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A Review of Control Techniques for Wind Energy Conversion System

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Abstract

Wind energy is the most efficient and advanced form of renewable energy (RE) in recent decades, and an effective controller is required to regulate the power generated by wind energy. This study provides an overview of state-of-the-art control strategies for wind energy conversion systems (WECS). Studies on the pitch angle controller, the maximum power point tracking (MPPT) controller, the machine side controller (MSC), and the grid side controller (GSC) are reviewed and discussed. Related works are analyzed, including evolution, software used, input and output parameters, specifications, merits, and limitations of different control techniques. The analysis shows that better performance can be obtained by the adaptive and soft-computing based pitch angle controller and MPPT controller, the field-oriented control for MSC, and the voltage-oriented control for GSC. This study provides an appropriate benchmark for further wind energy research.

Keywords: maximum power point tracking, pitch angle controller, grid side controller, wind energy conversion system, machine side controller

1. Introduction

Energy is key to every country's growth. Energy demand is increasing rapidly due to population growth and urbanization around the globe [1-6]. Fossil fuel (FF) is still the main source of energy [7]. The environmental effects of FF are strongly negative, like the greenhouse effect [8]. Electricity production from renewable energy sources (RES) is the replacement for FF. RESs are biomass, wave, solar, tidal, and wind. As wind and solar energy are readily usable, they are used to produce electrical energy [9]. The reliability of solar and wind power depends heavily on climate change and its unforeseeable nature. Therefore, grid integration and energy storage are serious concerns [10]. Wind energy is increasing dramatically, and researchers face many obstacles, such as grid integration, the wind's unpredictable existence, and wind turbine location [11-12]. More updated modern controllers, converters, and generators are required to integrate wind turbines (WT) into the power grid [13-14]. Fig. 1 shows the typical WECS connected to the grid. As shown in Fig. 2, the WECS operating region is divided into four regions. In region 1 and region 4, the WECS does not generate any power.

Extraction of maximum power can be accomplished using several MPPT algorithms, each of which is categorized according to power measurement, such as the direct and indirect power controllers discussed here. The advantages and disadvantages of the various MPPT algorithms are also highlighted in terms of complexity, speed, prior training, etc. [15]. Conventional and soft-computing MPPT approaches for wind and solar PV systems are discussed in [16]. A thorough evaluation of the concept, benefits, drawbacks, and potential applications was provided. Furthermore, there has also been a thorough investigation into the MPPT methods, taking into account factors such as tracking speed, memory, and the system's performance in rapidly changing climates. A comprehensive overview and a review of the relevant literature have been

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provided in this study on WT control. It was a thorough review because it looked at the three main concerns about WT control, which are MPPT methods, pitch control, and grid integration control. However, the author did not discuss the in-depth and available control methods that are directly associated with MPPT, pitch, and grid integration control [17].

It is observed from the published literature review that no research paper discusses the overall control techniques of the WECS. More recently, an attempt to investigate these control techniques was made, but the authors emphasized more on the WT MPPT technique. The authors paid attention to the pitch control method without discussing the pitch angle controller. This review paper bridges this gap. Therefore, the entire control techniques associated with WECS must be reviewed.

This review paper discussed different control techniques related to pitch angle controller, MPPT, GSC, and MSC in detail. Therefore, the paper incorporates an in-depth analysis of overall control strategies for WECS. Here, the authors also review and analyze the importance and limitations of the WECS control strategy. The paper provides an appropriate benchmark reference for further wind energy research.

The study is divided into seven sections. Section 2 contains wind turbine modeling, while Section 3 has a detailed review of the pitch angle controller. Section 4 explains the MPPT controller, while machine side and grid side controllers are discussed in Section 5. Section 6 contains overall discussions of all control techniques with the future scope, and the conclusion is incorporated in Section 7.

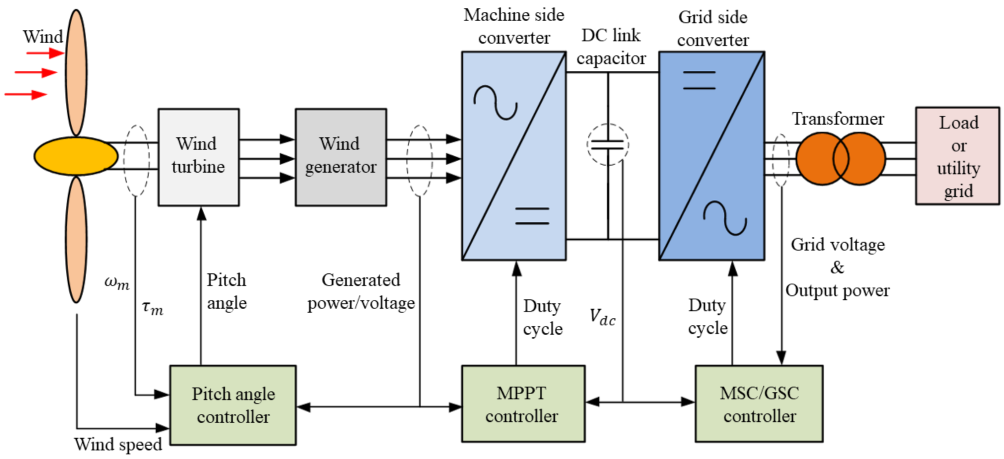


Fig. 1 WECS with grid connection [1]

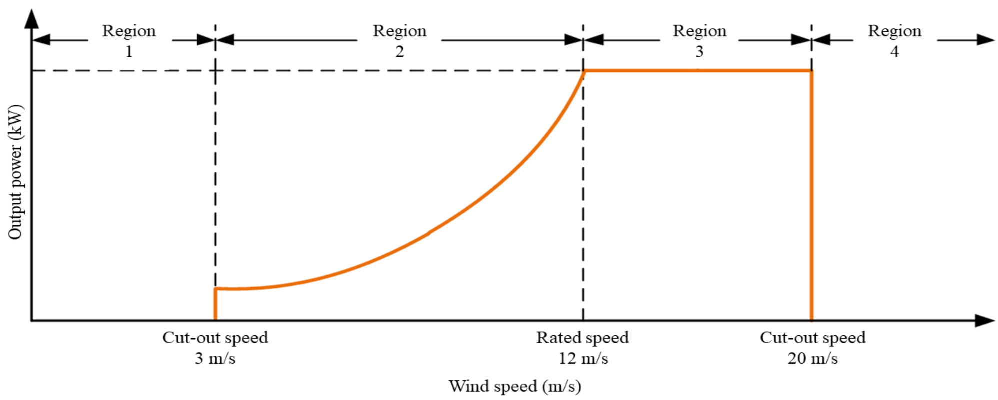


Fig. 2 WECS operating zone [15]

2. Wind Turbine Modeling

The WT input is wind, and the outcome is mechanical power (P_m) driving the generator. The P_m is expressed in Eq. (1) [1].

$$P_m = 0.5K_p(\alpha,\gamma)\sigma\pi D^2 S_W^3 \tag{1}$$

where K_p, γ, α, σ, D, and S_w represent rotor power coefficient, tip speed ratio, blade pitch angle, the density of air, WT blade radius, and wind speed, respectively. Eq. (2) describes the mechanical torque (τ_m).

$$\tau_m = \frac{P_m}{\omega_m} \tag{2}$$

where ω_m is the mechanical angular speed of the turbine.

Eq. (3) defines the K_p [1]. The efficiency of the alternator for K_p calculations and the blown air were considered, as reported in [18-22].

$$K_P = (0.44 - 0.0167\alpha)\sin\frac{\pi(\gamma-2)}{13-0.3\alpha} - 0.00184(\gamma-2)\alpha \tag{3}$$

Eq. (4) can obtain the γ:

$$\gamma = \frac{\omega_m D}{S_w} \tag{4}$$

Fig. 3 implies that WT performance depends on the K_p at a specific S_w. The manufacturer defines the WT parameters, and the geographic location of the WECS determines the air pressure. The pitch-angle reference (α_{ref}) needs to go up when the angular speed increases to minimize WT torque. The α is employed to regulate the torque and control the hydraulic strength of output to keep equilibrium. The WECS pitch angle control (PAC) technique is given in Eq. (5) [1].

$$\alpha_{red} = \begin{cases} \alpha_0 = -2, \ for \ 0 < \omega_m < \omega_n \\ \frac{\Delta\alpha}{\Delta\omega}(\omega_m - \omega_n) + \alpha_0, \ for \ \omega_m > \omega_n \end{cases} \tag{5}$$

where ω_n and α_0 are nominal angular speed and an initial pitch angle of WT.

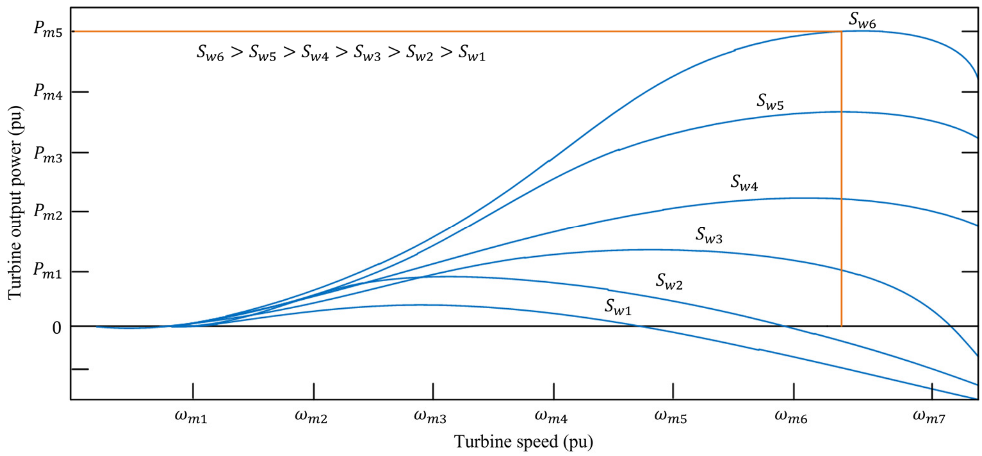


Fig. 3 Characteristics of WT [23]

In the case of wind speed variations, rotation speed always differs in such a way that optimum power is derived. The α adjusts the τ_m to attain P_m from the wind. The speed of the rotor can control the P_m. The wind generator's power depends on the change in wind speed. When the rotor rotates at ω_m, the maximum power is received.

The challenges of wind power plants are uncertainty, non-linearity, and fluctuation of wind speed. Therefore, an advanced controller needs an efficient solution. Integration of advanced WECS controllers makes power conversion and blade control design more efficient. Many researchers performed various research on a WECS control technique that implies into the grid. In addition, controllers need to be simpler, reliable, economical, and capable of dealing with the fluctuations in their operation. Fig. 4 shows the various control techniques used in WECS.

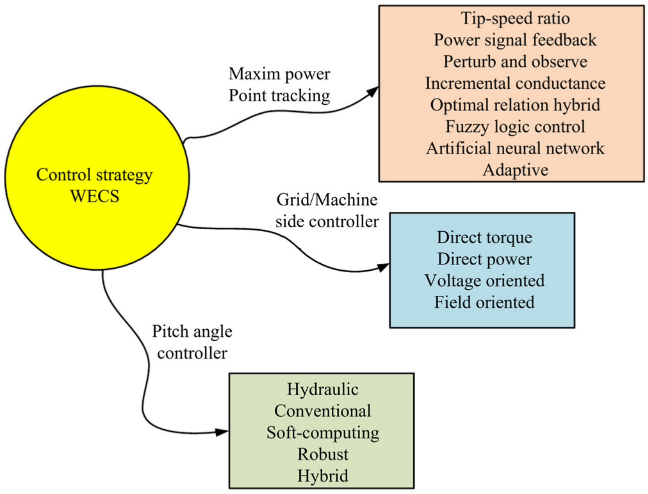


Fig. 4 Various control techniques of WECS

3. Pitch Angle Controller (PACR)

This controller mechanically controls the output (O/P) power. WT's O/P torque controls the angular velocity that governs the mechanical O/P power. The turbine's pitch angle shields the wind generator from abrupt wind gusts [24]. The blade's pitch is regulated to rotate the rotor at a higher speed during lower wind speed, which increases the machine's power.

PACR restricts the rotor speed at a higher wind speed, protects the generator, and serves as a braking mechanism when the controller cannot control the speed of the rotor lower than the optimum speed [25]. The rotational speed control and PAC are established based on the differences in wind speed. The WT's aerodynamic power is adjusted by changing the WT pitch angle. The pitching of the blade results in slight power loss, which guarantees that the captured power is equal to that of electrical power delivered by the generator [26].

The PACR controls the process continuously and changes blade pitch to regulate the speed of the rotor, as described above. PACR is also essential and valuable for enhancing WECS performance and output stability. The pitch mechanism typically involves an electric motor and an electromechanical actuator. Electrical pitch and hydraulic pitch controllers are the two pitch systems [27].

3.1. Hydraulic pitch controller (HPC)

The HPC utilizes a hydraulic actuator (HA) to control the function of all blades. The HA, which transforms corresponding energy into linear movements, is mounted in the rotational hub along with the accumulator tank. As seen in Fig. 5, the hydraulic control unit consists of a hydraulic pump inserted into the nacelle. The HPC has a significant advantage, including simple, safer functions and robust nature. HPC has low initial costs, but they are costly in maintenance and operation compared to the electromechanical controller (EMC).

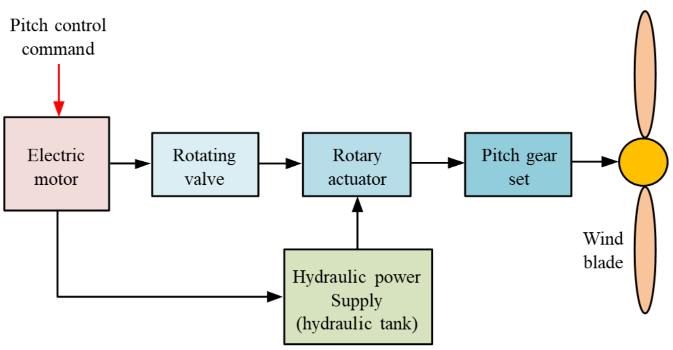


Fig. 5 Block diagram of HPC [28]

In previous literature, many researchers used various hydraulic-powered pitch angle controls. Hydraulic systems' latest work is focused solely on dynamic analysis, pitch system modeling, and effective control techniques. A slider-crank system was suggested using a modified mathematical model of the hydraulic variable pitch mechanism. The method selects a suitable electro-hydraulic proportional current value based on wind speed. The angle is constant when the wind speed is lower to obtain maximum power. If the speed exceeds the allowed speed, WT is stopped, and a braking mechanism is used. The blade angle is determined by pitch characteristics [29].

The hydraulic servo controller (HSC) is proposed based on a pitch controller. A research rig is designed for 2000 kW WT to carry out a real-time trial. An adaptive fuzzy controller is designed to monitor position control of the PACR with fuzzy sliding mode compensation. The system's functionality is tested by adding a load disturbance to various wind profiles [30].

The HPC is developed based on the Petri net model (PNM). Visual C++ uses VESTAS V39 WT as a base model to test the proposed pitch angle. The Petri model is highly reliable and establishes a logical link between faults that improves the system's condition [31]. Linear parameter varying fault tolerance control (LPFTC) is defined and evaluated to HPC. This system is designed for offshore WT. The identification of fault and subsequent compensation of the observed fault was calculated to resolve the signal of the applied sensor. The system has an automatic method that corrects the problem and prevents further damage to the WT due to the unbalanced load [32].

The authors recommended a new pitch control, considering the output power smoothing. The system is developed in an exterior loop, and the intrinsic hydro-mechanical position controller tracks the corresponding angle. For large WT, the system has a significant payload capability and a lot of potential [28]. The various research on the HPC is summarized in Table 1.

Table 1 Summary of past research based on HPC

Reference	Publication year	Control technique	Generator specification	Software
Yin et al. [28]	2015	HSC	1500 kW	LabView
Chen et al. [32]	2013	LPFTC	5000 KW	FAST
Chiang et al. [30]	2011	HSC	2000 KW	Experimental test
Yang et al. [31]	2011	PNM	500 KW	C++
Kong and Wang [29]	2007	Slider crank	1500 KW DFIG	Matlab/ Simulink

3.2. Electric pitch controller (EPC)

The EPC contained an electromechanical actuator to control the blade. It has a gearbox, an electric motor, an energy supply unit, and a storage energy facility. The power supply is mounted in the tank, while energy storage and actuator units are located in the revolving center. The gearbox is used to change the electric motor to the desired speed. Energy storage supplies adequate power in power failures to the Pitch Controller [33].

The EPC is more efficient and has a quick response time than HPC. Compared to HPC, the power/weight ratio is low, but they are still favored due to low maintenance and running costs [34]. Much research on the electro-mechanical angle controller was performed recently. EPC can be categorized into four different groups, and their comparison is given in Table 2.

Table 2 Comparative analysis of various EPC techniques

Controller name	Reliability	Performance	Performance with quick changes in wind speed	Complexity	Convergence speed	Cost
HPC	High	High	Very high	Moderate	Faster	Bearable
SPC	High	Moderate-high	High	Low	Faster	Bearable
RPC	Moderate-high	Moderate-high	High	High	Moderate	High
CPC	High	Low	Low	Low	Slow	Low

3.2.1. Conventional pitch controller (CPC)

The CPC uses a proportional-integral (PI)/ proportional-integral-derivative (PID) controller to control power output and rotor speed. CPC is best suited for small-scale WECS (SC-WECS). The typical control pitch relation derives from input parameters such as rotor velocity, power output, and wind velocity [35]. The α_{ref} of the sensors which use the S_w as feedback is taken directly from the S_w-α curve. Although this is a simple method, it is impractical to measure the S_w precisely [36]. Because of its reliability, the pitch angle controller based on generator power and the rotor speed is the most effective traditional controller.

Conventional converters with gain scheduling (GS) optimize the control efficiency of non-linear systems. Aerodynamic torque sensitivity to a pitch angle is resolved to employ gain scheduling [37]. The sensitivities depend on the change in pitch angle output power, respectively. The controller gain is inversely proportional to sensitivity. Fig. 6 demonstrates PI-based PAC with GS. Table 3 offers the new and most effective CPC overview.

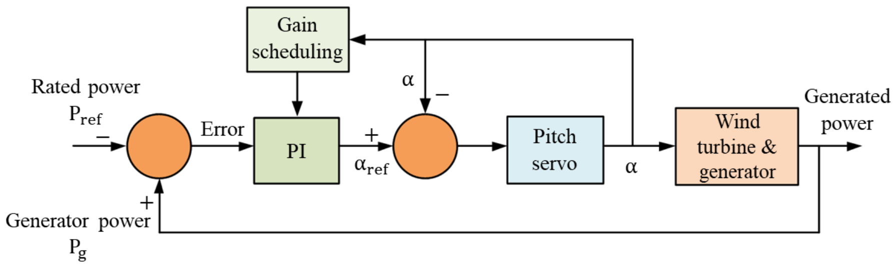


Fig. 6 PI-based PAC with GS [38]

The author describes the power generated by the WT optimally by the pitch and generator load control operation. The power is correlated to rotor speed, and acceleration is maintained to keep it at its maximum. The controller is designed for a fast and slow wind speed pitch rate. The impacts of the slow and fast pitches were analyzed based on the operating characteristics of various wind speed areas [26].

A fuzzy logic control (FLC) and PI controller with gain are proposed. The controller requires system knowledge, therefore increasing its complication. Due to the wind speed's nonlinearity, the traditional controller does not meet its dynamic characteristic. The control technique based on FLC is applied and compared to PI, revealing that the FLC-controlled system has a low fatigue load [38].

A PID-based PACR is developed and evaluated by the root locus method. The controller output is obtained by generating a short-circuit fault near WT in the Northern European energy grid. Stability is accomplished, which is necessary for grid integration. The pitch actuator can dampen the power system oscillation. The grid frequency and active stall of WT are examined, and an appropriate interface is identified [39].

The PI controller used to give a time delay to HPC was proposed. A graphical methodology is used to evaluate PI controller gain. MATLAB performs the testing approach, and the outcomes illustrate the reliability of the controller for reducing processing time and complexity [40]. Gain estimation for a PI-based pitch controller is discussed here. The authors define the analytic and simulation process to calculate the wind speed. The result suggests that the simulation-based calculation is straightforward and faster than the analytic approach. The result is validated based on the 5MW WT [41].

The issue related to the prediction correction of the pitch angle control technique was presented. A moving average method uses wind velocity data to estimate the pitch value, and a control error is analyzed by the corresponding PI controller [42]. The load curtailment of unbalanced loads employing a PI-Resonant (PI-R) pitch controller is presented. Such a technique uses the individual pitch controller (IPC) setup. PI controller is equipped with two resonant controllers. The proposed method leads to a reduced load on the wind turbine. The system mismatch is observed and minimized using pitch error [43]. The biggest downside to CPC is that the nonlinearity of the system cannot be tracked. Compared to other methods, the response time for traditional controllers is very high. For CPC, previous knowledge of the system is required [44]. They are ideal for small wind systems.

Table 3 Summary of past research based on CPC

Reference	Year of publish	Control technique	Input parameter	O/P parameter	Software
Zhang et al. [43]	2015	PI-R	Recent and reference generator power	α_{ref}	FAST
Qian et al. [42]	2012	PI	Rotor speed reference, generator power	α_{ref}	DIgSILENT/ Powerfactory
Hwas and Katebi [41]	2012	PI with GS	Recent and reference rotor speed	α_{ref}	Matlab/Simulink
Wang et al. [40]	2011	PI	S_w and direction	Blade flap degree	FAST
Zhang et al. [38]	2008	PI with GS	Generated and rated power	Power signal error (PSA)	Matlab/Simulink
Jauch et al. [39]	2007	PID	Power signal, frequency	PSA	Matlab/Simulink
Muljadi and Butterfield [26]	2001	Speed based PAC	Aerodynamic and generator power	Reference rotor speed	Matlab/Simulink

3.2.2. Robust pitch controller (RPC)

Fig. 7 demonstrates the fundamental topology of RPC for WECS. This controller incorporates sophisticated topology like the feed-forward and feedback method. To enhance the robustness of PACR, sliding mode control (SMC) is proposed [45]. This method, however, requires prior system expertise and relies on the WT mathematical model.

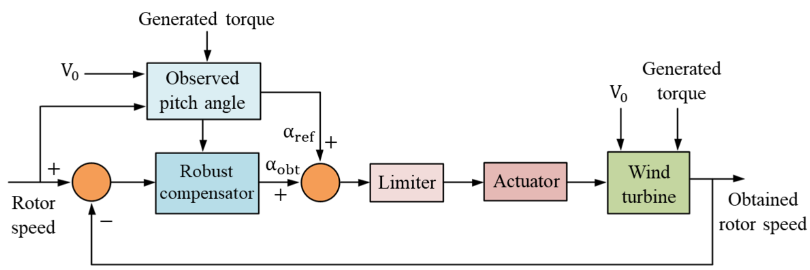


Fig. 7 Topology of RPC [46]

With the H-infinity Controller, the system sensitivity is reduced. It offers sufficient robustness to adjust the WT and speed parameters. The power output of the WT is improved as well. Only its complexity in the design of the system parameters and the weighting function constraints is a disadvantage of this method [47]. There is another robust controller that uses linear matrix inequalities (LMI) and linear quadratic gaussian (LQG) [48]. Due to the non-linear features of the WT, the linear controller does not achieve WECS stabilization.

Feedback/ feed-forward control is introduced to deal with the system's nonlinearity. With improvements to the operating system, the controller gains are constantly updated. This system responds more quickly because it requires no online parameter estimation. They depend on the characteristics of a particular WT. Therefore, the system's difficulty has increased because of its steady characteristic of controller gains at various operating points [49].

Minimax optimal based LQG control for low-voltage ride-through (LVRT) capability of WT is proposed. The author suggests that the controller improves modeling precision to reflect the wind system's nonlinearity and increases the system's tolerance to significant disturbances [50].

The feedback/ feed-forward PAC for blades is designed to lower the fatigue load and increase the turbine's lifetime. The wind speed provided by light detection and ranging (LIDAR) is the input of the feed-forward controller [51]. A multi-model predictive control system was presented. The power and speed of the generator are controlled to minimize the flicker emission and generate smooth power [52].

The author suggested a non-linear pitch controller. With an angular rotor speed, the pitch angle is controlled. The global stable closed-loop method proves the controller's optimum performance potential through Lyapunov-based analysis. Without specific knowledge of the WT model, the control system enables an aerodynamic rotor power control [53].

The author presented LMI based collective pitch controller (CPAC). A polytopic model-based approach is established to resolve operational constraints such as trading requirements and pole clustering of CPC. The author illustrates that such a controller can reduce speed regulation and mechanical load [54].

A robust, H_∞-based controller is proposed. Coordinate management techniques are used to manage the pitch angle to minimize the blade tension and monitor the system's frequency to minimize the entire system size. Wind Speed and WT o/p power are taken as i/p parameters for PACR [55].

Flicker emission and mitigation issues with the IPC system are discussed in this paper. The IPC is built with an azimuth angle and active power from the generator. Modeling and validation are done with fatigue, aerodynamics, structures, and turbulence (FAST). The active power oscillation under different wind conditions is dampened to minimize the emission of the flicker [56].

The author developed a system that balances mechanical and electrical uncertainty in the WT. An observer estimator is used to measure the rotor speed as an output, as the system correctly receives feedback information, resulting in stable outcomes and faster convergence [57]. A comparison between PI and H_∞ controllers is discussed here. The PID controller is based on an analysis of the root locus, while H_∞ is based on the DK iteration method. The H_∞ control mechanism offers stable and less oscillatory stability [58].

Integral SMC-based pitch angle control was suggested. The controller focusing on regulating derived power in zone 3 and optimum power production in zone 2 is calculated. In region 2, the integrated SMC is installed. Using an updated Newton Raphson estimator, wind speed is measured. The validation and investigation of the controller are done by FAST and Lyapunov's stability criterion, respectively [59].

The key method for turbine speed and power generation regulation is the collective timing regulation (CPC) in region 3. Modeling complexities, control limitations, and unmeasurable states are the main difficulties faced by a CPC design. A tube-based-model-predictive-output-feedback controller is implemented to build a CPC [60].

The author implements a discrete-time L1 adaptive controller for combined pitch control, variable pitch, and variable speed WT (VSWT). The pitch angle influences the generator and power generated during high wind speeds. The key advantages of the new controller are the robustness against the complexities of the WT model, maintaining reliability and stability of the closed-loop system, and its applicability in real-life operations [61].

A new electro-hydraulic pitch system is implemented to improve pitch regulation performance and thus smooth generator power variations for WT. Such a system consists of a variable speed hydraulic pump, motor, and pitch gear set. A projection-type adaptation law and adaptive robust integral SMC are analyzed to track the pitch angle accurately [62]. Collombo implemented a robust SMC with the blade pitch as the control input. The suggested control was tested on 5-MW three-blade WT with a FAST simulator [63].

The author suggested the latest L1 adaptive controller for blade pitch control of WECS to provide reliable generator speed and output power in the existence of wind disruptive circumstances [64]. Table 4 provides an analysis of the most recent literature on RPC technology. The above study suggests that the controller has robust performance to account for uncertainty and system stability. But the controller makes the system more complicated.

Table 4 Summary of past research based on RPC

Reference	Year of publish	Control techniques	Generator specification	I/P	Software
Yang et al. [64]	2020	L1 adaptive controller	1.5 MW	Generator speed	Simulation
Colombo et al. [63]	2020	SMC	5 MW	Blade pitch	FAST
Yin et al. [62]	2019	Adaptive robust integral sliding mode pitch angle controller	1.5 MW	The rotational speed of the servo motor	Matlab/Simulink
Lasheen et al. [61]	2020	L1 adaptive controller	5 MW	Generator speed and generated power	Matlab and real-time
Lasheen et al. [60]	2017	The tube-based model predictive output feedback controller	5 MW	Turbine speed and generated power	FAST
Saravanakumar and Jena [59]	2015	SMC	600 KW	S_w and generator torque	FAST
Moradi and Vossoughi [58]	2015	H∞	100 KW	Generator torque & aerodynamic	Simulation
Asl and Yoon [57]	2016	Feedback control	100 KW	Frequency & generator torque	Matlab/Simulink
Zhang et al. [56]	2014	Azimuth angle-based pitch	1500 KW DFIG	Generated power and reference	FAST
Jain et al. [55]	2015	H∞	275 KW	Output power error	Matlab/Simulink
Hassan et al. [54]	2012	LMI	5000 KW	S_w and generator torque	FAST
Iyasere et al. [53]	2012	Non-linear control	400 KW	Original & desired speed	Simulink
Soliman et al. [52]	2011	Predictive control	1500 KW	Generator torque & power	Simulink
Dunne et al. [51]	2011	Feed-forward/ Feedback	5000 KW	Wind speed	FAST
Hossain et al. [50]	2010	LQG	50000 KW	Slip of generator	Matlab/Simulink

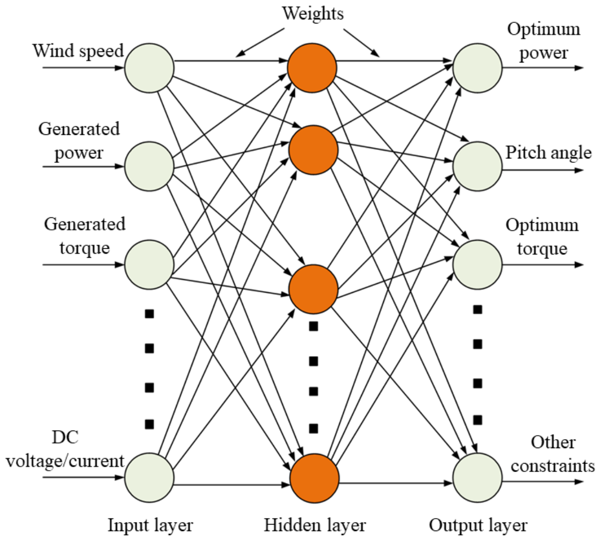
3.2.3. Soft-computing pitch controller (SPC)

To overcome WECS uncertainty due to a quick change in wind speed, SPC is designed. Artificial techniques provide an accurate, quick response and predictive technology compared to traditional methods. The soft computing technique, i.e., FLC, artificial neural network (ANN), adaptive neural-based ANN, and genetic algorithm (GA) based controller, solves a broad range of problems [64].

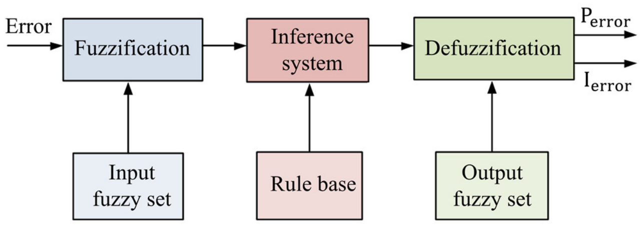
Most researchers use a pitch-angle controller based on ANN, FLC, and GA, which are listed in Table 5. The ANN includes an i/p layer, a hidden and an o/p layer, as illustrated in Fig. 8(a). The user determines each layer's number of nodes. The ANN technique takes three inputs: produced power, rotor speed, wind speed, or a combination of these. The ANN-based controller can easily adjust to different circumstances with fast response capability [65-69].

FLC is straightforward and recently developed because of its simplicity and adaptability; it gets interesting in the pitch controller. The FLC comprises inference, fuzzification, and defuzzification, as illustrated in Fig. 8(b). The FLC PACR relies on the user's knowledge and the membership function of correct error. The FLC memory allocation is the biggest downside to effective climate change control.

ANN-based pitch angle controller is suggested. Multilayer perceptrons (MLPs) with radial basis function neural networks (RBFNN) and backpropagation are utilized to model the operation. For the high wind speed zone, both controllers are verified. RBFNN provides better outcomes compared to the MLPs controller [70].



(a) ANN controller topology [1]



(b) FLC-based pitch controller [1]

Fig. 8 Structure of FLC and ANN

FLC-based PACR is implemented to enhance the microgrid output. Compared to battery storage, the suggested PACR approach is employed to deal with frequency deviation. The battery-based storage technique has been highly efficient than FLC, but FLC costs less than the battery storage technique [71].

The FLC-dependent PACR is suggested and employed to smooth wind power fluctuation at below-rated wind speeds. The output power is calculated according to the exponential moving average algorithm (EMA), and the factor of correction is chosen by the fuzzy reasoning method. FLC can be applied for choosing the destination power output based on the speed of wind [72].

An adaptive pitch control based on RBFNN is presented for various operating conditions. The torque control is applied for lower speed, while the PAC method is used for higher wind speed. It analyzes the smooth transition between the two modes. For upgrading the laws of neural networks (NN), Lyapunov's stability criteria (LSC) is used. With the help of the above techniques, noise reduction and linearity are obtained [73].

The authors suggested FLC-based PACR. It is impossible to operate the conventional PACR at a low wind speed, while FLC-dependent wind is analyzed for all areas of the operation. EMA technology provides the reference power generated by the WT. By evaluating the difference between real and generator reference power, FLC produces a command value for the pitch angle. The system's most significant downside is that the capacitor's involvement is costly [74].

An updated pitch control based on FLC was suggested. For full and partial load areas, it is introduced. The input parameters of FLC are generator speed and power. At rated speed, the aerodynamic speed and power are sustained during harsh wind blows without power variations [75]. Two FLCs were used to control the pitch angle and rotor speed of WECS. The pitch reference is estimated by the rotational and wind speed of WT [76]. The authors have developed an individual pitch controller (IPC). They gave online training to an RBFNN. The network input signals for training are received from a sensor. The network then changes the PID controller's parameters [77].

The goal is to implement a novel combined MPPT-pitch angle robust control system of a VSWT [78]. PAC is generated with an ANN-based low-cost circuit to allow the maximum speed of the PMSG. ANN comprises an input layer with two neurons for receiving tip speed ratio and power coefficient.

An RBFNN is used to estimate a WT system's nonlinear component. The network comprises an electric power error input, one hidden, and one output layer. The results are reliable in wind power extraction [79]. The authors suggested two techniques for pitch angle one is RBFNN, and another is a feed-forward-based back propagation network (BPN). With the control techniques used, the non-linear characteristic of wind speed can be compensated. The rotor can keep mechanical torque and generator power to the rated value without oscillation during quick changes in wind speed [80].

To stabilize the system in the event of non-linearity, GA-based PACR is developed. The techniques of optimization are used essentially for soft computing. A curve between the pitch angle and turbine power can be used to determine the GA controller. The generator speed is controlled by a control signal depending on the reference speed to achieve optimal speed. GA technology is used during low wind speed to obtain the maximum power by the pitch angle from the available wind speed.

Table 5 Summary of past research based on SPC

Reference	Year of publish	Control technique	Generator specification	Input	Software
Tiwari et al. [80]	2017	RBFNN and BPN	2 MW PMSG	Wind and generator speed	Simulation
Mijabber et al. [79]	2017	RBFNN	600 KW	Electrical power error	Simulation
Dahbi et al. [78]	2016	ANN	6.6 KW	Power coefficient and tip-speed ratio	Matlab/Simulink
Liu et al. [77]	2016	RBFNN	2 MW	Rotor speed	Simulation
Villanueva et al. [76]	2015	FLC	DFIG	Generated power error and its derivative	LabView
Van et al. [75]	2015	FLC	2 MW PMSG	S_w and Generator power output	Simulation and experiment
Kamel et al. [74]	2013	FLC	15 & 10 KW	Generated power error and its derivative	Matlab/Simulink
Jafarnejadsani et al. [73]	2013	ANN	5 MW	Wind speed & generator torque	FAST
Chowdhury et al. [72]	2011	FLC	1.5 MW	FLC 2-generator, FLC 1-rotor speed & o/p power	Simulink
Kamel et al. [71]	2011	FLC	10 & 15 KW	Generator power	Matlab/Simulink
Yilmaz and Özer [70]	2009	ANN	2 MW	Wind speed, change in generated power & error derivative	Simulink

3.2.4. *Hybrid pitch angle controller (HBPC)*

The HBPC was introduced to overcome the disadvantages of the above controller. To achieve efficiency and maximized power from the WECS, the HBPC overcomes all the drawbacks of the traditional controller. The robust controller and soft computing technology are hybridized so that the rotor speed is measured effectively without a sensor. This system demonstrates good stable performances [81]. Fuzzy and neural network controller techniques are combined with increasing output power for the entire operational area. The method is evaluated for stability determination during rapid operating point changes [82].

A fuzzy sliding mode control for loss minimization with RBFNN is proposed for PMSG-based WECS. The optimum boundary of uncertainties is estimated using a fuzzy inference system. Online training is provided to the RBFNN controller for the project and a relevant pitch reference. Even with parameter uncertainties, the system shows desired performance [83].

The Elman neural network (ENN) with modified particle swarm optimization (MPSO) technology is implemented to change the pitch mechanism. The BPN is used to train ENN weights. The pitch control has been adjusted to keep the output power lower than the rated power. MPSO calculates the ANN population. ANN weights are trained online to improve the learning rate [84].

The PI pitch control, combined with the RBFNN controller, is implemented to determine the optimal gain. The PSO is used to provide the RBFNN with an optimal dataset. The RBFNN analyzes the PI gain value. The system is decoupled from the WT non-linearity and complexity to provide adequate performance and controllability [85]. Differential evolution (DE) based ANN is presented. Training the output-input data by employing the DE technique, as displayed in Fig. 9. achieves nominal weights for BPNN. The author concludes that damping and grid capacity is increased [86].

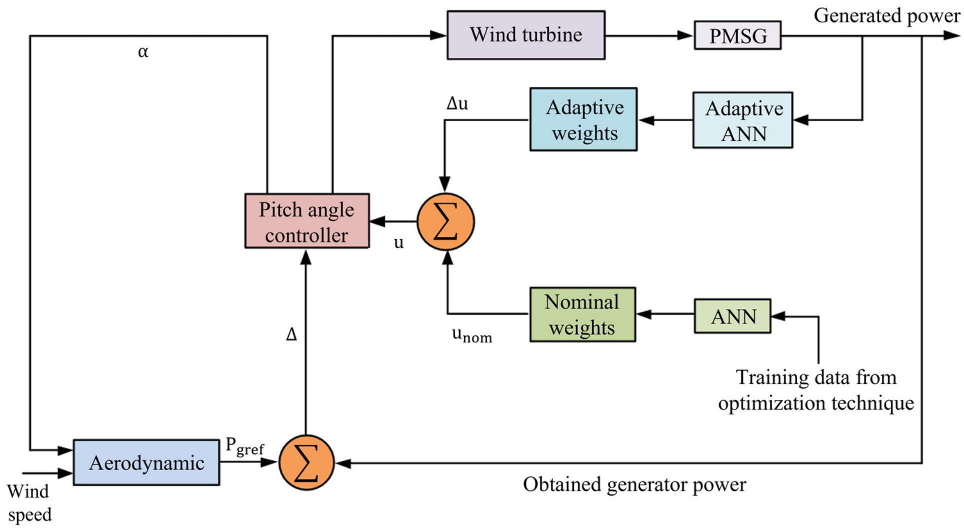


Fig. 9 DE-based HBPC [86]

The DE method is implemented and uses LQG rather than the ANN technique. The gain scheduling is carried out to control the power output at higher-rated wind speeds. The multi-input-multi-output (MIMO) is applied to minimize the wind system's mechanical load. It further increases the system's convergence speed to control operating constraints [87].

An HBPC combination of fuzzy and PI techniques for PACR is implemented. Here, the fluctuation in power and smoothing are considered. The power signal error and its rate of change are fed into the FLC. The suggested controller provides a good outcome in all operational areas and reduces system complexity [88].

The author combines the H_∞ controller with PSO to minimize the frequency fluctuation in PACR. The PSO-tuned PID controller was presented for comparative assessment. The performance has been calculated, and the controller is robust for variations [89].

The authors suggested the hybridized fuzzy with PI controller. The Kalman observer is intended for the estimation of the unmeasurable state. The suggested controller performs better than others [90]. Two advanced controllers, fuzzy PID (FPID) and fractional order fuzzy PID (FOFPID) were suggested to improve pitch control. In the meanwhile, chaotic evolutionary optimization is used to determine controller parameters. The mentioned optimization methods provide controller parameters and guarantee optimal functionality based on the selected objective function [91].

A FOFPID controller for PACR is proposed. A teaching-learning-based optimization (TLBO) algorithm is used to tune the proposed controller. In addition, the performance of TLBO is compared with GA to show effectiveness [92]. The HBPC discussed above provides a reliable solution for a non-linear system. The vital issue of the HPC is implementation and increasing the overall cost of the system. The study of different HPC in WECS is shown in Table 6.

Table 6 Summary of past research based on HBPC

Reference	Publication year	Control technique	Generator specification	Input	Software
Pathak et al. [92]	2019	FOFPID	2 MW	Wind speed	Matlab/Simulink
Asgharmia et al. [91]	2018	FPID and FOFPID	5 MW	Generator angular speed	FAST
Lasheen et al. [90]	2016	Fuzzy and PI	5 MW	*Sw* and generated power	FAST
Mohanty et al. [89]	2014	H_∞ based PSO	Hybrid system	Frequency deviation & Gain constant	Matlab/Simulink
Duong et al. [88]	2014	Fuzzy and PI	3 MW SCIG	Power error signal and rate of change of error signal	Matlab/Simulink
Taher et al. [87]	2013	DE and LQG	225 KW	Generator torque and α	Matlab/Simulink
Rahim et al. [86]	2013	DE and ANN	DFIG	Wind data	Simulink
Poultangari et al. [85]	2012	RBFN and PI	5 MW	S_w	Simulink
Lin et al. [84]	2011	ENN	750 W	α_{ref} & rotor speed	Dspace TMS320C32
Lin et al. [83]	2011	RBFN and Fuzzy sliding mode	750 W PMSG	Generator torque	Dspace TMS320C31
Senjyu et al. [82]	2006	FNN	275 KW induction generator	Power output and the average value of power	Simulink

4. MPPT Controller

WECS requires an MPPT algorithm to deliver maximum dynamically-based power from the wind. A specific generator speed extracts the maximum power associated with the wind speed. The power is dramatically reduced above a particular generator speed. Thus, the MPPT controller tracks specified speeds in a variable speed WT and extract maximum power. This controller is concentrated in the activity of the 2nd zone as defined in Fig. 2. The WT aims to produce maximum power from the wind in the second region [93]. The 3rd zone stabilizes the power output by reducing mechanical velocity to prevent damage to WT and generators [94].

Fig. 10 reflects the basic MPPT topology of WECS. Many sensorless strategies have been gaining popularity in recent years due to the absence of anemometers and other expensive sensors and adequate precision with a high switching rate. Table 7 compares the different forms of WECS-related MPPT controller techniques comprehensively. MPPT in WECS can be classified into the indirect power control (IPCM) and direct power control (DPC) method. The complete analysis of different MPPT algorithms is explored here;

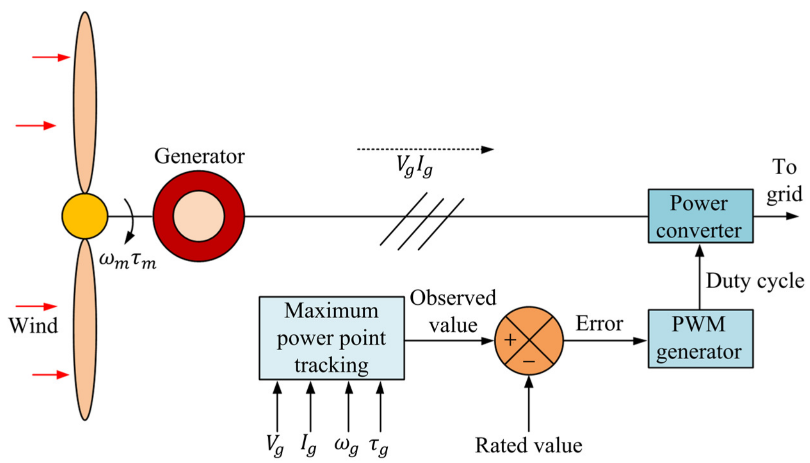


Fig. 10 MPPT-based WECS control

Table 7 Comparison of various MPPT techniques

Parameters	TSR	OTC	PSF	PO	IC	ORB	Hybrid	Fuzzy	ANN	Adaptive
Complexity	Simple	Simple	Simple	Simple	Simple	Simple	Medium	High	High	High
Memory requirement	No	No	Yes	No	No	No	No	Yes	Yes	Yes
Convergence speed	Fast	Fast	Fast	Low	Low	Medium	Fast	Medium	Medium	Medium
S_w measurement	Yes	No	Yes	No	No	No	Yes	Depends	Depends	Depends
Previous knowledge	No	Needed	Needed	No	No	No	No	Needed	Needed	Needed
Performance under fluctuating wind conditions	Medium	Medium	Medium	Medium	Medium	Medium	Good	Very good	Very good	Very good

4.1. Indirect power control technique

4.1.1. Tip speed ratio (TSR) MPPT algorithm

The TSR algorithm maintains the ratio between rotor speed and blade tip to an optimal value to obtain maximum power irrespective of wind fluctuation [16, 95]. Though the controller implementation is simple, its operation cost is high. Such an approach requires accurate wind speed estimation that increases the difficulty and expense of the system.

The application of effectual wind velocity evaluator (EWSE), which provides maximum power extraction in the commercial WT, is implemented and investigated by optimizing the industrial baseline controller through TSR tracking and optimal adjustment of the pitch angles [96].

The TSR and optimal torque (OT) methods are tested in a 1.5 MW WT model to determine their output under wind speed conditions. Comparison tests reveal that under all wind conditions, the TSR control system obtained relatively more wind energy at the expense of heavy component loads than the other. In addition, both control methods have similar power reduction trends, which are meaningful for wind speed and turbulence intensity [97]. The suggested strategy is based on the model reference adaptive power control method using TSR. The adaptive control method provides better results than traditional methods [98]. An integral sliding mode voltage regulator (ISMVR) method is used to increase the efficiency of the MPPT technique. This suggested method is used for the TSR MPPT technique. Quick and robust tracking is obtained from this method. Even to produce the control signal, there is no need to know the generator parameters [99].

4.1.2. Optimal torque control (OTC) MPPT algorithm

The suggested small-signal model includes TSR and OTC MPPT controller. These approaches are compared analytically to demonstrate MPPT and the potential for power smoothing. From the simulation result, OTC is highly effective for enhanced power smoothing and extracting maximum power [100].

The research is to improve efficiency in the MPPT method of the WT using a quantum neural network (QNN) controller in an adaptive control structure. QNN is used in TSR and OTC MPPT methods. The proposed control method is tested on a battery charging windmill system with PMSG to illustrate their superiority related to convolution neural networks (CNN) and PID [101].

TSR and OTC are tested in a 1.5 MW WT model to determine the performance under wind speeds. The TSR outperformed the OTC in terms of power generation output over an extensive range of wind speeds, but there was a variance in power that produced significant loads for the components of the WT [97].

4.1.3. Power signal feedback (PSF) MPPT technique

Prior information about the system is required for the PSF technique. In the lookup table, the obtained value is recorded. Instead of shaft speed and maximum power [102-103], the new PSF system uses DC and voltage [104]. The relationship with the lookup table parameter for the available wind speed offers the best power. The most significant downside of the program is its complexity.

4.2. Direct power control technique (DPC)

4.2.1. Perturb and observe (PO) algorithm

PO is very famous for its simple implementation and lower cost. Such an algorithm measures current output from the last cycle, generates the correct phase for the next cycle, and adjusts the various duty cycle or input voltage parameters [105]. This technique fails to track wind speed fluctuation. Different modified PO are implemented to overcome the downside of traditional PO [106-107]. The advanced PO technique is presented for searching for optimum power in wind systems. This MPPT method provides initial power demand dependent on the error-driven control. It uses intelligent memory data to control the inverter for maximum power extraction without knowing the WT characteristic [104]. The modeling of wind systems using Matlab software is discussed here. PO is used for MPPT [108].

MPPT algorithm for SC-WECS is provided. Such a method uses DC as the perturbing variable. The algorithm indirectly senses abrupt wind speed changes through the dc-link voltage slope. The voltage slope is utilized to improve the algorithm's tracking speed and to keep the generator from stalling under the strong wind velocity slowdown condition. Two modes of operation are employed; PO mode with adaptive step size under conditions of slow wind variability and prediction mode under conditions of rapidly changing wind speeds [109].

A new way of resolving the problems present in the PO MPPT for WECS is suggested. The solution presented addresses the tracking speed vs. control efficiency issue and ensures that changing wind conditions do not mislead PO in the wrong direction [110]. A novel optimal current is given (OCG) MPPT based on PO and the power feedback theory is introduced for permanent magnet-driven WECS. This technique improves the accuracy and stability of MPPT [111]. A simple and powerful MPPT modular sector algorithm is proposed to eliminate the shortcoming of the traditional fixed step-size PO method. The variable step PO (VS-PO) is used to segment the power speed curve into the modular sector with a specific step size. The simulation results show the superiority of VS-PO over conventional PO (CPO) and updated PO methods [112].

Fast-hybrid (FH-PO) and intelligent self-adaptive (SA-PO) PO for VS-WECS is implemented to eliminate current PO shortcomings and increase their dynamic performance. The technique of the FH-PO is to perturb the rotor speed with a fixed step size while operating below 90 percent of maximum power. This method increases the tracking speed and depends on the fixed step size. The SA-PO substitutes the use of a fixed step size with an idea of an optimal hypothetical circle based on the distance from actual to ideal points of control and the estimation of the correct perturbation step size. The SA-PO takes less time to control the maximum power point (MPP) than FH-PO [113].

4.2.2. Incremental conductance (IC) method

A new fractional-order IC (FOIC) method for MPPT of small wind systems is suggested. In addition, the changing wind system equipment increased the overall MPPT efficiency [114]. An updated IC algorithm for variable step size is proposed that automatically adapts the step size to control the MPP. The simulation result suggests that the approach enhances the steady-state and dynamic performance [115].

4.2.3. Optimal-relation-based (ORB) MPPT algorithm

The framework relies on the optimum interaction of quantities such as DC voltage converter, wind speed, and turbine power output electricity. It has the advantage that no sensor is needed for speed calculations, nor the look-up table is necessary. Its functions depend on the pre-obtained system curve.

4.2.4. Hybrid MPPT algorithm

A new MPPT algorithm based on PO and ORB hybridization is introduced. The PO is used as an initialization method to search online for MPP of a local wind speed for extracting parameters. These parameters are used to perform the ORB method [116]. A new hybrid intelligent strategy has been suggested in this literature for extracting maximum wind power from WT. The suggested MPPT uses TSR with RBFNN supervised by an MPSO-based hybrid controller (RBFNN-MPSO). A gradient descent algorithm trains the RBFNN, and the MPSO algorithm is applied to increase the learning capability of the training process [117].

A new algorithm of adaptive PO (AD-PO) and hybrid PO (HB-PO) based on variable speed-WECS (VS-WECS) is introduced to eliminate the downside of the traditional step size PO method and to enhance the tracking performance of the VS-PO algorithm. These two algorithms split the power speed curve into modular sectors by estimating the distance between optimum and actual rotor speed. HB-PO incorporates low oscillation and fast-tracking speed by determining the number of sectors to operate by VS-PO. In contrast, the other sectors are operated by the AD-PO algorithm [118].

4.3. Other MPPT algorithms

4.3.1. Fuzzy logic control (FLC) based MPPT algorithm

Various control techniques have been suggested to use FLC for MPPT application independently or with other approaches. For VS-WECS, an intelligent power electronic device based on FLC is introduced. This method uses a fuzzy logic approach to control the electromagnetic torque, optimize power accumulation, and improve the turbine generator performance. The system does not need wind speed information and can easily restrict electric power fluctuation [119].

The paper focuses on creating an MPPT controller of WECS, which is accomplished by applying the FLC technique. This controller aims to track maximum WES power, consisting of a WT coupled with a self-excited induction generator. Simulation demonstrates the performance and robustness of this controller [120]. An online MPPT control based on FLC is implemented for the indirect vector-controlled induction generator system. Such a controller tracks MPP and extracts power from wind generators under varying wind conditions [121].

The author describes the data-driven approach for Takagi-sugeno-kang (TSK) fuzzy model. The technique provides a “best” TSK fuzzy framework that can estimate the accuracy of maximum extractable power from a variable-speed WT based on the given input-output numerical data [122].

A new FLC MPPT (sensorless) approach for WECS is introduced. Such an approach dramatically reduces the speed variation range of the wind generator, leading to a reduction of about 40 percent of PWM back-to-back converters compared to conventional techniques [123]. The authors provide a comparative study of the various MPPT method for PMSG-based WECS. Integral control, PO, and FLC methods are used for comparative study [124].

The CPO MPPT algorithm is modified with FLC to enhance speed and accuracy. Vienna rectifier is used as a generator side converter for its significant advantages. A non-linear SMC, which has significant advantages over linear controls, is used for speed control [125]. An artificial intelligent technique on FLC is implemented to improve the MPPT of PMSG-based WT. The FLC approach clarifies the superior characteristics over the traditional MPPT technique [126].

4.3.2. Artificial neural network (ANN) based MPPT algorithm

The wind MPPT is implemented using the conventional ANN method. Such a method undergoes high training to design the MPPT method. In addition, the system is considered a better alternative to traditional controllers [127]. ANN-based MPPT algorithm is demonstrated in a variable speed WT (VSWT) [128]. To obtain the desired output power, the author experimented with the system under a regular change in pitch angle, power value, and rotor speed. Given the expense of wind energy systems, the author in [129] used TLS EXIN neurons to feel turbine speed by reducing the need for an anemometer.

A multi-layer NN algorithm is introduced for small WT [130]. The suggested algorithm was able to run the system effectively under variations in wind speed. Similarly, the backpropagation method of VSWT in ANN MPPT is used for extracting maximum power [131].

RBFNN-based MPPT algorithm is introduced to track the maximum power using the duty cycle. The WECS is based on the PMSG. This approach does not necessarily require knowledge of the WT power characteristic, so it minimizes the need for specific measurement instruments [132].

This paper provides a new control approach to ensure MPPT for a doubly-fed induction generator (DFIG) based WECS. This approach uses NN and FLC for controlling the power transfer between the grid and machine using reactive power and indirect vector control strategies [133].

4.3.3. Adaptive MPPT algorithm

Here an adaptive MPPT method for fast MPPT under unstable wind conditions has been suggested for SC-WECS. The system efficiency of this algorithm is comparable to the PO algorithm. Test results indicate that WECS produces more energy than the PO algorithm [134]. The study of different MPPT algorithms used in WECS is shown in Table 8.

Table 8 Summary of past research based on MPPT algorithm

Reference	Year of publish	Control technique	Generator specification	Software
Yokoyama et al. [95]	2011	TSR	925 W SG	Matlab/Simulink
Song et al. [96]	2017	TSR	1.5 MW DFIG	Simulation and field testing
Song et al. [97]	2017	TSR	1.5 MW DFIG	Simulation using bladed software
Saidi et al. [98]	2019	TSR	1.5 MW PMSG	Matlab/Simulink
Yazıcı and Yaylacı [99]	2017	TSR	PMSG	Simulink
Nasiri et al. [100]	2014	OTC	1.5 MW PMSG	Matlab/Simulink
Ganjefar et al. [101]	2014	OTC	PMSG	Matlab/Simulink
Song et al. [97]	2017	OTC	1.5 MW DFIG	Simulation using bladed software
Wang et al. [104]	2004	PSF	10 KW	Matlab/Simulink
Barakati [102]	2008	PSF	40 KW	Matlab/Simulink
Barakati et al. [103]	2009	PSF	0.4 KW	Matlab/Simulink
Daili et al. [105]	2015	P&O	6.4 KW PMSG	dSPACE DS1005
Wang and Chang [104]	2004	P&O	50 KW direct-drive synchronous generator	Matlab/Simulink
Soetedjo et al. [108]	2011	P&O	PMSG	Simulink
Dalala et al. [107]	2013	P&O	1.5 KW PMSG	Simulation
Raza et al. [110]	2008	P&O	PMSG	Matlab-dSpace
Linus and Damodharan [106]	2015	Modified P&O (MPO)	1 KW PMSG	Matlab/Simulink
Dalala et al. [109]	2013	MPO	1 KW PMSG	Hardware setup employing inverter circuit & IPM
Zhu et al. [111]	2012	MPO	5.5 KW PMSG	dSPACE1103
Mousa et al. [112]	2019	variable-step P&O	1.5 MW five-phase (PMSG)	Matlab/Simulink
Youssef et al. [113]	2020	fast-hybrid P&O	PMSG	Matlab/Simulink
Youssef et al. [113]	2020	self-adaptive P&O	PMSG	Matlab/Simulink

Table 8 Summary of past research based on MPPT algorithm (continued)

Reference	Year of publish	Control technique	Generator specification	Software
Yu and Liao [114]	2015	Fractional order IC	PMSG	Matlab/Simulink
Hosseini et al. [115]	2013	IC	14 KW PMSM	Matlab/Simulink
Abdullah et al. [116]	2014	Hybrid (ORB+PO)	PMSG	Matlab/Simulink
Sitharthan et al. [117]	2020	Hybrid (RBFNN-MPSO)	2.5 MW DFIG	Matlab/Simulink
Mousa et al. [118]	2020	Hybrid (VS-PO and AD-PO)	1.5 MW five-phase PMSG	Matlab/Simulink
Chen et al. [119]	2000	Fuzzy logic controller	600 KW SG	Matlab/Simulink
Mohamed et al. [120]	2001	FLC	Self-excited induction generator	Matlab/Simulink
Abo-Khalil et al. [121]	2004	FLC	3 KW squirrel cage induction generator	Experimental
Galdi et al. [122]	2008	FLC	1.5 MW DFIG	Matlab/SimPower systems
Belmokhtar et al. [123]	2014	FLC	3.7 KW DFIG	Matlab/Simulink
Tiwari and Babu [124]	2016	FLC	8.5 KW PMSG	Matlab/Simulink
Heshmatian et al. [125]	2017	FLC	5.7 KW PMSG	Matlab/Simulink
Salem et al. [126]	2019	FLC	PMSG	Matlab/Simulink
Cirrincione et al. [131]	2013	ANN	2.2 KW	Matlab/Simulink DSP TM320F240
Li et al. [127]	2005	ANN	2 KW PMSG	Matlab/Simulink and implemented by dspace
Ro et al. [128]	2005	ANN	1.5 MW induction generator	MATLAB/Simulink
Pucci and Cirrincione [129]	2011	ANN	2.2 KW Induction Motor	dSPACE card (DS1103)
Qiao et al. [130]	2008	ANN	3.6 MW DFIG	Experimental
Cirrincione et al. [131]	2013	ANN	2.2 KW IM	dSPACE card (DS1103)
Kumar et al. [132]	2019	ANN	6 KW PMSG	Matlab/Simulink and real-time digital simulator hardware, OPAL-RT 4510
Medjber et al. [133]	2016	ANN	DFIG	Matlab/Simulink
Hussain and Mishra [134]	2016	Adaptive MPPT	PMSG	Simulator

5. Machine Side Controller (MSC) and Grid Side Controller (GSC)

The MSC manages variable speed operation and ensures that maximum power is captured. MSC changes rotor speed to obtain system stability and maximum power. As shown in Fig. 11, the GSC governs the converter voltage and the reactive and active power delivered to the grid [23, 132]. MSC are categorized into direct torque control (DTC) and field-oriented control (FOC). These two controls have almost identical characteristics and dynamic performance [23]. For speed control of the generator, FOC requires a dual loop (internal and external loop) controller technique. The external loop control requires the rotor speed and position to produce reference current in the 3 phases. The operation of internal loop control typically depends on a natural frame or a synchronous frame of reference [135]. The current of the stator of the d-axis is fixed to zero to achieve optimal electromagnetic torque (ET) with minimal stator current [136], and produced ET is regulated by the stator current of the q-axis [137-138]. As FOC regulates the current directly, the entire line current is used to improve machine efficiency with torque generation.

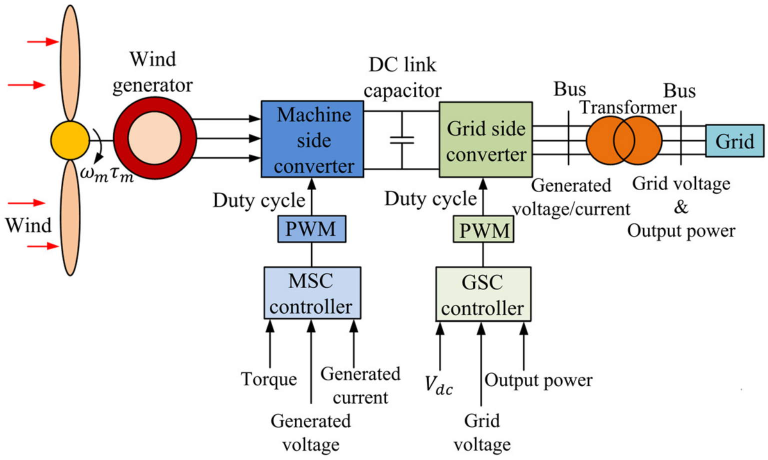


Fig. 11 MSC and GSC for WECS

DTC directly controls the power and torque, thus having simple control and faster response. Such a method removes dual-loop control. The internal loop is eliminated, and there is no need to transform between the reference frames. The hysteresis compensator output and flux angle are employed directly to generate converter switching pulses [139]. The current and torque ripple are the constraints to assess the DTC's performance. The same dynamic characteristic is present in both controllers [140]. The advantages of DTC are the absence of a current loop, the removal of the rotor speed sensor, and faster response. The main downside of this controller is the necessity of varying switching frequencies.

The grid side converter is separate from the generator converter type connected to the system. GSC primarily targets WECS grid integration. GSC is categorized into the direct power control (DPC) and voltage-oriented control (VOC) groups [141]. A VOC control is like a FOC consisting of double-loop control. Depending on the hysteresis control reference frame, the VOC involves DC-link voltage and an internal current control loop (CCL). When the q-axis current reference is zero, the unit power factor (UPF) can be achieved [142-143]. VOC has lower power ripple, enhances power quality, and faster response. The VOC's drawback is a reactive and active component and a reference frame requirement [143].

DPC comprises reactive and active power control variables. PWM block and CCL are not present in this method. When reactive power reference is set to zero, UPF operation can be accomplished. The system becomes simple, and there is no coordinate transformation [23, 132, 144].

A novel control approach for GSC and MSC is proposed to improve the LVRT of a DFIG-based WECS. The suggested MSC control approach is developed by replacing the PI controller of the existing current control loop using the passivity theory based on the generator's non-linear characteristics. The GSC uses a two-term control method to keep the DC-link voltage near a set value. The efficacy of the suggested control technique is demonstrated by a time-domain simulation of a 2.0 MW-575 V DFIG-WCES using various scenarios based on grid connection codes of wind power. The oscillation amplitudes under transient conditions of stator and rotor current, reactive and active power, DC-link voltage, and other parameters are significantly decreased by employing the suggested control approach. Additionally, the oscillations are damped out more quickly, and the DFIG-WECS reaches its steady state in a shorter time [145].

A novel fuzzy second-order integral terminal SMC has been developed for both MSC and GSC of a DFIG-based WT. Further, a series GSC is included in the design to prevent DFIG's disconnection from the grid during faulty situations. The proposed control approach was thoroughly investigated using DFIG's various operating conditions, such as standard, super, and sub-synchronous under single and three-phase voltage sags. This approach allowed the DFIG to ride through the fault and maintain grid connection even when the grid voltage was not ideal [146].

A modified rotor-voltage-reference-based method for the MSC control technique is presented to improve the LVRT capabilities for DFIG-WECS. The proposed technique revised the MSC control structure. It introduced a new rotor-voltage reference by considering AC voltage imbalance and DC-link voltage variation in the power system. The following are some of the benefits of the suggested method: (a) It is straightforward to implement because no observer, sequence decomposition technique, or extra hardware is required; (b) It does not affect the current loop stability; (c) It is insensitive to changes in the DFIG parameters; (d) Dedicated grid-voltage-dip-detection method is not required, therefore, the response time is fast and ideal for LVRT control [147].

GSC injects reactive and active power into the grid during grid fault situations to ensure grid stability, using a novel reduced order generalized integrator-based positive-negative sequence controller. Based on negative and positive sequences, this controller is used to damp power oscillations during imbalanced grid faults. The suggested control approach is then validated in the lab setup of a 1 KW grid-connected DFIG-based WECS under both fault and typical situations [148]. A detailed review of the MSC and GSC technique is provided in Table 9 [149-152]. VOC and FOC strategies exhibit adequate performance with improved efficiency for grid integration in the above analysis.

Table 9 MSC and GSC technique comparison

Parameter	MSC		GSC	
	FOC	DTC	VOC	DPC
Implementation	Complex	Simple	Complex	Simple
Response time	Higher	Lesser	Higher	Lesser
Quality of power	Better	Poor	Better	Poor
Coordinate transformation	Needed	Not needed	Needed	Not needed
Internal CCL	Needed	Not needed	Needed	Not needed
DC-ink ripple voltage	-	-	Less	Higher
Ripple torque	Lower	Higher	-	-

6. Discussions and Future Aspects

Wind energy is one of the significant sources of green energy. It meets the electricity demand and leads to a healthy environmental system. Therefore, an appropriate controller must extract the maximum output from existing resources and generate clean energy for grid integration.

PACR is used primarily for large WT because of cost and maintenance problems. The major benefits of hydraulic pitch controllers are safer operation, low complexity, and robustness. The electric pitch controller has higher efficiency and faster response time than HPC. The power/ mass ratio is low, although it is mainly favored for low operating and maintenance costs compared to the hydraulic controller. The major drawback of a traditional pitch controller is that the system's nonlinearity is not controlled. In contrast with other methods, traditional controllers' response time is significant. For traditional controllers, prior knowledge of the system is needed. These are also ideal for small wind turbines. While this method is simple, wind speed cannot be accurately measured. The robust controller has good efficiency in case of system robustness to compensate for the system stability and uncertainties.

However, robust controllers make the control system more arduous, therefore, fail to respond to the primary system. SPC control techniques such as ANN, FLC, ANFIS, and GS have been introduced to solve WECS uncertainties due to rapid wind speed variations. In comparison to another conventional approach, the artificial technique provides an accurate, predictive, quick response and tends to solve a wide variety of problems. The HBPC was used to overcome the downside of the above controller.

It solves all the downsides of traditional controllers to provide optimal and efficient power from WECS. The robust controller and soft computing techniques are hybridized to estimate rotor speed without a sensor. This system offers good stability results. The HBPC provides a stable non-linear solution that is subject to input constraints. The main concern with HBPC is its implementation and the total expense of the entire system. Since HBPC is used, the payback period is reduced.

The main objective of the MPPT method is to monitor optimum wind turbine power points. It is a challenging task to pick a suitable MPPT technique. The indirect power control technique like TSR, PSF, and OT is fast and straightforward, but it maximizes mechanical wind power instead of electrical power output. TSR control has good performance with high efficiency and rapid response. Due to the turbulence and gust, an accurate anemometer is needed, which increases the system's additional cost, especially for small WECS. Such an algorithm is difficult to apply as the wind speed near the turbine varies from the free stream speed. OT is fast, efficient, and simple without a wind speed sensor.

However, it does not calculate wind speed directly; as a result, the difference in wind speed does not reflect immediately and substantially on the reference torque, which makes the efficiency of this algorithm less than the TSR. In terms of performance and complexity, PSF and OT are almost identical. This algorithm provides inexpensive and robust MPPT control for WECS. DPC techniques like PO, ORB, and IC are simple, and memory needs are also less.

These techniques directly determine the optimum electrical power without requiring prior training and wind speed measurement. However, these algorithms' efficiency is inadequate during wind changes, and their use is thus restricted to different wind conditions. These algorithms are reliable and cheaper as they are sensorless. The PO algorithm is popular and easy since measurement of mechanical quantities such as rotor, wind, and turbine speed is not required. The algorithm is system independent, and the generator or turbine parameter change does not influence its tracking. The PO algorithm captures the optimal power corresponding to any wind speed. But it takes a long time to hit MPP, and a significant power failure happens during the monitoring phase. It can also cause small wind turbines to stall. The improved PO overcomes the traditional PO algorithm disadvantages, which are incorrect directionality and slow response under rapid wind change.

The PO also leads to slower tracking when the step size is too small and high; it oscillates around MPP; these issues are solved using a fixed and adaptive step PO algorithm. No additional sensors are required for measuring wind or rotor speeds, neither PO nor IC methods. The IC approach provides better tracking of MPP compared to the PO algorithm as regards power efficiency. Flexibility and simplicity are the main advantages of these two algorithms but fluctuate near MPP to reduce system efficiency. An updated IC is used to improve MPPT efficiency and increase convergence speed and system precision, automatically changing the step size for tracking MPP.

The ORB is straightforward because only the DC and voltage measurements are required. This algorithm is flexible, independent, and simple since it does not require previous knowledge of the energy system or mechanical sensors. Moreover, MPPT is efficient and accurate. A hybrid approach or modification of the specific algorithm resolves the unique algorithm's demerits.

The other MPPT methods, such as soft computing (NN, FLC) and adaptive algorithms, are more efficiently predicting the optimal power and handling of system nonlinearity, but previous system information is required. The fuzzy control-based technique is good, but the computation time depends on the number of controller rules based on the system's complexity. NN-based MPPT control gives a better deal regarding power response and dynamic system speed. NN-based control strategies have good efficiency.

Since aging and under various environmental conditions, most mechanical parts have varying characteristics. To guarantee accurate MPPT, the NN has to be periodically trained. The adaptive MPPT method has significant benefits compared to other algorithms since it is more adaptive, robust, and accurate, mainly when the power demand and wind speed change are unexpected. The MCS and GSC controller primarily connects the WECS with the grid. The simple and reliable GSC controller provides faster active power control when connected to the grid.

LIDAR for WT control is an ancient technique in use for over four decades but seldom used in research papers for WT control, but its use in WT control was limited because of the high cost. However, this old technology remains highly researched and relevant for WT control in the future. The LIDAR concept must be thoroughly investigated as it is not developed commercially in WTs. Innovative rotor applications are also a recent development in WT control. It is a significant area of research dealing with eliminating the load for potential WTs. This concept uses sensors and actuators that are spread along with the WT blades with embedded intelligence. Unlike pitch angle control, which turns the entire blade with a pitch motor, the relative wind flow is regulated by individual actuators located along the blade, making the WT rotor an intelligent mechanism that can adjust faster and more precisely to load events.

The stability of wind energy systems connected to the grid is becoming more complicated. One primary concern related to electronic-based high penetration wind energy systems is the decrease in overall system inertia. Since fewer synchronous machine (SM) present in the system deals with the inertial response, in the case of generation failure or significant load variation, there is a large deviation in the rate of change of frequency. Moreover, poor power management restricts fault-ride ability during grid disturbances and raises the risk of voltage collapse. In the case of transient stability, when traditional SMs are substituted with electronics-based sources, there are fewer margins available.

As a result, typical grid-following control approaches for wind turbine converters may be insufficient to assure reliable wind power plant integration. A switch from traditional grid-following (GFL) to grid-forming (GFM) control is currently being studied as a possible solution to the above concerns. The GFM converters are voltage sources that can be controlled, having coupling impedance.

It also incorporates the features of the SM. GFM converters work with energy storage systems during the grid's disconnection from wind power plants to maintain frequency and voltage. It avoids the complete collapse by preparing for the reconnection. Many researchers investigated GFM operation in wind turbines. Different techniques have been proposed, such as distributed voltage and frequency control and PLL-based control. The most widely used technique is the virtual synchronous generator, which benefits in delivering the inertial response. GFM should have these qualities in the future.

- The regulation of phase angle and voltage amplitude should be done by wind turbine converters within wind power plants.
- It should actively reduce the power system inertia with substantial electronic-based generation penetration.
- Avoid oscillations among GFM.
- After disconnection, enable the islanding signal quickly.
- To avoid disturbance during system restoration, enable black start.

7. Conclusion

For wind energy production, Control techniques are receiving more significance nowadays. They are significant in the energy conversion process. The erratic character of the wind speed continues to be challenging to maintain a high-quality and efficient power supply plan. Due to the increasing penetration of WTs in the grid, it is required to get power efficiently by the grid code. As previously indicated, several analyses of MSC, GSC, and MPPT-based control techniques are carried out. However, in detail, none of the review papers discussed different control techniques related to pitch angle controllers, MPPT, GSC, and MSC. Therefore, the paper incorporates an in-depth analysis of overall control strategies for WECS. The benefits and drawbacks of various control strategies and the limitations of each controller are explored and assessed. This review aims to describe the most updated control technique approach, thus providing a current and efficient research approach to WECS controllability and stability. In the future, these technologies will lead to efficient power generation, reduced computational speed, and the system's total cost.

Nomenclature

Pm	Mechanical power of WT (W)		S_w	Wind Speed (m/s)
K_p	Rotor power coefficient		ω_m	Mechanical angular speed of turbine (rad/s)
γ	Tip speed ratio		α_0	Initial pitch angle (deg)
α	Blade pitch angle (degree)		α_{ref}	Pitch angle reference (deg)
σ	Density of air (kg/m^3)		τ_m	Mechanical torque (Nm)
D	Blade radius (m)		ω_n	Nominal angular speed (rad/s)
RE	Renewable energy		HBPC	Hybrid pitch angle controller
MPPT	Maximum power point tracking		MPSO	Modified particle swarm optimization
MSC	Machine side controller		MIMO	Multi-input-multi-output
GSC	Grid side controller		FPID	Fuzzy PID
WECS	Wind energy conversion system		FOFPID	Fractional order fuzzy PID
RES	Renewable energy sources		TLBO	Teaching-learning-based optimization
FF	Fossil fuel		DE	Differential evolution
WT	Wind turbine		IPCM	Indirect power control
PAC	Pitch angle control		DPC	Direct power control
PACR	Pitch angle controller		TSR	Tip speed ratio
HA	Hydraulic actuator		EWSE	Effectual wind velocity evaluator
HPC	Hydraulic pitch controller		OT	Optimal torque
EMC	Electromechanical controller		ISMVR	Integral sliding mode voltage regulator
HSC	Hydraulic servo controller		OTC	Optimal torque control
PNM	Petri net model		QNN	Quantum neural network
LPFTC	Linear parameter varying fault tolerance control		CNN	Convolution neural networks
EPC	Electric pitch controller		PMSG	Permanent magnet synchronous generator
CPC	Conventional pitch controller		PSF	Power signal feedback
PI	Proportional-integral		PO	Perturb and observe
PID	Proportional-integral-derivative		OCG	Optimal current given
SC-WECS	Small Scale WECS		VS-PO	Variable step PO
GS	Gain scheduling		CPO	Conventional PO
FLC	Fuzzy logic control		FH-PO	Fast-hybrid PO
IPC	Individual pitch controller		SA-PO	Self-adaptive PO
PI-R	PI-Resonant		MPP	Maximum power point
RPC	Robust pitch controller		IC	Incremental conductance
LVRT	Low-voltage ride-through		VS-WECS	Variable speed-WECS
CPAC	Collective pitch controller		FOIC	Fractional order IC
SMC	Sliding mode control		ORB	Optimal relational based
LMI	Linear matrix inequalities		AD-PO	Adaptive PO
LQG	Linear quadratic gaussian		HB-PO	Hybrid PO
SPC	Soft-computing pitch controller		TSK	Takagi-sugeno-kang
CPAC	Collective pitch controller		DFIG	Doubly-fed induction generator
CPC	Collective timing regulation		NN	Neural network
VSWT	Variable speed wind turbine		DTC	Direct torque control
ANN	Artificial neural network		FOC	Field-oriented control
GA	Genetic algorithm		ET	Electromagnetic torque
RBFNN	Radial basis function neural networks		LIDAR	Light detection and ranging
MLP	Multilayer perceptron		VOC	Voltage-oriented control
EMA	Exponential moving average		CCL	Current control loop
LSC	Lyapunov's stability criteria		UPF	Unit power factor
BPN	Back propagation network		ENN	Elman neural network

Conflicts of Interest

The authors declare no conflict of interest.

References

[1] R. Tiwari and N. R. Babu, “Recent Developments of Control Strategies for Wind Energy Conversion System,” Renewable and Sustainable Energy Reviews, vol. 66, pp. 268-285, December 2016.

[2] M. Valipour, “A Comprehensive Study on Irrigation Management in Asia and Oceania,” Archives of Agronomy and Soil Science, vol. 61, no. 9, pp. 1247-1271, 2015.

[3] M. Valipour, “Future of Agricultural Water Management in Africa,” Archives of Agronomy and Soil Science, vol. 61, no. 7, pp. 907-927, 2015.

[4] M. Valipour, “Drainage, Waterlogging, and Salinity,” Archives of Agronomy and Soil Science, vol. 60, no. 12, pp. 1625-1640, 2014.

[5] M. Valipour, “Comparison of Surface Irrigation Simulation Models: Full Hydrodynamic, Zero Inertia, Kinematic Wave,” Journal of Agricultural Science, vol. 4, no. 12, pp. 68-74, 2012.

[6] D. K. Singh, A. K. Akella, and S. Manna, “Deterministic and Probabilistic Analysis of Different Empirical Models to Estimate Monthly Mean Diffuse Solar Radiation for Composite Climatic Region of India,” Environmental Progress & Sustainable Energy, in press. https://doi.org/10.1002/ep.13917

[7] Y. Kumar, J. Ringenberg, S. S. Depuru, V. K. Devabhaktuni, J. W. Lee, E. Nikolaidis, et al., “Wind Energy: Trends and Enabling Technologies,” Renewable and Sustainable Energy Reviews, vol. 53, pp. 209-224, January 2016.

[8] S. Saravanan and N. R. Babu, “Maximum Power Point Tracking Algorithms for Photovoltaic System – A Review,” Renewable and Sustainable Energy Reviews, vol. 57, pp. 192-204, May 2016.

[9] E. Strantzali and K. Aravossis, “Decision Making in Renewable Energy Investments: A Review,” Renewable and Sustainable Energy Reviews, vol. 55, pp. 885-898, March 2016.

[10] H. Ibrahim, M. Ghandour, M. Dimitrova, A. Ilinca, and J. Perron, “Integration of Wind Energy into Electricity Systems: Technical Challenges and Actual Solutions,” Energy Procedia, vol. 6, pp. 815-824, April 2011.

[11] L. Y. Pao and K. E. Johnson, “A Tutorial on the Dynamics and Control of Wind Turbines and Wind Farms,” American Control Conference, pp. 2076-2089, June 2009.

[12] Z. Alnasir and M. Kazerani, “A Small-Scale Standalone Wind Energy Conversion System Featuring SCIG, CSI and a Novel Storage Integration Scheme,” Renewable Energy, vol. 89, pp. 360-370, April 2016.

[13] S. Behera, S. K. Behera, and B. B. Pati, “Impact of DFIG in Wind Energy Conversion System for Grid Disturbances,” Proceeding of Engineering and Technology Innovation, vol. 13, pp. 10-19, September 2019.

[14] A. M. Howlader and T. Senjyu, “A Comprehensive Review of Low Voltage Ride through Capability Strategies for the Wind Energy Conversion Systems,” Renewable and Sustainable Energy Reviews, vol. 56, pp. 643-658, April 2016.

[15] D. Kumar and K. Chatterje, “A Review of Conventional and Advanced MPPT Algorithms for Wind Energy Systems,” Renewable and Sustainable Energy Reviews, vol. 55, pp. 957-970, March 2016.

[16] J. P. Ram, N. Rajasekar, and M. Miyatake, “Design and Overview of Maximum Power Point Tracking Techniques in Wind and Solar Photovoltaic Systems: A Review,” Renewable and Sustainable Energy Reviews, vol. 73, pp. 1138-1159, June 2017.

[17] E. J. N. Menezes, A. M. Araújo, and N. S. B. da Silva, “A Review on Wind Turbine Control and Its Associated Methods,” Journal of Cleaner Production, vol. 174, pp. 945-953, February 2018.

[18] O. Ozgener and L. Ozgener, “Exergy and Reliability Analysis of Wind Turbine Systems: A Case Study,” Renewable and Sustainable Energy Reviews, vol. 11, no. 8, pp. 1811-1826, October 2007.

[19] O. Ozgener, “A Small Wind Turbine System (SWTS) Application and Its Performance Analysis,” Energy Conversion and Management, vol. 47, no. 11-12, pp. 1326-1337, July 2006.

[20] O. Baskut, O. Ozgener, and L. Ozgener, “Effects of Meteorological Variables on Exergetic Efficiency of Wind Turbine Power Plants,” Renewable and Sustainable Energy Reviews, vol. 14, no. 9, pp. 3237-3241, December 2010.

[21] O. Baskut, O. Ozgener, and L. Ozgener, “Second Law Analysis of Wind Turbine Power Plants: Cesme, Izmir Example,” Energy, vol. 36, no. 5, pp. 2535-2542, May 2011.

[22] S. Manna, A. K. Akella, and D. K. Singh, “A Novel MRAC-MPPT Scheme to Enhance Speed and Accuracy in PV Systems,” Iranian Journal of Science and Technology, Transactions of Electrical Engineering, in press. https://doi.org/10.1007/s40998-022-00542-0

[23] 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, pp. 1288-1305, November 2015.

[24] Y. E. Tous, “Pitch Angle Control of Variable Speed Wind Turbine,” American Journal of Engineering and Applied Sciences, vol. 1, no. 2, pp. 118-120, June 2008.

[25] B. Lu, Y. Li, X. Wu, and Z. Yang, “A Review of Recent Advances in Wind Turbine Condition Monitoring and Fault Diagnosis,” IEEE Power Electronics and Machines in Wind Applications, article no. 5208325, June 2009.

[26] E. Muljadi and C. P. Butterfield, “Pitch-Controlled Variable-Speed Wind Turbine Generation,” IEEE Transactions on Industry Applications, vol. 37, no. 1, pp. 240-246, January-Febuary 2001.

[27] W. Tong, Wind Power Generation and Wind Turbine Design, 1st ed., Boston: WIT Press, 2010.

[28] X. X. Yin, Y. G. Lin, W. Li, Y. J. Gu, X. J. Wang, and P. F. Lei, “Design, Modeling and Implementation of a Novel Pitch Angle Control System for Wind Turbine,” Renewable Energy, vol. 81, pp. 599-608, September 2015.

[29] Y. Kong and Z. Wang, “Modelling and Analysing the Hydraulic Variable-Pitch Mechanism for a Variable-Speed Wind Turbine,” Wind Engineering, vol. 31, no. 5, pp. 341-352, October 2007.

[30] M. H. Chiang, “A Novel Pitch Control System for a Wind Turbine Driven by a Variable-Speed Pump-Controlled Hydraulic Servo System,” Mechatronics, vol. 21, no. 4, pp. 753-761, June 2011.

[31] X. Yang, J. Li, W. Liu, and P. Guo, “Petri Net Model and Reliability Evaluation for Wind Turbine Hydraulic Variable Pitch Systems,” Energies, vol. 4, no. 6, pp. 978-997, June 2011.

[32] L. Chen, F. Shi, and R. Patton, “Active FTC for Hydraulic Pitch System for an Off-Shore Wind Turbine,” Conference on Control and Fault-Tolerant Systems (SysTol), pp. 510-515, October 2013.

[33] H. Geng and G. Yang, “Linear and Nonlinear Schemes Applied to Pitch Control of Wind Turbines,” The Scientific World Journal, vol. 2014, article no. 406382, September 2014.

[34] P. J. Tanver, J. P. Xiang, and F. Spinato, “Reliability Analysis for Wind Turbines,” Wind Energy, vol. 10, no. 1, pp. 1-18, January/February 2007.

[35] E. Hau and H. Renouard, “Wind-Turbines Fundamentals, Technologies, Application, Economics,” IEEE Electrical Insulation Magazine, vol. 19, no. 2, pp. 48-48, March-April 2003.

[36] A. M. Knight and G. E. Peters, “Simple Wind Energy Controller for an Expanded Operating Range,” IEEE Transactions on Energy Conversion, vol. 20, no. 2, pp. 459-466, June 2005.

[37] W. J. Rugh and J. S. Shamma, “Research on Gain Scheduling,” Automatica, vol. 36, no. 10, pp. 1401-1425, October 2000.

[38] J. Zhang, M. Cheng, Z. Chen, and X. Fu, “Pitch Angle Control for Variable Speed Wind Turbines,” Third International Conference on Electric Utility Deregulation and Restructuring and Power Technologies, pp. 2691-2696, April 2008.

[39] C. Jauch, S. M. Islam, P. Sørensen, and B. B. Jensen, “Design of a Wind Turbine Pitch Angle Controller for Power System Stabilisation,” Renewable Energy, vol. 32, no. 14, pp. 2334-2349, November 2007.

[40] J. Wang, N. Tse, and Z. Gao, “Synthesis on PI-Based Pitch Controller of Large Wind Turbines Generator,” Energy Conversion and Management, vol. 52, no. 2, pp. 1288-1294, February 2011.

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

[42] M. Qian, N. Chen, L. Zhao, D, Zhao, and L. Zhu, “A New Pitch Control Strategy for Variable-Speed Wind Generator,” IEEE PES Innovative Smart Grid Technologies, article no. 6303274, May 2012.

[43] Y. Zhang, M. Cheng, and Z. Chen, “Load Mitigation of Unbalanced Wind Turbines Using PI-R Individual Pitch Control,” IET Renewable Power Generation, vol. 9, no. 3, pp. 262-271, April 2015.

[44] S. Bouabdallah, A. Noth, and R. Siegwart, “PID vs LQ Control Techniques Applied to an Indoor Micro Quadrotor,” IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), vol. 3, pp. 2451-2456, September-October 2004.

[45] B. Beltran, T. Ahmed-Ali, and M. E. H. Benbouzid, “High-Order Sliding-Mode Control of Variable-Speed Wind Turbines,” IEEE Transactions on Industrial Electronics, vol. 56, no. 9, pp. 3314-3321, September 2009.

[46] H. Geng and G. Yang, “Output Power Control for Variable-Speed Variable-Pitch Wind Generation Systems,” IEEE Transactions on Energy Conversion, vol. 25, no. 2, pp. 494-503, June 2010.

[47] J. Laks, L. Pao, and A. Wright, “Combined Feed-Forward/Feedback Control of Wind Turbines to Reduce Blade Flap Bending Moments,” 47th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition, article no. 6.2009-687, January 2009.

[48] X. Yao, S. Liu, G. Shan, Z. Xing, C. Guo, and C. Yi, “LQG Controller for a Variable Speed Pitch Regulated Wind Turbine,” International Conference on Intelligent Human-Machine Systems and Cybernetics, vol. 2, pp. 210-213, August 2009.

[49] S. Muller, M. Deicke, and R. W. De Doncker, “Doubly Fed Induction Generator Systems for Wind Turbines,” IEEE Industry Applications Magazine, vol. 8, no. 3, pp. 26-33, May-June 2002.

[50] M. J. Hossain, H. R. Pota, V. A. Ugrinovskii, and R. A. Ramos, “Simultaneous STATCOM and Pitch Angle Control for Improved LVRT Capability of Fixed-Speed Wind Turbines,” IEEE Transactions on Sustainable Energy, vol. 1, no. 3, pp. 142-151, October 2010.

[51] F. Dunne, L. Y. Pao, A. D. Wright, B. Jonkman, and N. Kelley, “Adding Feedforward Blade Pitch Control to Standard Feedback Controllers for Load Mitigation in Wind Turbines,” Mechatronics, vol. 21, no. 4, pp. 682-690, June 2011.

[52] M. Soliman, O. P. Malik, and D. T. Westwick, “Multiple Model Predictive Control for Wind Turbines with Doubly Fed Induction Generators,” IEEE Transactions on Sustainable Energy, vol. 2, no. 3, pp. 215-225, July 2011.

[53] E. Iyasere, M. Salah, D. Dawson, J. Wagner, and E. Tatlicioglu, “Optimum Seeking-Based Non-Linear Controller to Maximise Energy Capture in a Variable Speed Wind Turbine,” IET Control Theory & Applications, vol. 6, no. 4, pp. 526-532, March 2012.

[54] H. M. Hassan, A. L. ElShafei, W. A. Farag, and M. S. Saad, “A Robust LMI-Based Pitch Controller for Large Wind Turbines,” Renewable Energy, vol. 44, pp. 63-71, August 2012.

[55] A. Jain, G. Schildbach, L. Fagiano, and M. Morari, “On the Design and Tuning of Linear Model Predictive Control for Wind Turbines,” Renewable Energy, vol. 80, pp. 664-673, August 2015.

[56] Y. Zhang, Z. Chen, W. Hu, and M. Cheng, “Flicker Mitigation by Individual Pitch Control of Variable Speed Wind Turbines with DFIG,” IEEE Transactions on Energy Conversion, vol. 29, no. 1, pp. 20-28, March 2014.

[57] H. J. Asl and J. Yoon, “Power Capture Optimization of Variable-Speed Wind Turbines Using an Output Feedback Controller,” Renewable Energy, vol. 86, pp. 517-525, February 2016.

[58] H. Moradi and G. Vossoughi, “Robust Control of the Variable Speed Wind Turbines in the Presence of Uncertainties: A Comparison between $H\infty$ and PID controllers,” Energy, vol. 90, no. 2, pp. 1508-1521, October 2015.

[59] R. Saravanakumar and D. Jena, “Validation of an Integral Sliding Mode Control for Optimal Control of a Three Blade Variable Speed Variable Pitch Wind Turbine,” International Journal of Electrical Power & Energy Systems, vol. 69, pp. 421-429, July 2015.

[60] A. Lasheen, M. S. Saad, H. M. Emara, and A. L. Elshafei, “Robust Model Predictive Control for Collective Pitch in Wind Energy Conversion Systems,” IFAC-PapersOnLine, vol. 50, no. 1, pp. 8746-8751, July 2017.

[61] A. Lasheen, M. Elnaggar, and H. Yassin, “Adaptive Control Design and Implementation for Collective Pitch in Wind Energy Conversion Systems,” ISA Transactions, vol. 102, pp. 251-263, July 2020.

[62] X. Yin, W. Zhang, Z. Jiang, and L. Pan, “Adaptive Robust Integral Sliding Mode Pitch Angle Control of an Electro-Hydraulic Servo Pitch System for Wind Turbine,” Mechanical Systems and Signal Processing, vol. 133, article no. 105704, November 2019.

[63] 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 Transactions, vol. 96, pp. 95-102, January 2020.

[64] Q. Yang, X. Jiao, Q. Luo, Q. Chen, and Y. Sun, “L1 Adaptive Pitch Angle Controller of Wind Energy Conversion Systems,” ISA Transactions, vol. 103, pp. 28-36, August 2020.

[65] M. M. Khasraghi, M. A. G. Sefidkouhi, and M. Valipour, “Simulation of Open- and Closed-End Border Irrigation Systems Using SIRMOD,” Archives of Agronomy and Soil Science, vol. 61, no. 7, pp. 929-941, 2015.

[66] M. Valipour, “Optimization of Neural Networks for Precipitation Analysis in a Humid Region to Detect Drought and Wet Year Alarms,” Meteorological Applications, vol. 23, no. 1, pp. 91-100, January 2016.

[67] M. Valipour, M. E. Banihabib, and S. M. R. Behbahani, “Comparison of the ARMA, ARIMA, and the Autoregressive Artificial Neural Network Models in Forecasting the Monthly Inflow of Dez Dam Reservoir,” Journal of Hydrology, vol. 476, pp. 433-441, January 2013.

[68] M. Valipour, M. A. G. Sefidkouhi, and S. Eslamian, “Surface Irrigation Simulation Models: A Review,” International Journal of Hydrology Science and Technology, vol. 5, no. 1, pp. 51-70, May 2015.

[69] M. Valipour, “Sprinkle and Trickle Irrigation System Design Using Tapered Pipes for Pressure Loss Adjusting,” Journal of Agricultural Science, vol. 4, no. 12, pp. 125-133, 2012.

[70] A. S. Yilmaz and Z. Özer , “Pitch Angle Control in Wind Turbines above the Rated Wind Speed by Multi-Layer Perceptron and Radial Basis Function Neural Networks,” Expert Systems with Applications, vol. 36, no. 6, pp. 9767-9775, August 2009.

[71] R. M. Kamel, A. Chaouachi, and K. Nagasaka, "Enhancement of Micro-Grid Performance during Islanding Mode Using Storage Batteries and New Fuzzy Logic Pitch Angle Controller," Energy Conversion and Management, vol. 52, no. 5, pp. 2204-2216, May 2011.

[72] M. A. Chowdhury, N. Hosseinzadeh, and W. X. Shen, "Smoothing Wind Power Fluctuations by Fuzzy Logic Pitch Angle Controller," Renewable Energy, vol. 38, no. 1, pp. 224-233, February 2011.

[73] H. Jafarnejadsani, J. Pieper, and J. Ehlers, "Adaptive Control of a Variable-Speed Variable-Pitch Wind Turbine Using Radial-Basis Function Neural Network," IEEE Transactions on Control Systems Technology, vol. 21, no. 6, pp. 2264-2272, November 2013.

[74] R. M. Kamel, A. Chaouachi, and K. Nagasaka, "Three Control Strategies to Improve the Microgrid Transient Dynamic Response during Isolated Mode: A Comparative Study," IEEE Transactions on Industrial Electronics, vol. 60, no. 4, pp. 1314-1322, April 2013.

[75] T. L. Van, T. H. Nguyen, and D. C. Lee, "Advanced Pitch Angle Control Based on Fuzzy Logic for Variable-Speed Wind Turbine Systems," IEEE Transactions on Energy Conversion, vol. 30, no. 2, pp. 578-587, June 2015.

[76] I. Villanueva, P. Ponce, and A. Molina, "Interval Type 2 Fuzzy Logic Controller for Rotor Voltage of a Doubly-Fed Induction Generator and Pitch Angle of Wind Turbine Blades," IFAC-PapersOnLine, vol. 48, no. 3, pp. 2195-2202, 2015.

[77] Z. Liu, F. Huo, S. Xiao, X. Zhang, S. Zhu, G. Ji, et al., "Individual Pitch Control of Wind Turbine Based on RBF Neural Network," 35th Chinese Control Conference (CCC), pp. 5769-5773, July 2016.

[78] A. Dahbi, N. Nait-Said, and M. S. Nait-Said, "A Novel Combined MPPT-Pitch Angle Control for Wide Range Variable Speed Wind Turbine Based on Neural Network," International Journal of Hydrogen Energy, vol. 41, no. 22, pp. 9427-9442, June 2016.

[79] E. K. E. Mjabber, A. ElHajjaji, and A. Khamlichi, "Analysis of a RBF Neural Network Based Controller for Pitch Angle of Variable-Speed Wind Turbines," Procedia Engineering, vol. 181, pp. 552-559, 2017.

[80] R. Tiwari, N. R. Babu, and P. Sanjeevikumar, "Fuzzy Logic-Based Pitch Angle Controller for PMSG-Based Wind Energy Conversion System," Advances in Smart Grid and Renewable Energy, vol. 435, pp. 277-286, October 2017.

[81] M. A. Abdullah, A. H. M. Yatim, C. W. Tan, and A. S. Samosir, "Particle Swarm Optimization-Based Maximum Power Point Tracking Algorithm for Wind Energy Conversion System," IEEE International Conference on Power and Energy (PECon), pp. 65-70, December 2012.

[82] T. Senjyu, R. Sakamoto, N. Urasaki,T. Funabashi, and H. Sekine, "Output Power Leveling of Wind Farm Using Pitch Angle Control with Fuzzy Neural Network," IEEE Power Engineering Society General Meeting, article no. 1709377, June 2006.

[83] W. M. Lin, C. M. Hong, T. C. Ou, and T. M.Chiu, "Hybrid Intelligent Control of PMSG Wind Generation System Using Pitch Angle Control with RBFN," Energy Conversion and Management, vol. 52, no. 2, pp. 1244-1251, February 2011.

[84] W. Lin and C. M. Hong, "A New Elman Neural Network-Based Control Algorithm for Adjustable-Pitch Variable-Speed Wind-Energy Conversion Systems," IEEE Transactions on Power Electronics, vol. 26, no. 2, pp. 473-481, February 2011.

[85] I. Poultangari, R. Shahnazi, and M. Sheikhan, "RBF Neural Network Based PI Pitch Controller for a Class of 5-MW Wind Turbines Using Particle Swarm Optimization Algorithm," ISA Transactions, vol. 51, no. 5, pp. 641-648, September 2012.

[86] A. H. M. A. Rahim and S. A. Raza, "A Differential Evolution Based Adaptive Neural Network Pitch Controller for a Doubly Fed Wind Turbine Generator System," Research Journal of Applied Sciences, Engineering and Technology, vol. 6, no. 22, pp. 4271-4280, December 2013.

[87] S. A.Taher, M. Farshadnia, and M. R. Mozdianfard, "Optimal Gain Scheduling Controller Design of a Pitch-Controlled VS-WECS Using DE Optimization Algorithm," Applied Soft Computing, vol. 13, no. 5, pp. 2215-2223, May 2013.

[88] M. Q. Duong, F. Grimaccia, S. Leva, M. Mussetta, and E. Ogliari, "Pitch Angle Control Using Hybrid Controller for All Operating Regions of SCIG Wind Turbine System," Renewable Energy, vol. 70, pp. 197-203, October 2014.

[89] S. R. Mohanty, N. Kishor, and P. K. Ray, "Robust H-Infinite Loop Shaping Controller Based on Hybrid PSO and Harmonic Search for Frequency Regulation in Hybrid Distributed Generation System," International Journal of Electrical Power & Energy Systems, vol. 60, pp. 302-316, September 2014.

[90] A. Lasheen and A. L. Elshafei, "Wind-Turbine Collective-Pitch Control via a Fuzzy Predictive Algorithm," Renewable Energy, vol. 87, no. 1, pp. 298-306, March 2016.

[91] A. Asgharnia, R. Shahnazi, and A. Jamali, "Performance and Robustness of Optimal Fractional Fuzzy PID Controllers for Pitch Control of a Wind Turbine Using Chaotic Optimization Algorithms," ISA Transactions, vol. 79, pp. 27-44, August 2018.

[92] D. Pathak and P. Gaur, "A Fractional Order Fuzzy-Proportional-Integral-Derivative Based Pitch Angle Controller for a Direct-Drive Wind Energy System," Computers and Electrical Engineering, vol. 78, pp. 420-436, September 2019.

[93] O. P. Mahela and A. GafoorShaik, “Comprehensive Overview of Grid Interfaced Wind Energy Generation Systems,” Renewable and Sustainable Energy Reviews, vol. 57, pp. 260-281, May 2016.

[94] W. M. Lin and C. M. Hon, “Intelligent Approach to Maximum Power Point Tracking Control Strategy for Variable-Speed Wind Turbine Generation System,” Energy, vol. 35, no. 6, pp. 2440-2447, June 2010.

[95] H. Yokoyama, F. Tatsuta, and S. Nishikata, “Tip Speed Ratio Control of Wind Turbine Generating System Connected in Series,” International Conference on Electrical Machines and Systems, article no. 6073595, August 2011.

[96] D. R. Song, J. Yang, Z. Cai, M. Dong, M. Su, and Y. Wang, “Wind Estimation with a Non-Standard Extended Kalman Filter and Its Application on Maximum Power Extraction for Variable Speed Wind Turbines,” Applied Energy, vol. 190, pp. 670-685, March 2017.

[97] D. Song, J. Yang, M. Su, A. Liu, Y. Liu, and H. J. Young, “A Comparison Study between Two MPPT Control Methods for a Large Variable-Speed Wind Turbine under Different Wind Speed Characteristics,” Energies, vol. 10, no. 5, article no. 613, May 2017.

[98] Y. Saidi, A. Mezouar, Y. Miloud, M. Yahiaoui, and M. A. Benmahdjoub, “Modeling and Adaptive Power Control-Designed Based on Tip Speed Ratio Method for Wind Turbines,” Przeglad Elektrotechniczny, vol. 2019, no. 6, pp. 40-46, 2019.

[99] İ. Yazıcı and E. K. Yaylacı, “Improving Efficiency of the Tip Speed Ratio-MPPT Method for Wind Energy Systems by Using an Integral Sliding Mode Voltage Regulator,” Journal of Energy Resources Technology, vol. 140, no. 5, article no. 051203, May 2018.

[100] M. Nasiri, J. Milimonfared, and S. H. Fathi, “Modeling, Analysis and Comparison of TSR and OTC Methods for MPPT and Power Smoothing in Permanent Magnet Synchronous Generator-Based Wind Turbines,” Energy Conversion and Management, vol. 86, pp. 892-900, October 2014.

[101] S. Ganjefar, A. A. Ghassemi, and M. M. Ahmadi, “Improving Efficiency of Two-Type Maximum Power Point Tracking Methods of Tip-Speed Ratio and Optimum Torque in Wind Turbine System Using a Quantum Neural Network,” Energy, vol. 67, pp. 444-453, April 2014.

[102] S. M. Barakati, “Modeling and Controller Design of a Wind Energy Conversion System Including a Matrix Converter,” Ph.D. dissertation, Department of Electrical and Computer Engineering, University of Waterloo, Waterloo, Ontario, 2008.

[103] S. M. Barakati, M. Kazerani, and J. D. Aplevich, “Maximum Power Tracking Control for a Wind Turbine System Including a Matrix Converter,” IEEE Transactions on Energy Conversion, vol. 24, no. 3, pp. 705-713, September 2009.

[104] Q. Wang and L. Chang, “An Intelligent Maximum Power Extraction Algorithm for Inverter-Based Variable Speed Wind Turbine Systems,” IEEE Transactions on Power Electronics, vol. 19, no. 5, pp. 1242-1249, September 2004.

[105] Y. Daili, J. P. Gaubert, and L. Rahmani, “Implementation of a New Maximum Power Point Tracking Control Strategy for Small Wind Energy Conversion Systems without Mechanical Sensors,” Energy Conversion and Management, vol. 97, pp. 298-306, June 2015.

[106] R. M. Linus and P. Damodharan, “Maximum Power Point Tracking Method Using a Modified Perturb and Observe Algorithm for Grid Connected Wind Energy Conversion Systems,” IET Renewable Power Generation, vol. 9, no. 6, pp. 682-689, August 2015.

[107] Z. M. Dalala, Z. U. Zahid, and J. S. Lai, “New Overall Control Strategy for Small-Scale WECS in MPPT and Stall Regions with Mode Transfer Control,” IEEE Transactions on Energy Conversion, vol. 28, no. 4, pp. 1082-1092, December 2013.

[108] A. Soetedjo, A. Lomi, and W. P. Mulayanto, “Modeling of Wind Energy System with MPPT Control,” International Conference on Electrical Engineering and Informatics, article no. 6021836, July 2011.

[109] Z. M. Dalala, Z. U. Zahid, W. Yu, Y. Cho, and J. S. Lai, “Design and Analysis of an MPPT Technique for Small-Scale Wind Energy Conversion Systems,” IEEE Transactions on Energy Conversion, vol. 28, no. 3, pp. 756-767, September 2013.

[110] K. S. M. Raza, H. Goto, H. J. Guo, and O. Ichinokura, “A Novel Algorithm for Fast and Efficient Maximum Power Point Tracking of Wind Energy Conversion Systems,” 18th International Conference on Electrical Machines, article no. 4800030, September 2008.

[111] Y. Zhu, M. Cheng, W. Hua, and W. Wang, “A Novel Maximum Power Point Tracking Control for Permanent Magnet Direct Drive Wind Energy Conversion Systems,” Energies, vol. 5, no. 5, pp. 1398-1412, May 2012.

[112] H. H. H. Mousa, A. R. Youssef, and E. E. M. Mohamed, “Variable Step Size P&O MPPT Algorithm for Optimal Power Extraction of Multi-Phase PMSG Based Wind Generation System,” International Journal of Electrical Power & Energy Systems, vol. 108, pp. 218-231, June 2019.

[113] A. R. Youssef, H. H. H. Mousa, and E. E. M. Mohamed, "Development of Self-Adaptive P&O MPPT Algorithm for Wind Generation Systems with Concentrated Search Area," Renewable Energy, vol. 154, pp. 875-893, July 2020.

[114] K. N. Yu and C. K. Liao, "Applying Novel Fractional Order Incremental Conductance Algorithm to Design and Study the Maximum Power Tracking of Small Wind Power Systems," Journal of Applied Research and Technology, vol. 13, no. 2, pp. 238-244, April 2015.

[115] S. H. Hosseini, A. Farakhor, and S. K. Haghighian, "Novel Algorithm of Maximum Power Point Tracking (MPPT) for Variable Speed PMSG Wind Generation Systems through Model Predictive Control," 8th International Conference on Electrical and Electronics Engineering (ELECO), pp. 243-247, November 2013.

[116] M. A. Abdullah, A. H. M. Yatim, and C. W. Tan, "An Online Optimum-Relation-Based Maximum Power Point Tracking Algorithm for Wind Energy Conversion System," Australasian Universities Power Engineering Conference (AUPEC), article no. 6966524, September-October 2014.

[117] R. Sitharthan, M. Karthikeyan, D. S. Sundar, and S. Rajasekaran, "Adaptive Hybrid Intelligent MPPT Controller to Approximate Effectual Wind Speed and Optimal Rotor Speed of Variable Speed Wind Turbine," ISA Transactions, vol. 96, pp. 479-489, January 2020.

[118] H. H. H. Mousa, A. R. Youssef, and E. E. M. Mohamed, "Hybrid and Adaptive Sectors P&O MPPT Algorithm Based Wind Generation System," Renewable Energy, vol. 145, pp. 1412-1429, January 2020.

[119] Z. Chen, S. A. Gomez, and M. McCormick, "A Fuzzy Logic Controlled Power Electronic System for Variable Speed Wind Energy Conversion Systems," Eighth International Conference on Power Electronics and Variable Speed Drives, pp. 114-119, September 2000.

[120] A. Z. Mohamed, M. N. Eskander, and F. A. Ghali, "Fuzzy Logic Control Based Maximum Power Tracking of a Wind Energy System," Renewable Energy, vol. 23, no. 2, pp. 235-245, June 2001.

[121] A. G. Abo-Khalil, D. C. Lee, and J. K. Seok, "Variable Speed Wind Power Generation System Based on Fuzzy Logic Control for Maximum Output Power Tracking," IEEE 35th Annual Power Electronics Specialists Conference, vol. 3, pp. 2039-2043, June 2004.

[122] V. Galdi, A. Piccolo, and P. Siano, "Designing an Adaptive Fuzzy Controller for Maximum Wind Energy Extraction," IEEE Transactions on Energy Conversion, vol. 23, no. 2, pp. 559-569, June 2008.

[123] K. Belmokhtar, M. L. Doumbia, and K. Agbossou, "Novel Fuzzy Logic Based Sensorless Maximum Power Point Tracking Strategy for Wind Turbine Systems Driven DFIG (Doubly-Fed Induction Generator)," Energy, vol. 76, pp. 679-693, November 2014.

[124] R. Tiwari and N. R. Babu, "Fuzzy Logic Based MPPT for Permanent Magnet Synchronous Generator in Wind Energy Conversion System," IFAC-PapersOnLine, vol. 49, no. 1, pp. 462-467, February 2016.

[125] S. Heshmatian, A. Kazemi, M. Khosravi, and D. A. Khaburi, "Fuzzy Logic Based MPPT for a Wind Energy Conversion System Using Sliding Mode Control," 8th Power Electronics, Drive Systems & Technologies Conference (PEDSTC), pp. 335-340, February 2017.

[126] A. A. Salem, N. A. N. Aldin, A. M. Azmy, and W. S. E. Abdellatif, "A Fuzzy Logic-Based MPPT Technique for PMSG Wind Generation System," International Journal of Renewable Energy Research-IJRER, vol. 9, no. 4, pp. 1751-1760, December 2019.

[127] H. Li, K. L. Shi, and P. G. McLaren, "Neural-Network-Based Sensorless Maximum Wind Energy Capture with Compensated Power Coefficient," IEEE Transactions on Industry Applications, vol. 41, no. 6, pp. 1548-1556, November-December 2005.

[128] K. Ro and H. H. Choi, "Application of Neural Network Controller for Maximum Power Extraction of a Grid-Connected Wind Turbine System," Electrical Engineering, vol. 88, no. 1, pp. 45-53, November 2005.

[129] M. Pucci and M. Cirrincione, "Neural MPPT Control of Wind Generators with Induction Machines without Speed Sensors," IEEE Transactions on Industrial Electronics, vol. 58, no. 1, pp. 37-47, January 2011.

[130] W. Qiao, W. Zhou, J. M. Aller, and R. G. Harley, "Wind Speed Estimation Based Sensorless Output Maximization Control for a Wind Turbine Driving a DFIG," IEEE Transactions on Power Electronics, vol. 23, no. 3, pp. 1156-1169, May 2008.

[131] M. Cirrincione, M. Pucci, and G. Vitale, "Neural MPPT of Variable-Pitch Wind Generators with Induction Machines in a Wide Wind Speed Range," IEEE Transactions on Industry Applications, vol. 49, no. 2, pp. 942-953, March-April 2013.

[132] R. Kumar, H. P. Agrawal, A. Shah, and H. O. Bansal, "Maximum Power Point Tracking in Wind Energy Conversion System Using Radial Basis Function Based Neural Network Control Strategy," Sustainable Energy Technologies and Assessments, vol. 36, article no. 100533, December 2019.

[133] A. Medjber, A. Guessoum, H. Belmili, and A. Mellit, “New Neural Network and Fuzzy Logic Controllers to Monitor Maximum Power for Wind Energy Conversion System,” Energy, vol. 106, pp. 137-146, July 2016.

[134] J. Hussain and M. K. Mishra, “Adaptive Maximum Power Point Tracking Control Algorithm for Wind Energy Conversion Systems,” IEEE Transactions on Energy Conversion, vol. 31, no. 2, pp. 697-705, June 2016.

[135] B. M. Wilamowski and J. D. Irwin, The Industrial Electronics Handbook: Power Electronics and Motor Drives, 2nd ed., UK: CRC Press, 2011.

[136] N. Freire, J. Estima, and A. Cardoso, “A Comparative Analysis of PMSG Drives Based on Vector Control and Direct Control Techniques for Wind Turbine Applications,” Przeglad Elektrotechniczny, vol. 2012, no. 1a, pp. 184-187, 2012.

[137] M. Allagui, O. B.k. Hasnaoui, J. Belhadj, “A 2MW Direct Drive Wind Turbine; Vector Control and Direct Torque Control Techniques Comparison,” Journal of Energy in Southern Africa, vol. 25, no. 2, pp. 117-126, Jun 2014.

[138] M. E. Emna, K. Adel, and M. F. Mimouni, “The Wind Energy Conversion System Using PMSG Controlled by Vector Control and SMC Strategies,” International Journal of Renewable Energy Research, vol. 3, no.1, pp. 41-50, March 2013.

[139] S. R. Bowes, S. Grewal, and D. Holliday, “Novel Adaptive Hysteresis Band Modulation Strategy for Three-Phase Inverters,” IEE Proceedings - Electric Power Applications, vol. 148, no. 1, pp. 51-61, January 2001.

[140] M. Merzoug and F. Naceri, “Comparison of Field-Oriented Control and Direct Torque Control for Permanent Magnet Synchronous Motor (PMSM),” World Academy of Science, Engineering and Technology, Open Science Index 21, International Journal of Electrical and Computer Engineering, vol. 2, no. 9, pp. 1797-1802, 2008.

[141] S. Li, T. A. Haskew, R. P. Swatloski, and W. Gathings, “Optimal and Direct-Current Vector Control of Direct-Driven PMSG Wind Turbines,” IEEE Transactions on Power Electronics, vol. 27, no. 5, pp. 2325-2337, May 2012.

[142] T. K. A. Brekken and N. Mohan, “Control of a Doubly Fed Induction Wind Generator under Unbalanced Grid Voltage Conditions,” IEEE Transactions on Energy Conversion, vol. 22, no. 1, pp. 129-135, March 2007.

[143] J. Dai, D. Xu, and B. Wu, “A Novel Control Scheme for Current-Source-Converter-Based PMSG Wind Energy Conversion Systems,” IEEE Transactions on Power Electronics, vol. 24, no. 4, pp. 963-972, April 2009.

[144] J. Dannehl, C. Wessels, and F. W. Fuchs, “Limitations of Voltage-Oriented PI Current Control of Grid-Connected PWM Rectifiers with LCL Filters,” IEEE Transactions on Industrial Electronics, vol. 56, no. 2, pp. 380-388, February 2009.

[145] V. Le, X. Li, Y. Li, T. L. T. Dong, and C. Le, “An Innovative Control Strategy to Improve the Fault Ride-Through Capability of DFIGs Based on Wind Energy Conversion Systems,” Energies, vol. 9, no. 2, article no. 69, February 2016.

[146] M. J. Morshed and A. Fekih, “A New Fault Ride-Through Control for DFIG-Based Wind Energy Systems,” Electric Power Systems Research, vol. 146, pp. 258-269, May 2017.

[147] M. A. S. Ali, K. K. Mehmood, S. Baloch, and C. H. Kim, “Modified Rotor-Side Converter Control Design for Improving the LVRT Capability of a DFIG-Based WECS,” Electric Power Systems Research, vol. 186, article no. 106403, September 2020.

[148] C. R. Raghavendran, J. P. Roselyn, U. Sowmmiya, and D. Devaraj, “Effective Power Transfer and Reduced-Order Generalized Integrator Sequence Based Fault Ride Through Strategy in Grid Connected DFIG Based WECS,” International Journal of Electrical Power & Energy Systems, vol. 130, article no. 106809, September 2021.

[149] D. M. Vilathgamuwa, X. Wang, C. J. Gajanayake, “Z-Source Converter Based Grid-Interface for Variable-Speed Permanent Magnet Wind Turbine Generators,” IEEE Power Electronics Specialists Conference, pp. 4545-4550, June 2008.

[150] B. Andresen and J. Birk, “A High Power Density Converter System for the Gamesa G10x 4,5 MW Wind Turbine,” European Conference on Power Electronics and Applications, article no. 4417312, September 2007.

[151] F. Z. Peng, “Z-Source Inverter,” IEEE Transactions on Industry Applications, vol. 39, no. 2, pp. 504-510, March-April 2003.

[152] X. D. T. Garcia, B. Zigmund, A. A. Terlizzi, R. Pavlanin, and L. Salvatore, “Comparison between FOC and DTC Strategies for Permanent Magnet Synchronous Motors,” Advances in Electrical and Electronic Engineering, vol. 5, no. 1, pp. 76-81, March-June 2006.