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Different Types of Pitch Angle Control Strategies Used in Wind Turbine System Applications

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A B S T R A C T

Wind energy is the most accessible source and is one of the fastest growing renewable energy systems. If this energy is exploited properly and well-suited to the turbine system, it would have the ability to compete economically and even be superior to other sources. For this purpose, in the high wind speed areas different methods are applied in the bases of harvesting as much wind energy as possible with respect to harness rotor speed at the rated value. In this paper, an extensive literature review on control and manufacturing strategies in power production and system performance of wind energy conversion system (WECS) has been highlighted. Classic control, adaptive non-linear control, robust control and intelligent control are among the control methods presented in this study. In comparing the controllers, although adaptive and robust controllers, with less sensitivity to changes in environmental conditions, outperformed the classic controller, and the intelligent controller presented better control flexibility and power quality through estimating the system variables and appropriate adaptation to changes at the operating point.

1. INTRODUCTION

As a consequence of technological progress, wind energy usage was increased dramatically in the last years [1-10]. The wind turbines are contributive sources of energy and can be exploited at different levels [11-17]. In order to get the maximum energy from the wind on one side and the aerodynamic requirements for generators on the other, existence and supplication of an accurate controller is necessary which would cover uncertainties [18,19]. This controller can be installed to control the pitches. When the wind speed and as a result, the turbine speed exceeds its nominal values, the pitch controller activates and reduces the wind power by increasing the angle [20-22].

To achieve this objective, various control methods are proposed, among which the proportional-integral (PI) and proportional-integral-derivative (PID) controls are the most common controllers usually designed due to their simplicity and easy implementation [23,24], based on a linear model system, at an operating point [25,26]. In wind turbines, every controllable component includes different disturbances and uncertainties caused by changes in the parameters, due to changes in wind speed or errors in modelling [27,28]. Since the wind turbine system is nonlinear, the operating point of the system is changing in a broad range [29]. But the changes around the operating point are few and they can be considered as linear in a small range [30,31]. By ranging the changes, a better realization of PI control would be achieved. These controllers certainly respond only to a specific range of operating points. Hence the controllers, of such type, have limitations. One of the limitations is lack of controller's adaptability to changes in the operating conditions and system parameters, especially if it is affected by uncertainties and parameter changes [32].

All of these issues can reduce the efficiency of the controllers designed based on a nominal point which might weaken the dynamic response. Due to changes in wind speed, the operating point is subjected to given constant change; therefore, these controllers might not be suitable for all operating points in the systems [33,34].

In recent years, various control methods like: adaptive, robust, predictive and intelligent are introduced for the pitch angle control [35,36]. Adaptive control is one of the most important control methods applied in recent years. The purpose of applying this type of control is to decrease the sensitivity of the systems in relation to changes in parameters. Adaptive controllers usually require a detailed model and a complex parameter estimator which commonly leads to the limitation of this

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type of controllers [37]. Moreover, estimation of the variables of a power system using adaptive control methods is difficult. In robust controllers, not only one of the goals was having a good dynamic response, but also the proper functioning of the system in the case of changes in parameters. Therefore, robust control methods can explain a good physical sense of wind turbine, but due to the non-linear operation of the turbine system, the controller operation might be changed. Therefore, these controllers can be applied along with other controllers [38,39]. Considering the mentioned reasons, the efficiency of the classic, conventional adaptive and robust controls has been reduced in recent years, making the intelligent methods more applicable. In this regard, neural and fuzzy methods and evolutionary algorithms have become the most common controlling methods in WECS [40,41]. The existing intelligent approaches are often taken from nature and the environment where human lives. However, the disadvantage of such type of controllers is that they are very time consuming in producing the coefficient controller to properly control the system [42,43].

In [44], different kinds of advanced controllers in capturing as much as power from WTs are categorized. But the void of intelligent control in this article is a critical point that is worth to complain. In [45], only the predictive control applications in maximizing the power production of WTs were reviewed [46]. Concentrated on coefficients that can be served as general mathematical expressions for each function of WTs to evaluate their behaviors. This article provides an overview in sinusoidal models related to the variations in the pitch angle and there is no discuss regarding the controlling methods. In [47], individual pitch controls, as mitigation for the fluctuating loads of WTs, are reviewed. However, other aspects of pitch control are not discussed.

In this paper, a variety of control strategies and mechanical changes in controlling WECS, specifically the pitch angle and power tracking with respect to the dynamic performance of the system, are discussed and the advantages and disadvantages of each method are reviewed. More than 150 research publications are reviewed and classified broadly into 7 categories.

2. WIND TURBINE CONTROL METHODS AND MANUFACTURING STRATEGIES

The purpose of the blade angle control is to limit the input power to the gearbox, but, in addition to achieving this, the controller should be able to get the maximum power and maintain it at the highest possible levels [48,49]. In maximum power point tracking (MPPT) zone, the blade angle is usually fixed at 10° and in the pitch angle control zone, the blade pitch changes from 10 to 90°, considering the wind speed and the machine dynamic [50-52]. Through this controller, the output power can be increased or decreased in less time than the thermal power or gas turbine plants, commanding the pitch actuator [53]. The pitch actuator sets the blades swing around a longitudinal axis. Hydraulic or electromechanical devices are used as the actuator of the blades. These actuators are nonlinear operators which swing the whole or part of the blade [54]. In a closed-loop WECS, these actuators can be considered as an integrator or a delayed first-order system with a time constant (τ_c). The angle actuator dynamic behavior is presented by following equation [55]:

$$\frac{d\beta}{dt} = \frac{1}{\tau_c}(-\beta + \beta_{ref}) \qquad (1)$$

where, β is the pitch angle and β_{ref} is the reference value of this angle. The pitch angle response depends on time constant of the pitch actuator, which usually ranges between 0.2 to 0.25 seconds [56]. This limiting is necessary for showing the real output of the controller's response. Typically, the β ranges from −2 to 30 degrees (depends on the wind turbine system) and varies at the maximum pitch rate of ±10°/sec [57]. Thus, the rate of change has a significant effect on the performance of power settings. In the following, a variety of control methods to control the blade pitch angle control and maximum power at wind turbines will be elaborated on.

2.1. Blade pitch angle control using PID controller

Due to its simplicity, linearity in functionality, easy implementation in control systems, the PID controller is considered as the most versatile controller [58-61]. Gains of the controller will be regulated either on the basis of human experience and intuition of engineers or by using intelligent methods, or a combination of both [62]. The block diagram of the blade pitch angle control with angle actuator placement by a delayed system which is regulated with a conventional PID controller is shown in Fig. 1.

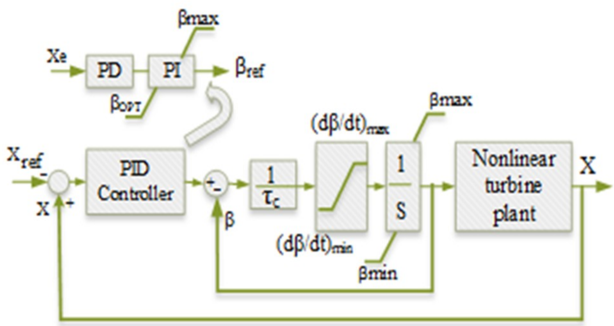

Figure 1. Block diagram of the typical pitch angle control system

The parameter X is either output power or rotor speed. This X will be compared with its reference value X_{ref}

and makes the signal error of X_{ERR}. This X_{ERR} is directed toward PID controller and is recommended for a better sensitive functionality; eventually, it is directed toward PI controller and changes the angle of the reference blade β_{ref}.

According to [63,64], by linearizing the turbine parameters and applying them in design, power production is increased. In designing this controller, the nonlinear dynamic parameters of the wind turbine system is linearized at its own operating point in order to get the optimized values of ($V_{\omega o}$, β_{op}, ω_{rop}). The block diagram of the blade angle control of the wind turbine system with this linearized model by PID controller is shown in Fig. 2 [65]. The γ variable represents the aerodynamic characters of the wind turbine system which should be negative for stability. To maintain the stability in windy areas, $K_i>0$ and $K_P>-1$ must be met. When the operating point of the system changes, the controller gains should be redesigned to maintain the dynamic response and the stability of the system.

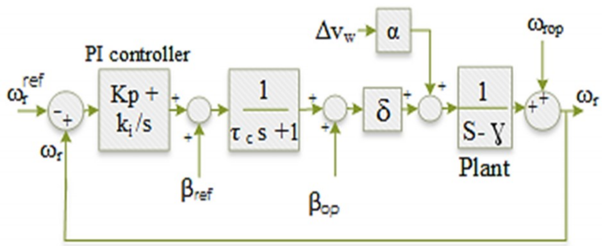

Figure 2. Block diagram of pitch control system using PI controllers for the linearized wind turbine

PID with modified gains is applied to improve the performance of PID controller in wind turbine [66], that is proposed to compensate the changes in the sensitivity of the aerodynamic torque to the blade pitch angle. The block diagram of Fig. 3 shows the design of this controller on the angle actuator. The gains of the angle control loop are presented by K_{sys}. These gains are obtained by multiplying the K_{PI} of this design by dp/dβ. The dp/dβ is the aerodynamic sensitivity of the turbine that depends on the changes in the output power of the generator. To ensure the proper functioning of the blade angle controller in windy areas, K_{PI} is calculated in three categories related to angle of β (follow [67]).

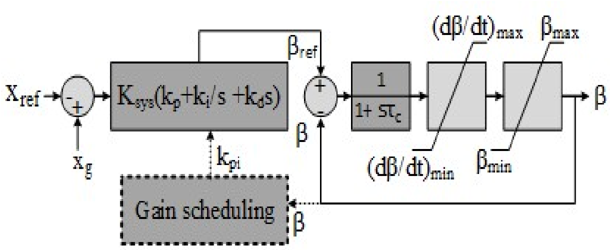

Figure 3. Block diagram of the pitch control system using PI and PID controllers

Today, several methods have been proposed for optimizing the PID controller coefficients. One of these methods is adding a time constant or a zero and pole. Furthermore, the tuned PID regulator can be added to compare the controllers [68]. In [69], different manners in adjusting the pitch angle of the blade of a variable speed wind turbine were presented and discussed. Three controllers, namely PID, fuzzy and adaptive fuzzy PID are designed for an angle actuator in which the conversion function was detected. Mathematical equations and system analysis are based on the block diagram of Fig. 4. By adding extra degree of freedom to the PID controller to get the proper phase margin, considering the frequency stability, this method tries to improve the coefficients.

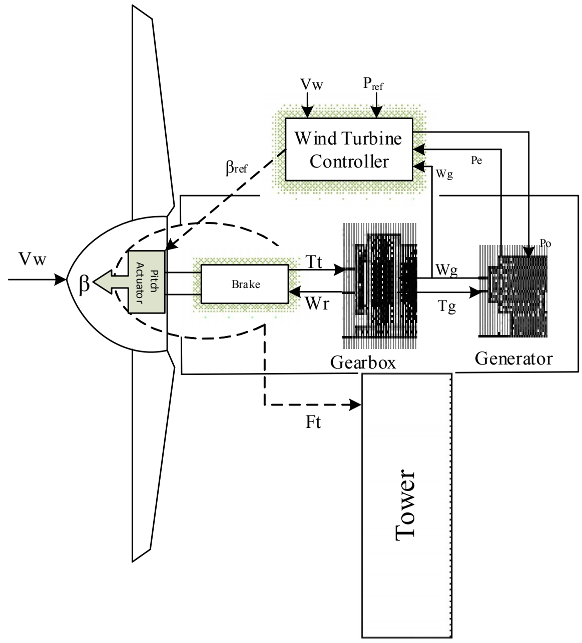

Figure 4. Block diagram of wind turbine model

By receiving feedback from the system output, the controller will be automatically regulated until the proper response is obtained. Coefficients obtained in this manner are: the interest margin of 17.2 dB (3.1 rad/s) and the phase margin of 6.72 degrees (236rad) that represent the desired stability of the system. In pitch control purpose, the fuzzy logic controller is used in regulating the coefficients of the PID controller.

Fuzzy logic has been applied as one of the intelligent manners to adjust the PID controllers [70]. Based on the human experiences, the rules of fuzzy logic are presented in linguistic variables. With the assistance of these rules and implementing the fuzzy state on power systems, better realization of the tracing purpose would be achieved [71,72]. The improved version of this controller, could be used in regulating the PID coefficients. To address this issue and ensure its optimal performance, the fuzzy PID regulator is recommended.

The coefficients of K_p, K_i, and K_d depend on the modified fuzzy entries and are the entries of the system blade angle changes and their derivation of changes. PID coefficients are added with the coefficients of the fuzzy controller and make the new parameters of the PID controller. By receiving feedback from the output and comparing it with the available angle, the system will be regulated at the moment ($K_{pid} = K_{pid\ current} + \Delta K_{pid\ fuzzy.}$). In comparing the controllers it is found that, the fuzzy controller has a higher rise time and lower settling time with no overshoot. In the PID regulator coefficients with fuzzy controller, the control settling time is less than the two previous controllers; however, its rise time is not as that of the rise time of the PID controller. Comparing the simulation by Matlab Simulink is shown in Fig. 5. Features of classical controller is shown in Table 1.

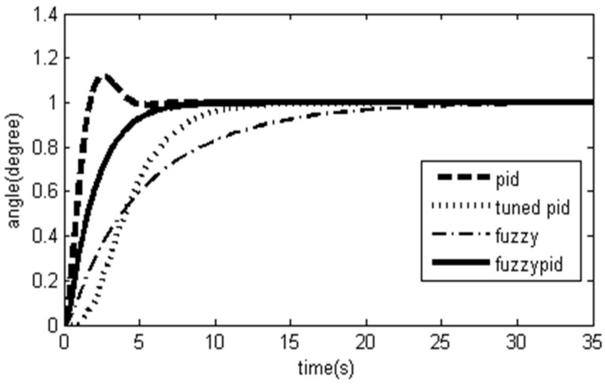

Figure 5. Comparison of unit step response of wind turbine pitch control system

TABLE 1. Features of classical controller

Strategy	Advantage	Disadvantage
Classical-Conventional Controller	- Simplicity - High efficiency -Easy tunable	-Non applicable in non-linear wind turbines - Low performance when sudden change of wind speed occurs - Non applicable in windy areas - Low incoming power with unnecessary adjustment of blade angle

2.2. Torque and blade pitch angle control using adaptive nonlinear methods

Sliding mode control is one of the appropriate methods of nonlinear control since it provides the system with a reliable dynamic robustness when the system faces uncertainties in turbine parameters [73,74]. In controlling wind turbines, the sliding mode should provide a close fit between changes in efficiency and torque fluctuations [75-77].

There exist various strategies regulating the sliding mode control, one of which is expressed in [78]. In this strategy, by selecting the power error as the controlled parameter and estimating its derivation, and with changes in other parameters, the objective of zero error is achieved to a great extent. In the same studies, by selecting the dynamic sliding mode control according to torque deviation, the objective of zero error is accomplished [79,80]. Although sliding modes proposed in these articles are not directly related to the pitch control, they were effective in building an appropriate input for conventional pitch controllers. The controllers are designed through the approximation methods to reduce the chattering effect of generator torque by reducing the effects of turbine parameters and the dynamic pressure on turbine.

To promote the stability, the Lyapunov function, based on the error square and the error square integral, was applied in [79]. Based on the LaSalle theorem, it is concluded that the tracking error has converged to zero in an asymptotical manner. The block diagram of the target system with the following dynamic sliding mode controller can be applied as shown in Fig. 6:

$$\dot{\varepsilon}_p = \dot{P}_{ref} - T_g\,\dot{\omega}_r - (B(t)+\lambda)\,\mathrm{sgn}\left(\frac{\varepsilon_p}{|\varepsilon_p| + a_0}\right) \qquad (2)$$

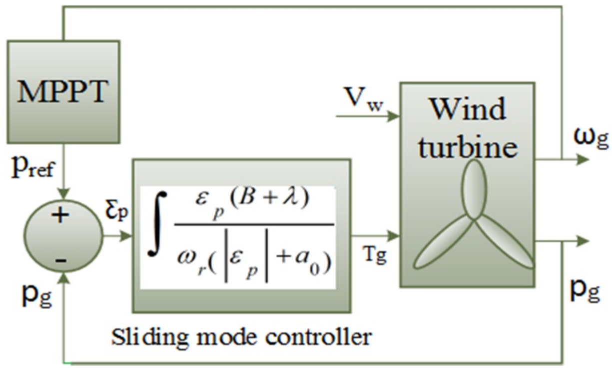

Figure 6. Sliding controller used to wind turbine

where, ε_p is the tracking error, $\lambda<0$, a_0 is a small positive constant and $dB/dt=|\varepsilon_p|$.

P_{ref} (reference of generator power) will be obtained by the strategy of tracking the maximum power and power-speed curve. The sliding mode designed in [78] is implemented by an adaptive gain which increases as long as the error of the extracting power has not reached zero. When zero is achieved using the sliding mode, it is considered as the angle controller input. As a result, the blade angle changes so that more power would be received.

In [81], a sliding controller was used to control the blade angle of a SCIG wind turbine. This controller is effective only when the rotor speed is faster than its nominal speed. In this case, the blade angle is controlled in a manner where this process is reversed. The process of this method follows the sequence of: first, the electrical speed of the rotor is chosen as the state variable; next, the primary sliding surface is defined by the rotor speed to make it converged to its nominal value and remain constant and finally, by selecting K_β as the gain of sliding mode control and with the assistance of the Lyapunov function proving, this controller is implemented. Here, the objective is to control the β_{ref} in Eq. (1), which is realized by the sliding surface. Here, with respect to closed-loop system, a sliding surface in a limited time is achieved. The above mentioned of sliding control has demonstrated a good robustness against uncertainties of turbine parameters, and has improved the stability properties. But, sliding control depends on the mathematical models of the wind turbines and needs the wind data. Moreover, if the control parameters encounter with sudden change(s), a considerable pressure will be imposed on turbine and as a result, the chattering effect increases.

Multivariable control strategy is a non-linear controller and usually is designed based on torque control in wind turbine. In [82], by applying this strategy, an appropriate adjustment was introduced, while no attempt was made regarding fluctuation in rotor speed. In [83], a rapid controller was designed for torque and a slow controller was designed for blades, the block diagram of which is presented in Fig. 7. In this method, the torque equation is simplified to reduce the complexity of controller and adjust the rotor speed. The electrical power of the torque is calculated by replacing a first-order dynamic in electrical power error and in order to maintain rotor speed and electric power in proper limit and the pitch angle controller is used.

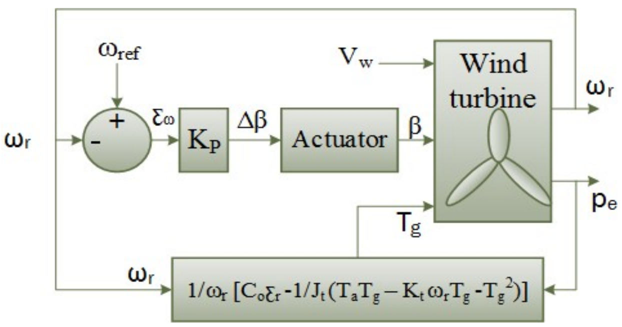

Figure 7. Multivariable controller scheme of the pitch angle control

LQG is one of the most basic non-linear optimization methods which is able to design linear feedback control for unknown non-linear systems [84-86]. This method was used in [87] to control the blade angle. This combined method includes a linear quadratic estimator (LQE) accompanied with a linear quadratic regulator (LQR) which are calculated and designed separately. This strategy contains a Kalman filter found by calculating the linear minimum variance state estimation of the system and implemented by vector signal measurements. Profit matrix is applied in finding a solution corresponding to the deterministic quadratic state feedback regulator. This method is implemented by the presented system in Fig. 8 for wind turbines. This controller is designed based on rotor speed estimation and electric power maintenance. In fact, this is a control of maximum power input of wind. This controller enhances the gain margin and phase margin. The performance of this controller is limited because of many non-linear characters existing in wind turbines and is not reliable as an automatic optimizer.

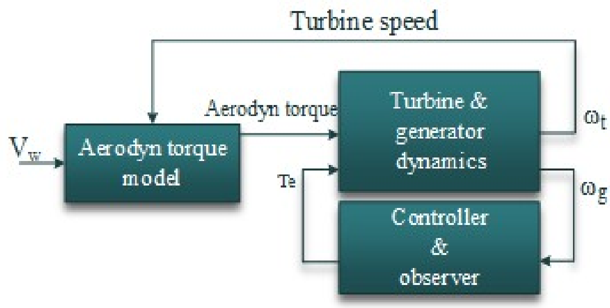

Figure 8. LQG controller scheme of the wind turbine

Another non-linear method used for the maximum target power is considering uncertainties in turbine parameters [89-90]. In [91], an advanced nonlinear strategy is designed to control the blades and active power in MPPT and pitch angle areas. This is accomplished by adjusting the rotor voltage and blades. The block diagram of this implementation for angular control of blades is shown in Fig. 9.

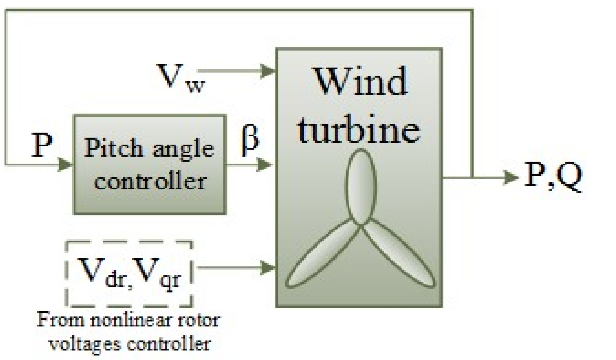

Figure 9. Architecture of the non-linear controller of the wind turbine

In this study, voltage control and blade pitch angle of a doubly fed induction generator (DFIG) are applied to have the maximum active input. Turbine inputs, blade pitch angle control and rotor voltage are all obtained in accordance with the target controller. The mechanical and aerodynamic parameters of target controller are modeled based on uncertainties. A similar designing is presented in [92], with known mechanical and aerodynamic parameters. This approach does not require the data of wind velocity, air density and Cp level. But modelling of mechanical turbine parameters with uncertainly is not a simple task. Features of non-linear control strategies is shown in Table 2.

TABLE 2. Features of non-linear control strategies

Strategy	Advantage	Disadvantage
Sliding Mode Control	- Providing a reliable dynamic strength in the case of uncertainties in turbine parameters - Suitable consistency between efficiency change and torque fluctuations	- Dependency on mathematical model of Wind turbine - Need for wind data - High pressure on turbine in case of sudden change in controlling parameters - High chattering effect
Multivariable Control Strategy	- Suitable setting of output power - Rotor speed maintenance without any fluctuations	- Should be applied along with other control methods
Linear Quadratic Gaussian control	- Linear feedback control for unknown non-linear systems - Rotor speed estimation gain margin and phase margin is improved	- Limited performance of controller due to nonlinear characters on the top of wind turbine - Low reliability as an automatic optimizer
Considering Uncertainties	- Setting and obtaining the maximum active power based on uncertainties - No need for wind, air density, and Cp level data	- The complexity of modeling of mechanical parameters

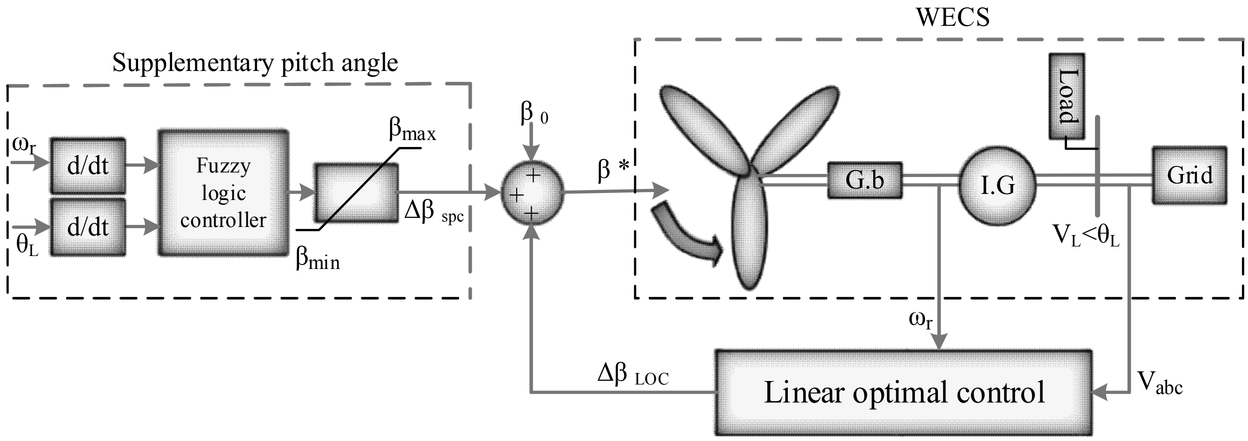

Figure 10. Pitch angle control with LOC

2.3. Blade pitch angle control using optimal control

According to [93], the role of linear optimal control (LOC) is to determine the control input, in order to minimize the performance index of the system. In [94], a unified voltage and a controller of the blade angle, with the objective of voltage control and stabilization of the generator speed and the system frequency are implemented. Fuzzy control and LOC are applied to control the blade angle. The block diagram of this design is shown in Fig. 10.

By defining a function based on the system state variables and with assistant of the Riccati equation, the minimum function is obtained. The PI gains in voltage supplement regulator, presented in this article, are refined through LOC. The state observer through Kalman filter is used to separate state variables from output variables. Furthermore, a fuzzy controller is used as well.

TABLE 3. Features of LOC

Strategy	Advantage	Disadvantage
Linear Optimal Control	- Minimizing the system performance - Rotor speed stabilization	- Complexity in correlation and finding the best state variables - Not appropriate in connection mode

Fuzzy inputs of the rotor speed changes and changes in bus voltage phase angle are considered in this study. When wind energy conversion system encounters a major disturbance, like network disconnection, the fuzzy logic regulates the output power, through appropriate rules. The consolidation of the rotor speed and voltage control is the objective of this article. The complexity of relationships and finding appropriate state variables are among the disadvantages of this method. Moreover, adjusting the blade angle, in addition to its dependency on wind speed, depends on the changes in load moment. Features of LOC is shown in Table 3.

2.4. Power regulation and torque control through Robust strategies

In [95], in order to decrease the fluctuations of wind turbine power, a technique is presented based on leveling the output power through H-infinity (H∞). This objective is sought by a linear matrix inequality (LMI) to optimize the controllers and identify the system. In [96,97] control gains are adjusted by the changes in operating conditions of the systems. Using the Matrix Inequality, it is easier to choose weighs for H∞ rather than using Riccati equation and is more valid. The results of stimulation in the article indicate the improvement in system performance toward PI controller in parameters' change. Here, first, by writing Taylor series which is a function of (ωt, Vw, β), and by inserting it in angular velocity equation, the system becomes linear [95]:

$$\Delta \dot{\omega}_w = \frac{1}{J}\left\{\begin{matrix}(A_{slope} - k_g)\Delta\omega_w + B_{slope}\Delta V_w \\ + C_{slope}\Delta\beta\end{matrix}\right\} \quad (3)$$

where, $A_{slope}=\partial f / \partial\omega_w$, $B_{slope}=\partial f / \partial V_w$ and $C_{slope}=\partial f / \partial\beta$ is considered.

After making the system linear and expressing the small-signal equation of angular velocity and torque, the assistance of a Linear Matrix Inequality implementation of H_∞ controller, is expressed. Here, the $\Delta T_{w,ref}$ is obtained through LMI.

The objective of the controller is to minimize the inductions arose from transmission operand w to z, where w represents fluctuation and z represents the controller error [98]. The problem of H∞ controller is to find matrix k which can be pursued by Matrix Inequality. For this purpose, first, the state model is obtained based on recognizable and consistent matrices that guarantee control stability. Then the close-loop transfer function of the system of w to z can be written by matrix controller. The block diagram is shown in Fig. 11.

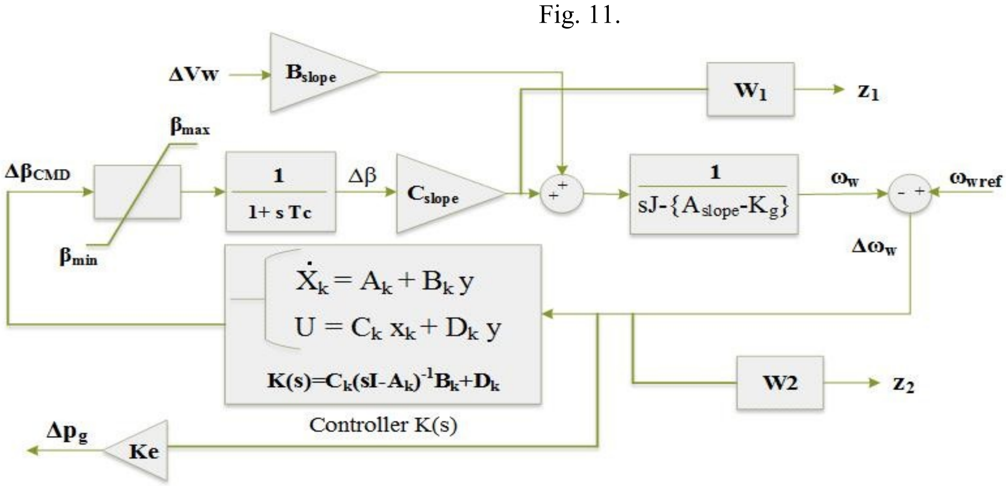

Figure 11. Block diagram of WTG system including H∞ controller

In [99], a controller is deigned that covers all different wind speed types based on H∞. This controller has the advantage of PI controller with gain scheduling. This is implemented through Lyapunovfunction and by changes in linear parameters at high wind speed and a quadratic speed-torque controller in MPPT section. This article is a combination of PI controller and H∞ in no load and full load and both sections of power-speed had proper performance. However, H∞ does not need any system performance momentary estimator and offers an almost rapid response to changes in operating conditions. The main drawback of this model is that its function depends on the turbine of linear model. In addition, designing a programing function for the control gains in different functional points, is not easy.

Since the usual H∞ control is based on a conservative approach, the performance of this controller is not as appropriate as other conventional controllers such as PI controller with gain scheduling. It goes without saying that mechanical resonance at high frequencies includes uncertainties, consequently the bandwidth control will be limited and designing bandwidth might become more difficult. Therefore, in [100], H∞ with less conservative robust control can help to improve the controller performance. In [101], a new H∞ is designed in order to decrease the conservative robust control using the separation method of the perturbations to the multiplicative and the feedback perturbations. In [102], the model set of uncertainties in this article is a subset of linear fraction scale. The general system of H∞

method with less conservative robust control is shown in Fig. 12, where Pn is the nominal model and α and β are the uncertainty weighs, respectively.

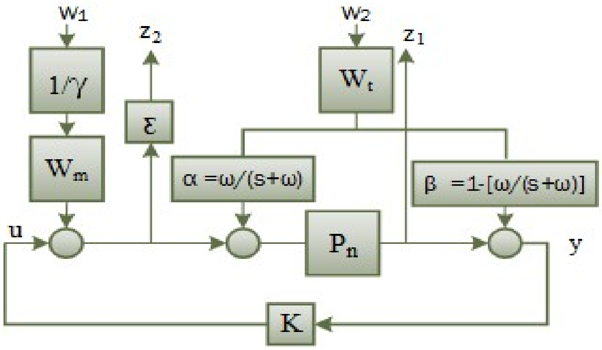

Figure 12. Generalized plant for H∞ with less conservative robust control (ξ is a constant coefficient and 1/γ is a regulative parameter which is minimized for this model)

In this diagram, W_t is considered as weighting function for strength resistance and W_m plays an important role as weight function for the performance of controller. To increase the bandwidth of the controller with less conservativeness, the maximum ω equals to $\omega = 2\pi * 10^{-4}$. In [103], the frequency response of H∞ controller standard is compared with H∞ with less conservative robust control by fitting the control parameters, where the superiority of this controller was increased. This finding is compared with PI gain scheduling. Features of H_∞ is shown in Table 4.

2.5. Blade pitch angle control using generalized predictive control

method, generalized predictive control (GPC) is widely recommended for windy areas [104]. GPC was proposed in [105] and has been widely applied in engineering systems. This method is adopted in different articles to predict the next reaction system with respect to parameters' change [106,107]. The block diagram of this adopted method is shown in Fig. 13. In this block diagram, P_{go} (k) is the output power command, P_g (k) is the output power and e (k) is the generator output error, $u_2(k)$ is the input of control strategy and k is the sampling number.

The error output mostly disappears when the performance index is minimized by derivation of the performance index J [108,109]:

$$J = E\left[\overbrace{\sum_{j=1}^{N}\left\{\underbrace{e(k+j)}_{\text{sum min g output error}}\right\}^2 + \sum_{j=1}^{NU}\lambda_2(j)\left\{\underbrace{\Delta u(k+j-1)}_{\text{difference of control input}}\right\}^2}^{\text{Expected value}}\right] \qquad (4)$$

The λ_2 (j) is a weighting function. Differences in input control (Δu) assistant minimize the output power error [e(k+j)]. The u_2 input of generalized predictive controller is limited by λ_2 (j) to prevent the system divergence.

Here, the control signal error mostly disappears in each area, through minimizing the performance index. However, if big errors occur in the output power, the control system will turn to be unstable since the general predictive control generator strongly depends on the output power error, indicating that the P_{go} is much smaller than the maximum wind energy. If the wind speed changes in a sudden and rapid manner, the P_{go} might not be able to adjust itself. This drawback is removed through fuzzy logic, by modifying the standard deviation of the output power. This correction process is run by squaring the square integral of the wind speed difference and average wind speed, where the proportion of the wind speed standard deviation is obtained. Now, through multiplying this standard by compensation coefficient, obtained from fuzzy logic, the dependence of controller on output power error is eliminated. By adjusting this compensation coefficient, the commanding output power of P_{go} can adapt itself to changes in wind speed and system conditions. In [110], the modification of standard deviation is conducted with Fuzzy Neural Network which subsequently leaded to better results in comparison with the fuzzy results. Features of GPC is shown in Table 5.

TABLE 5. Features of GPC

Strategy	Advantage	Disadvantage
General Predicting Controller	- Control signal error is removed by minimizing the performance index - High efficiency windy areas	- In case of big errors, the system control will lose stability - No compatibility of power output with conditions in the case of sudden wind change

2.6. Blade angle command manufactured by hydraulic operator

In general, there exist two operand systems: electrochemical and hydraulic [111,112]. In electromechanical systems the blades move by an electrical motor [113,114]. Such motors have low strength and power and they are bulky. In hydraulic type, the cylinder is operated through a slider-crank mechanism [115,116]. According to [117], the hydraulic systems are of power-mass ratio and high reliability, while their control accuracy is weak due to slider-crank mechanism. In [118], to harmonize the output power and torque fluctuations, a new method is used for blade pitch command. This has the advantages of both mechanical and aerodynamic systems. Here, a circular hydraulic operand is applied instead of crank for enhancing the controller accuracy and a hydraulic motor is applied instead of electrical motor to improve the power-mass ratio. In comparison of the generator output power with its reference, and adjusting it with PI controller, the blade pitch angle is transferred to the electrical motor driver. The driver output, delivers the angle change order to the blade actuators. The block diagram of this system is depicted in Fig. 14.

TABLE 4. Features of H∞

Strategy	Advantage	Disadvantage
H∞	- Low fluctuations along with wind turbine using developed output power - Control gains with the change of performance conditions - No need of momentary estimator concerning system parameters -Providing a proper response which is related to the change in functional system	- Performance dependency on linearized turbine model - Difficulty in functional designing for controlling gains in different points - Limited bandwidth control in the case of mechanical resonance in high frequencies - Difficult designing of a high bandwidth

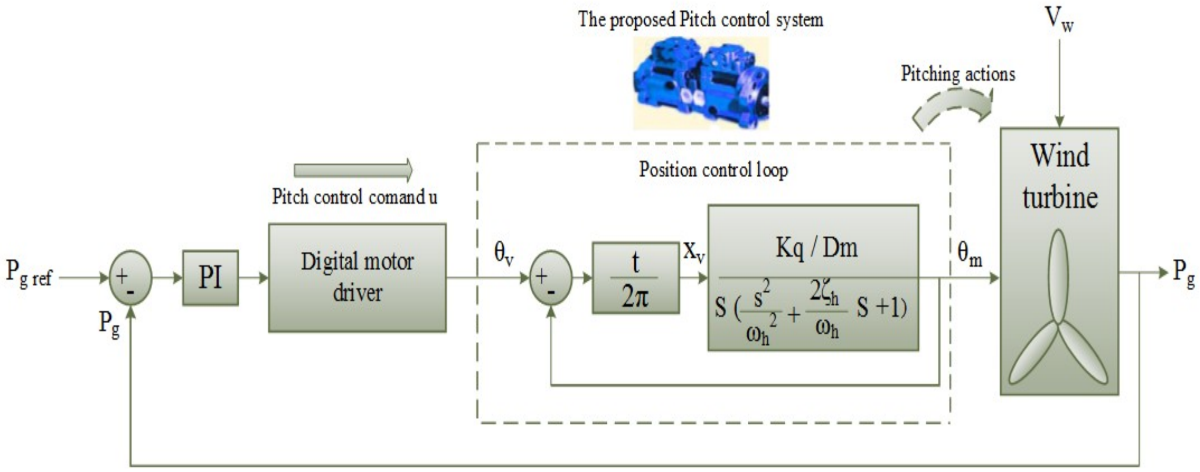

Figure 14. Hydraulic pitch actuator

In this diagram, the spool displacement of the rotational valve and transfer function are modeled. Here, t is the helical pitch of the screw and nut combination, θ_m is the rotary displacement of the hydraulic motor, θ_v is the spool displacement of the rotational valve, Kq is the flow gain of the rotational valve, ω_h is the hydraulic natural frequency and ζ_h is the damping ratio. In this block diagram the pitch angle control is implemented through the following equation [118]:

$$u = k_{p1}(P_{gr} - P_g) + k_{i1}\int_0^t (P_{gr} - P_g)dt \tag{5}$$

where, u is the pitch control command, Pg is the output power, Pgr is the rated value of Pg, and Ki1 and Kp1 are integral and proportional gains, respectively. The advantages of this structure are: compactness, high reliability, high power-mass ratio, adequate accuracy and better application in industrial areas. These actuators are used in large scale wind turbine.

2.7. Blade angle control using intelligent control

Controlling systems in variable speed wind turbine is subject to evolution for a better and more efficient and innovative solutions through newly introduced techniques. Among these techniques, fuzzy logic is the most well-known, because of its simplicity and remarkable practicability. Fuzzy logic control (FLC) is a helpful choice as an overcoming factor with respect to lack of information compared to the PI controller. One of the conventional strategies of the variable speed wind turbine control is the use of the rotor speed as a function of the wind speed. The factors of rotor speed, torque and dynamic of system heavily depend on the wind speed, which are very problematic like, distraction in system parameters and changes in environmental condition; consequently, fuzzy logic is an effective approach for controlling wind turbines functionality [119]. Ensuring fast convergence and independence in changing the parameters even in the presence of noise signals and non-integer types are the main factors of this controller [120,121].

The first fuzzy controller in wind turbines which promoted both the system efficiency and economy by demonstrating its superiority, was introduced in [122]. There exist several reports on blade pitch angle control through fuzzy logic. In [123], the average wind speed and average frequency are applied as fuzzy inputs; though this finding is not problem-free. The problems are: the nonlinearity of the aerodynamic system and the dependency of this method on wind speed. In [124], considering the wind speed, power variations and their derivatives are introduced as fuzzy inputs. In [125], rotor speed variations and their derivatives are added to wind speed factor, where the data of wind speed and anemometer is needed. In [126], a blade pitch controller is designed for PM generator wind turbines. The main advantage of this design is related to the replacement of rotor speed in the controller input. Mechanical power (Δp), the derivative of mechanical power (£Δp), and rotor speed are considered as the inputs of fuzzy systems. Mechanical power of generator is compared with the reference value and generates (Δp), according to [127]. Next, the fuzzy controller converts the numerical errors, the changes in error and rotor speed error into fuzzy and then forms the linguistic variables. In continuation, a variety of control PID and fuzzy controller in wind speed with an average of 12 and 14 meters per second are compared with one another and results indicate the superiority of the fuzzy controller, especially when the wind changes in a sudden manner. The block diagram in Fig. 15 is of fuzzy control implementation.

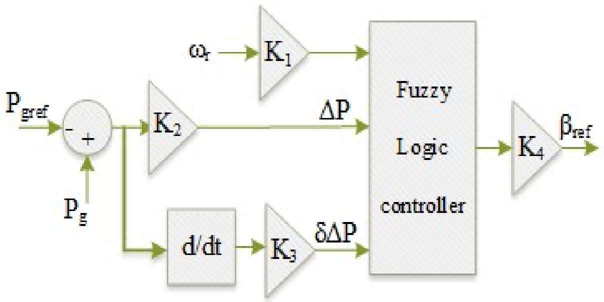

Figure 15. Block diagram of the pitch angle control with FLC

A pitch angle control strategy, including normal scheme and fault-ride-through (FRT) scheme, based on hybrid PI and fuzzy logic approach is shown in [128], in which the dynamic simulation results show that the hybrid controller can be effective in enhancing output power smoothness and FRT requirements for squirrel-cage induction generators in wind power system. In [129], the only fuzzy input applied is the mechanical power variations. Albeit during the sudden changes in wind speed low fluctuation is observed in the aerodynamic response in comparison with the conventional controllers, considering the mechanical power as fuzzy input is not satisfying. Moreover, no discussion is run on MPPT. In fact, pitch angle control must be able to meet both the requirements of aerodynamic fluctuations reduction and yield maximum energy, simultaneously. In [130], fuzzy controller is applied along with a dead zone to reduce the voltage fluctuations and frequency in island mode. A block diagram of this controller is illustrated in Fig. 16.

In this dead zone, the angular variations range and its derivative is less than the specified amount (e.g. 0/1 degrees per second). This new zone is added to the activator in order to prolong the actuator durability and eliminate the potential noise signal. Since the storage batteries are engaged in the system, considering the mechanical power as fuzzy input alone is not so appealing. In fuzzy control, Parameters fix in their terms; which is the main drawback of such type controllers. Continual and sudden changes in the wind speed, makes the fuzzy controller dependent on an online optimizer.

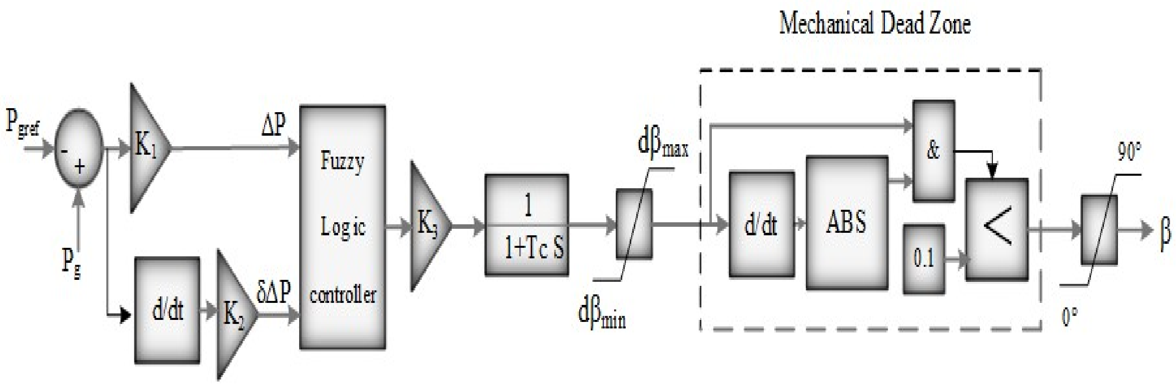

Figure 16. Pitch angle control through FLC with disturbances limiter

The function of Neural networks is usually considered as estimator [131,132], while they can be applied in controlling and organizing engineering systems as well [133,134]. Training neural networks are based on learning rules through specific training algorithms; this process is discussed in [135]. A pitch angle control strategy based on reinforcement learning algorithm for wind turbine is proposed in [136], which the framework of actor-critic is adopted in this algorithm and RBF neural network is used to process continuous input and output space. The structure of RBF networks is similar to that of the MLP networks. RBF networks as an alternative of MLP are applied in engineering fields [137,138]. In [139], MLP (multi-layer perceptron) and RBF (radial basis function) neural network are applied in controlling the blade angle. Here, the angular velocity and generator output power are limited subject to different wind conditions. It is observed that, there is less settling time in RBF in comparison with MLP. It is also observed that, there are magnetic fluctuations at low frequencies after a wind speed change in MLP. In [140], RBF three-layer neural network is applied to control the blade angle accompanied with a fuzzy controller. The design of the block diagram is shown in Fig. 17, where the power failure and its derivative forms are both considered as the inputs of neural networks.

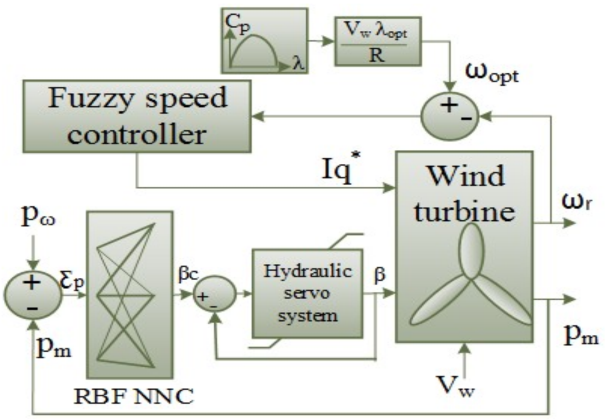

Figure 17. Pitch angle control with RBF NN $(x_1^1 = p_W - p_m = \varepsilon_p)$ and $(x_2^1 = \dot{\varepsilon}_p)$

The output of this network is known as the main component for pitch angle command. Two input layers, nine hidden layers and one output layer are applied in this network. In order to use this controller, the wind turbine is linearized. To adjust weighing gains, the error input power is differentiated in relation to blade angle of βc.

As mentioned earlier, the total output can be calculated through the following equation [140]:

$$y_k^3(N) = \sum w_j y_j^{\,2}(N) = \beta_c \tag{6}$$

where N is the node count, W_j is the j^{th} weigh between hidden layer and output. Rapid response capability and easy adaptability under various conditions are considered as the advantages of this controller in neural network. Nevertheless, after training the network, a new training system enters the network, that is, the training phase should be repeated. Also, the cost of the implementation of this method does not justify.

In [141], a fuzzy-neural controller is used to adjust the angle between input wind direction and chord line of the blades. The main advantage of this approach is that, in the case of new changes, the fuzzy-neural adaptive networks can obtain new learning methods and adapt themselves to the new data. From the outcome of this assessment it can be deduced that a more reliable performance is evident in the response of rotor speed and output power of the generator.

Stability analysis [142,143] and optimal controller [144,145] of wind turbines have been assessed in several papers [146,147]. In these articles, also the pitch angle control has been evaluated. However, the complexity of optimization in large wind farms and the procedure to identify a single form of control parameters is the leading issue of further study. Rather than the optimization of all control parameters, in [148], sensitivity to first main identified parameters is considered to reduce the complexity of the optimization. This objective is achieved through the PSO (particle swarm optimization) algorithm to find the optimal value of the main controlling parameters which has led to the improvement of the dynamic performance of wind turbine [148,150]. The controlling parameters of the blades will be optimized by considering the proportional and integral gains of the blade angle control section with the gain values of rotor current regulator and optimizing this regulator.

TABLE 6. Features of the intelligent controllers

Strategy	Advantage	Disadvantage
Fuzzy	- Lack of dependency on changes of the parameters in presence of noisy signals - High simplicity and effectiveness -Earn extra power due to less involvement of the blade angle	-Difficulty in adjusting the weighting coefficients and membership functions with the appropriate rules of the system under control - For fixing the parameters in their terms, an online optimizer in windy areas is needed.
Neural Network	- Rapid response capability and easy adaptation with different conditions - Appropriate as an estimator	- Difficulty in training weights - High potential of instability
Evolutionary Algorithm	- Improved dynamic performance - Determining the optimum values of weigh factors of fuzzy control	- Complexity in optimization by increasing the number of turbines

In the optimization process, a 10% increase in the controlling parameters and then a 10% decrease in the same parameters, would yield DFIG output power. Finally, based on the average sensitivity equation, the optimal amount of each of the control parameters is calculated. The optimal coefficients of k1 to k4 gains (Fig. 16) can be obtained through genetic algorithm. By this process, the input and output weight coefficients are removed and by constant updating of the given algorithm, a better results is obtained. In order to identify the structure and optimal parameters of the fuzzy controller, a genetic algorithm is applied to adjust the blade angle [151]. By adjusting the reference value of duty cycle used in the DC-DC converter driver, fuzzy regulator is introduced to maximize the energy tracking. Features of the intelligent controllers is shown in Table 6.

3. CONCLUSIONS

Control systems for variable-speed WECS are continuously evolving toward innovative and more efficient solutions. In this paper, a variety of control methods regarding the adjustment of blade angle of wind turbines and aerodynamic parameters are reviewed in order to limit the incoming power and to get maximum power in a manner that the system would not be damaged. Overall, it is essential to have less sensitivity toward dependency on the changes in parameters, which would yield better functionality.

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NOMENCLATURE

DFIG	doubly fed induction generator
FLC	fuzzy logic control
FRT	fault ride through
GPC	generalized predictive control
H_∞	H-infinity
LMI	linear matrix inequality
LOC	linear optimal control
LQE	linear quadratic estimator
LQG	linear quadratic Gaussian
LQR	linear quadratic regulator
MLP	multi-layer perceptron
MPPT	maximum power point tracking
PI	proportional-integral
PID	proportional-integral-derivative
PM	permanent magnet
PSO	particle swarm optimization
RBF	radial basis function
STR	self-tuning regulator
WECS	wind energy conversion system

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