021.

[7] S. Chatterjee and S. Chatterjee, "Review on the techno-commercial aspects of wind energy conversion system," IET Renew. Power Gener., vol. 12, no. 14, pp. 1581–1608, 2018.

[8] E. F. Morgan, O. Abdel-Rahim, T. F. Megahed, J. Suehiro, and S. M. Abdelkader, "Fault Ride-Through Techniques for Permanent Magnet Synchronous Generator Wind Turbines (PMSG-WTGs): A Systematic Literature Review," *Energies*, vol. 15, no. 23, p. 9116, Dec. 2022.

[9] S. Vadi, F. B. Gürbüz, R. Bayindir and E. Hossain, "Design and Simulation of a Grid Connected Wind Turbine with Permanent Magnet Synchronous Generator", *8th IEEE International Conference on Smart Grid (icSmartGrid)*, pp. 169-175, 2020.

[10] E. Mohammadi, R. Fadaeinedjad, and H. R. Naji, "Design, electromechanical simulation, and control of a variable speed stall-regulated PMSG-based wind turbine," Int. J. Green Energy, vol. 16, no. 12, pp. 890–900, 2019.

[11] D. Rekioua, Wind Power Electric Systems: Modeling, Simulation and Control.London: Springer; 2014.

[12] Y. Chen, M. H. Shaheed, and R. Vepa, "Active blade pitch control and stabilization of a wind turbine driven PMSG for power output regulation," Wind Eng., vol. 47, no. 1, pp. 126–140, Feb. 2023.

[13] S. Chudzik, "Wind Microturbine with Adjustable Blade Pitch Angle," Energies, vol. 16, no. 2, 2023.

[14] Q. V. Ngo, C. Yi, and T. T. Nguyen, "The fuzzy-PID based-pitch angle controller for small-scale wind turbine," Int. J. Power Electron. Drive Syst., vol. 11, no. 1, pp. 135–142, 2020.

[15] A. Iqbal, D. Ying, A. Saleem, M. A. Hayat, and K. Mehmood, "Efficacious pitch angle control of variable-speed wind turbine using fuzzy based predictive controller," in Energy Reports, Elsevier Ltd, Feb. 2020.

[16] C. Jia, L. Wang, E. Meng, L. Chen, Y. Liu, W. Jia, Y. Bao, and Z. Liu, "Combining LIDAR and LADRC for intelligent pitch control of wind turbines," Renew. Energy, vol. 169, pp. 1091–1105, 2021.

[17] L. Colombo, M. L. Corradini, G. Ippoliti, and G. Orlando, "Pitch angle control of a wind turbine operating above the rated wind speed: A sliding mode control approach," ISA Trans., vol. 96, pp. 95–102, 2020.

[18] X. Zhang, J. Jia, L. Zheng, W. Yi, and Z. Zhang, "Maximum power point tracking algorithms for wind power generation system: Review, comparison and analysis," Energy Sci. Eng., no. September, 2022.

[19] M. A. Abdullah, A. H. M. Yatim, C. W. Tan, and R. Saidur, "A review of maximum power point tracking algorithms for wind energy systems," Renewable and Sustainable Energy Reviews, vol. 16, no. 5. pp. 3220–3227, Jun. 2012.

[20] R. Tiwari and N. R. Babu, "Recent developments of control strategies for wind energy conversion system," Renewable and Sustainable Energy Reviews, vol. 66. Elsevier Ltd, pp. 268–285, Dec. 01, 2016.

[21] D. Kumar and K. Chatterjee, "A review of conventional and advanced MPPT algorithms for wind energy systems," Renew. Sustain. Energy Rev., vol. 55, pp. 957–970, 2016.

[22] S. Morimoto, H. Nakayama, M. Sanada, and Y. Takeda, "Sensorless output maximization control for variable-speed wind generation system using IPMSG," IEEE Trans. Ind. Appl., vol. 41, no. 1, pp. 60–67, 2005.

[23] H. B. Zhang, J. Fletcher, N. Greeves, S. J. Finney, and B. W. Williams, "One-power-point operation for variable speed wind/tidal stream turbines with synchronous generators," IET Renew. Power Gener., vol. 5, no. 1, pp. 99–108, 2011.

[24] J. Pande, P. Nasikkar, K. Kotecha, and V. Varadarajan, "A review of maximum power point tracking algorithms for wind energy conversion systems," J. Mar. Sci. Eng., vol. 9, no. 11, pp. 1–30, 2021.

[25] A. Asri, Y. Mihoub, S. Hassaine, P. O. Logerais, and T. Allaoui, "Intelligent maximum power tracking control of a PMSG wind energy conversion system," in Asian Journal of Control, Wiley-Blackwell, Jul. 2019, pp. 1980–1990.

[26] R. Tiwari, K. Kumar, R. B. Neelakandan, S. Padmanaban, and P. W. Wheeler, "Neural network based maximum power point tracking control with quadratic boost converter for PMSG—wind energy conversion system," Electron., vol. 7, no. 2, 2018.

[27] M. Bouderbala, B. Bossoufi, H. A. Aroussi, M. Taoussi, and A. Lagrioui, "Novel deadbeat predictive control strategy for DFIG's back to back power converter," Int. J. Power Electron. Drive Syst., vol. 13, no. 1, pp. 139–149, 2022.

[28] S. M. Tripathi, A. N. Tiwari, and D. Singh, "Grid-integrated permanent magnet synchronous generator based wind energy conversion systems: A technology review," Renewable and Sustainable Energy Reviews, vol. 51. Elsevier Ltd, pp. 1288–1305, Aug. 03, 2015.

[29] M. Allagui, O. B. Hasnaoui, and J. Belhadj, "A 2MW direct drive wind turbine; Vector control and direct torque control techniques comparison," J. Energy South. Africa, vol. 25, no. 2, pp. 117–126, 2014.

[30] B. Majout, H. El Alami, H. Salime, N. Zine Laabidine, Y. El Mourabit, S. Motahhir, M. Bouderbala, M. Karim, and B. Bossoufi, "A Review on Popular Control Applications in Wind Energy Conversion System Based on Permanent Magnet Generator PMSG," *Energies*, vol. 15, no. 17, p. 6238, Aug. 2022.

[31] B. Yang, T. Yu, H. Shu, X. Zhang, K. Qu, and L. Jiang, "Democratic joint operations algorithm for optimal power extraction of PMSG based wind energy conversion system," Energy Convers. Manag., vol. 159, no. October 2017, pp. 312–326, 2018.

[32] B. Desalegn, D. Gebeyehu, and B. Tamirat, "Wind energy conversion technologies and engineering approaches

to enhancing wind power generation: A review," Heliyon, vol. 8, no. 11, p. e11263, 2022.

[33] A. C. Mahato and S. K. Ghoshal, "Various power transmission strategies in wind turbine: an overview," International Journal of Dynamics and Control, vol. 7, no. 3. Springer Berlin Heidelberg, pp. 1149–1156, Sep. 01, 2019.

[34] R. Kumar, K. Raahemifar, and A. S. Fung, "A critical review of vertical axis wind turbines for urban applications," Renewable and Sustainable Energy Reviews, vol. 89. Elsevier Ltd, pp. 281–291, Jun. 01, 2018.

[35] K. Kim, H. G. Kim, Y. Song, and I. Paek, "Design and simulation of an LQR-PI control algorithm for medium wind turbine," Energies, vol. 12, no. 11, pp. 1–18, 2019.

[36] C. A. Ramos-Paja, E. E. Henao-Bravo, and A. J. Saavedra-Montes, "MPPT Solution for Commercial Small Wind Generation Systems with Grid Connection," Energies, vol. 16, no. 2, pp. 1–24, 2023.

[37] G. Kenne, R. M. Douanla, and F. B. Pelap, "An adaptive nonlinear control strategy for a stand-alone permanent magnet synchronous generator driven by a variable speed wind turbine," Int. J. Dyn. Control, vol. 5, no. 4, pp. 1103–1113, Dec. 2017.

[38] A. Jain and R. Saravanakumar, "Intelligent Proportional Integral Terminal Sliding Mode Control for variable speed standalone wind energy conversion system," Environ. Prog. Sustain. Energy, vol. 40, no. 2, pp. 1–16, 2021.

[39] R. Syahputra, K. Purwanto, and I. Soesanti, "Performance investigation of standalone wind power system equipped with sinusoidal PWM power inverter for household consumer in rural areas of Indonesia," Energy Reports, vol. 8, pp. 4553–4569, 2022.

[40] K. Anoune, M. Bouya, A. Astito, and A. Ben Abdellah, "Sizing methods and optimization techniques for PV-wind based hybrid renewable energy system: A review," Renewable and Sustainable Energy Reviews, vol. 93. Elsevier Ltd, pp. 652–673, Oct. 01, 2018.

[41] K. Kayisli, R. zafer Caglayan, N. Zhakiyev, A. Harrouz, and I. Colak, "A Review of Hybrid Renewable Energy Systems and MPPT Methods," *Int. J. Smart Grid*, vol. 6, no. 3, pp. 72–78, 2022.

[42] M. Abbes and M. Allagui, "Participation of PMSG-based wind farms to the grid ancillary services," Electr. Power Syst. Res., vol. 136, pp. 201–211, 2016.

[43] K. E. Okedu, "A variable-speed wind turbine flywheel-based coordinated control system for enhancing grid frequency dynamics," Int. J. Smart Grid, vol. 2, no. 2, pp. 123–134, 2018.

[44] Z. Tasneem, A. Al Noman, S. K. Das, D. K. Saha, R. Islam, F. Ali, F. R. Badal, H. Ahamed, S. I. Moyeen, and F. Alam, "An analytical review on the evaluation of wind resource and wind turbine for urban application: Prospect and challenges," Developments in the Built Environment, vol. 4. Elsevier Ltd, Nov. 01, 2020.

[45] J. Li, G. Wang, Z. Li, S. Yang, W. T. Chong, and X. Xiang, "A review on development of offshore wind energy conversion system," International Journal of Energy Research, vol. 44, no. 12. pp. 9283–9297, 2020.

[46] X. Sun, Z. Cao, Y. Zhuang, D. Huang, and Y. Cao, "Numerical modeling and optimization of a power augmented S-type vertical axis wind turbine," Int. J. Green Energy, vol. 15, no. 1, pp. 13–19, 2018.

[47] A. Dilimulati, T. Stathopoulos, and M. Paraschivoiu, "Wind turbine designs for urban applications: A case study of shrouded diffuser casing for turbines," J. Wind Eng. Ind. Aerodyn., vol. 175, no. January, pp. 179–192, 2018.

[48] J. A. C. Lipiao, N. M. M. Divina, R. V. M. Santiago and C. C. Hortinela, "Hybrid J-Type Darrieus and Savonius Vertical Axis Wind Turbine Capable of Harvesting Roadside Wind Energy," *2022 11th International Conference on Renewable Energy Research and Application (ICRERA)*, Istanbul, Turkey, pp. 1-6, 2022.

[49] D. Cevasco, S. Koukoura, and A. J. Kolios, "Reliability, availability, maintainability data review for the identification of trends in offshore wind energy applications," Renewable and Sustainable Energy Reviews, vol. 136, no. September 2020. Elsevier Ltd, p. 110414, 2021.

[50] S. Amani, A. Prabhakaran, and S. Bhattacharya, "Design of monopiles for offshore and nearshore wind turbines in seismicnearshore wind systemsally liquefiable soils: Methodology and validation," Soil Dyn. Earthq. Eng., vol. 157, no. March, p. 107252, 2022.

[51] B. D. Lago, L. Flessati, P. Marveggio, P.Martinelli, G. Fraraccio, C. di Prisco, and M. di Prisco, "Experimental tests on shallow foundations of onshore wind turbine towers," Struct. Concr., vol. 23, no. 5, pp. 2986–3006, 2022.

[52] W. Tjiu, T. Marnoto, S. Mat, M. H. Ruslan, and K. Sopian, "Darrieus vertical axis wind turbine for power generation II: Challenges in HAWT and the opportunity of multi-megawatt Darrieus VAWT development," Renew. Energy, vol. 75, pp. 560–571, 2015.

[53] J. Chen and M. H. Kim, "Review of Recent Offshore Wind Turbine Research and Optimization Methodologies in Their Design," J. Mar. Sci. Eng., vol. 10, no. 1, 2022.

[54] Z. Xu, J. Wei, S. Zhang, Z. Liu, X. Chen, Q. Yan, and J. Guo, "Review article A state-of-the-art review of the vibration and noise of wind turbine drivetrains," Sustain. Energy Technol. Assessments, vol. 48, no. October, p. 101629, 2021.

[55] X. Wu, Y. Hu, Y. Li, J. Yang, L. Duan, T. Wang, T. Adcock, Z. Jiang, Z. Gao, Z. Lin, A. Borthwick, and S. Liao, "Foundations of offshore wind turbines: A review," Renew. Sustain. Energy Rev., vol. 104, pp. 379–393, Apr. 2019.

[56] H. Polinder, J. A. Ferreira, B. B. Jensen, A. B. Abrahamsen, K. Atallah, and R. A. McMahon, "Trends in wind turbine generator systems," IEEE J. Emerg. Sel. Top. Power Electron., vol. 1, no. 3, pp. 174–185, 2013.

[57] M. Cheng and Y. Zhu, "The state of the art of wind energy conversion systems and technologies: A review," Energy Conversion and Management, vol. 88. Elsevier Ltd, pp. 332–347, 2014.

[58] Z. Alnasir and M. Kazerani, "An analytical literature review of stand-alone wind energy conversion systems from generator viewpoint," Renewable and Sustainable Energy Reviews, vol. 28. Elsevier, pp. 597–615, 2013.

[59] M. Hallouz, N. Kabache, S. Moulahoum, and S. Kouadria, "Neural Network Based Field Oriented Control for Doubly-Fed Induction Generator," *Int. J. Smart grid*, vol. 2, no. 3, pp. 2–6, 2018.

[60] N. Goudarzi and W. D. Zhu, "A review on the development of wind turbine generators across the world," Int. J. Dyn. Control, vol. 1, no. 2, pp. 192–202, 2013.

[61] A. Dani, Z. Mekrini, M. El Mrabet, and M. Boulaala, (2023). A Review of Different Structures Generators and Control Strategies Applied to the Wind Turbine. In: Kacprzyk, J., Ezziyyani, M., Balas, V.E. (eds) International Conference on Advanced Intelligent Systems for Sustainable Development. AI2SD 2022. Lecture Notes in Networks and Systems, vol 714. Springer, Cham. https://doi.org/10.1007/978-3-031-35245-4_18.

[62] O. Apata and D. T. O. Oyedokun, "An overview of control techniques for wind turbine systems," Scientific African, vol. 10. Elsevier B.V., p. e00566, 2020.

[63] M. Ben Smida and A. Sakly, "Different conventional strategies of pitch angle control for variable speed wind turbines," in STA 2014 - 15th International Conference on Sciences and Techniques of Automatic Control and Computer Engineering, pp. 803–808, 2014.

[64] Z. Civelek, M. Lüy, E. Çam, and H. Mamur, "A new fuzzy logic proportional controller approach applied to individual pitch angle for wind turbine load mitigation," Renew. Energy, vol. 111, pp. 708–717, 2017.

[65] E. A. Bossanyi, "Individual blade pitch control for load reduction," Wind Energy, vol. 6, no. 2, pp. 119–128, 2003.

[66] H. Matayoshi, A. M. Howlader, M. Datta, and T. Senjyu, "Control strategy of PMSG based wind energy conversion system under strong wind conditions," Energy Sustain. Dev., vol. 45, no. 2017, pp. 211–218, 2018.

[67] Xiong, L., Li, P., Ma, M., Wang, Z., & Wang, J. (2020). Output power quality enhancement of PMSG with fractional order sliding mode control. International Journal of Electrical Power & Energy Systems, 115, p105402, 2020.

[68] H. M. Hassan, A. L. Elshafei, W. A. Farag, and M. S. Saad, "A robust LMI-based pitch controller for large wind turbines," Renew. Energy, vol. 44, pp. 63–71, 2012.

[69] Y. Yuan, X. Chen, and J. Tang, "Multivariable robust blade pitch control design to reject periodic loads on wind turbines," Renew. Energy, vol. 146, pp. 329–341, 2020.

[70] M. E. M. Salem, H. M. El-Batsh, A. A. El-Betar, and A. M. A. Attia, "Application of neural network fitting for pitch angle control of small wind turbines," in IFAC-PapersOnLine, Elsevier Ltd, 2021, pp. 185–190.

[71] H. H. H. Mousa, A. R. Youssef, and E. E. M. Mohamed, "Optimal power extraction control schemes for five-phase PMSG based wind generation systems," Eng. Sci. Technol. an Int. J., vol. 23, no. 1, pp. 144–155, 2020.

[72] H. H. H. Mousa, A. R. Youssef, I. Hamdan, M. Ahamed, and E. E. M. Mohamed, "Performance Assessment of Robust PO Algorithm Using Optimal Hypothetical Position of Generator Speed," *IEEE Access*, vol. 9, pp. 30469–30485, 2021.

[73] Y. Berrada and I. Boumhidi, "New structure of sliding mode control for variable speed wind turbine," IFAC J. Syst. Control, vol. 14, p. 100113, 2020.

[74] X. C. Le, M. Q. Duong, and K. H. Le, "Review of the Modern Maximum Power Tracking Algorithms for Permanent Magnet Synchronous Generator of Wind Power Conversion Systems," Energies, vol. 16, no. 1, 2023.

[75] B. Lahfaoui, S. Zouggar, B. Mohammed, and M. L. Elhafyani, "Real Time Study of P&O MPPT Control for Small Wind PMSG Turbine Systems Using Arduino Microcontroller," in Energy Procedia, Elsevier B.V., 2017.

[76] H. H. H. Mousa, A. R. Youssef, and E. E. M. Mohamed, "State of the art perturb and observe MPPT algorithms based wind energy conversion systems: A technology review," International Journal of Electrical Power and Energy Systems, vol. 126, no. PA. Elsevier Ltd, p. 106598, 2021.

[77] E. J. Novaes Menezes, A. M. Araújo, and N. S. Bouchonneau da Silva, "A review on wind turbine control and its associated methods," Journal of Cleaner Production, vol. 174. pp. 945–953, 2018.

[78] L. Xiong, P. Li, M. Ma, Z. Wang, and J. Wang, "Output power quality enhancement of PMSG with fractional order sliding mode control," Int. J. Electr. Power Energy Syst., vol. 115, no. July 2019, p. 105402, 2020.

[79] L. Pan and C. Shao, "Wind energy conversion systems analysis of PMSG on offshore wind turbine using improved SMC and Extended State Observer," Renew. Energy, vol. 161, pp. 149–161, 2020.

[80] H. H. H. Mousa, A. R. Youssef, and E. E. M. Mohamed, "Adaptive P&O MPPT algorithm based wind generation system using realistic wind fluctuations," Int. J. Electr. Power Energy Syst., vol. 112, no. April, pp. 294–308, 2019.

[81] E. Mahersi and A. Khedher, "Backstepping flux observer for nonlinear control of the direct-drive permanent magnet synchronous generator wind turbines," *Wind Engineering*, vol. 40, no. 6, pp. 540–54 2016.

[82] Y. El Mourabit, A. Derouich, A. El Ghzizal, N. El Ouanjli, and O. Zamzoum, "Nonlinear backstepping control for PMSG wind turbine used on the real wind profile of the Dakhla-Morocco city," Int. Trans. Electr. Energy Syst., vol. 30, no. 4, Apr. 2020.