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Review Article

Modeling and Control of Wind Turbine

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In recent years, the energy production by wind turbines has been increasing, because its production is environmentally friendly; therefore, the technology developed for the production of energy through wind turbines brings great challenges in the investigation. This paper studies the characteristics of the wind turbine in the market and lab; it is focused on the recent advances of the wind turbine modeling with the aerodynamic power and the wind turbine control with the nonlinear, fuzzy, and predictive techniques.

1. Introduction

Wind energy is gaining increasing importance worldwide. The processes of industrialization and economic development require energy. Fuels are the main energy resource in the world and are at the center of the energy demands [1–4]. Wind turbines using aerodynamic lift can be divided according to the orientation of the axis of rotation on the horizontal axis and vertical axis turbines. The horizontal axis or propeller-type approach currently dominates wind turbine applications [5]. A horizontal axis wind turbine comprises a tower; a nacelle is mounted on top of the tower. The nacelle contains the generator, gearbox, and rotor. There are several mechanisms to signal the gondola to the wind direction or to move the nacelle of the wind in the case of high wind speeds. In small turbines, the rotor and nacelle are oriented into the wind with a tail vane. In larger turbines, the gondola with the rotor is electrically yawed out of the wind in or in response to a signal from a vane.

Horizontal axis wind turbines typically use a different number of blades, depending on the purpose of the wind turbine. Turbines with two sheets or three blades are generally used for power generation. The most common design of modern turbines is based on the horizontal shaft structure. This design of wind turbine towers is assembled as shown in Figure 1. The role of the tower is to raise the wind turbine above the ground to intercept the strongest winds to get more energy. Wind energy has evolved rapidly during the past three decades with increasing diameters of the rotor and the use of sophisticated power electronics to allow operation at rotor speed varies; see Figure 2.

These turbines are operated such tightly that when you turn the rotor plane to be positioned directly upwind of the tower through the use of a yaw motor, that rotates the entire nacelle (housing for all components in the upper tower). Wind passes through the turbine blades and this then produces lift inducing a torque [2, 6]. The aerodynamic torque captured by the blades is transferred to the hub which connects the blades to a power train and after a generator. Typically, the drive train includes a scale gearbox rotation speed and torque levels that are suitable for the configuration of the generator. Although the gearbox is still used in most turbines, direct drive wind turbines developed to connect the shaft of the generator directly with one axis to increase reliability and reduce maintenance costs are largely associated with gearbox failures.

The aim of this survey is to address all the aspects involved in wind turbines. Compared to the previous reviews, this literature discusses the dynamic modeling of wind turbines, actuators, and wind turbines-actuator combined system in detail using both linear and nonlinear methods. The paper deals with different control strategies including the nonlinear,

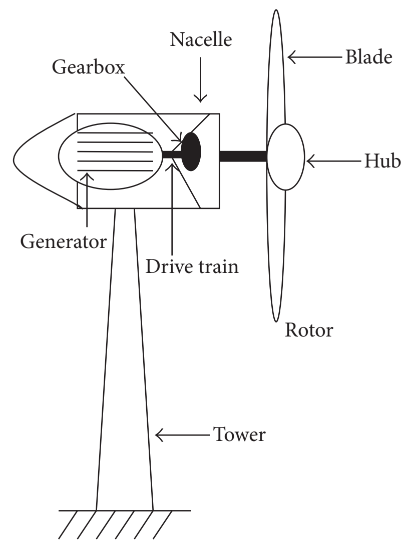

Figure 1: A horizontal axis wind turbine [7, 8].

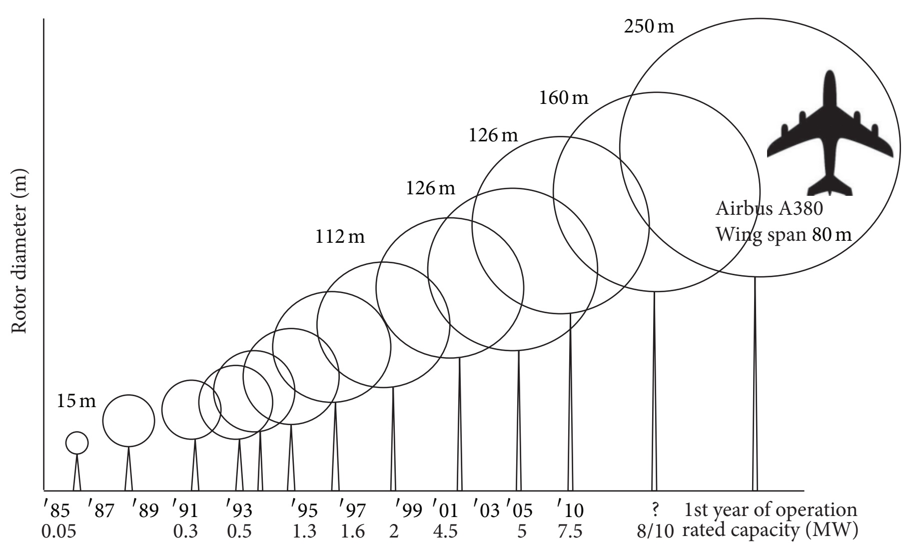

Figure 2: Evolution of the wind turbine dimensions.

fuzzy logic, and predictive control techniques. The survey concludes with some of the observations noticed throughout the review.

2. Wind Turbine Structure

The wind turbines can be classified based on thier orientation and thier axis of rotation, into horizontal axis wind turbines (HAWT) and vertical axis wind turbines (VAWT), which can be installed on the land or sea [1, 3]. The HAWT feature higher wind energy conversion efficiency due to the blade design and access to stronger wind, but they need a stronger tower to support the heavy weight if the nacelle and its installation cost is higher. The VAWT have the advantage of lower installation; however, their wind energy conversion efficiency is lower due to the weaker wind on the lower portion of the blades and limited aerodynamic performance of the blades [9]. A comparison between the horizontal and vertical axis wind turbines is summarized in Table 1.

Another form to classify the wind turbines is by speed control methods and power control methods. The wind energy conversion is divided into fixed and variable speeds [10]. As the name suggests, fixed speed wind turbines (FSWT) rotate at almost a constant speed, which is determined by the gear ratio, grid frequency, and number of poles of the generator. The maximum conversion efficiency can be achieved only at a given wind speed, and the system efficiency degrades at other wind speeds. The wind turbine is protected by aerodynamic control of the blades from possible damage caused by high wind gusts. On the other hand, variable speed wind turbines (VSWT) can achieve maximum energy conversion efficiency over a wide range of wind speeds. The turbine can continuously adjust its rotational speed according to the wind speed. In doing so, the tip speed radio which is the

Table 1: Properties of HAWT over VAWT.

	Advantages
HAWT	(i) Higher wind energy conversion efficiency (ii) Access to stronger wind due to high tower
VAWT	(i) Lower installation cost and easier maintenance due to the ground level gearbox and generator (ii) Operation independent of wind direction
	Disadvantages
HAWT	(i) Higher installation cost, stronger tower to support heavy weight of nacelle (ii) The orientation is required
VAWT	(i) Lower wind energy conversion efficiency (ii) Higher torque fluctuations and prone to mechanical vibrations

Table 2: Advantages and disadvantages of FSWT and VSWT [9].

	Advantages
FSWT	(i) Simple, robust, reliable (ii) Low cost and maintenance
VSWT	(i) High energy conversion, efficiency (ii) Improved power quality (iii) Reduced mechanical stress
	Disadvantages
FSWT	(i) Relatively low energy conversion efficiency (ii) High mechanical stress (iii) High power fluctuations to the grid
VSWT	(i) Additional cost and losses due to use of converters (ii) More complex control system

ratio of the blade tip speed to the wind speed can be kept at an optimal value to achieve the maximum power conversion efficiency at different wind speeds. A comparison between the fixed speed wind and variable speed turbines is summarized in Table 2.

2.1. Generator. Basically, a wind turbine can be equipped with any type of three-phase generator. Today, the demand for the grid-compatible electric current can be met by frequency converters when the generator supplies the alternating current (AC) of variable frequency or direct current (DC). Synchronous and asynchronous generators are the most common devices that are used in wind turbines [1, 3, 5, 11–14], as shown in Figures 3, 4, 5, and 6. They are classified into four types:

(1) asynchronous (induction) generator:

- (i) squirrel cage induction generator (SCIG) [15, 16]; see Figure 3,
- (ii) wound rotor induction generator (WRIG) [11, 17, 18]; see Figure 4,

(2) synchronous generator:

- (i) permanent magnet synchronous generator (PMSG) [19]; see Figure 5,
- (ii) wound rotor synchronous generator (WRSG) [20]; see Figure 6,

(3) other types of potential interest:

- (i) high-voltage generator (HVG) [21, 22],
- (ii) switch reluctance generator (SRG) [23, 24],
- (iii) transverse flux generator (TFG) [25, 26].

Wind turbine configurations can also be classified with both the speed control and power control criterion [10]; see Table 3.

The advantages and disadvantages of these typical wind turbine configurations are as follows:

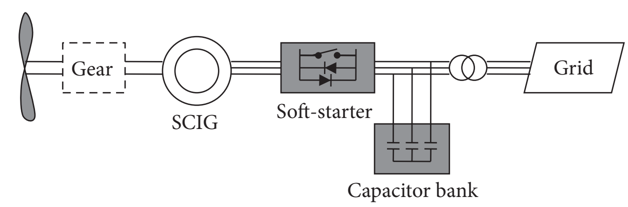

Figure 3: A. Wind Turbine with a Squirrel Cage Induction Generator [5].

(A) *Fixed speed*: This configuration denotes the fixed speed wind turbine with an SCIG directly connected to the grid via a transformer [21, 23].

(A0) *Passive Stall Control*: This is the conventional concept applied by many Danish wind turbine manufacturers during the years 1980 and 1990, that is, a postwindward-regulated three-bladed wind turbine concept. It has been very popular because of its relatively low cost, its simplicity, and robustness. Passive stall controlled wind turbines cannot start assisted conduct, which means that the power of the turbine cannot be controlled during the connection sequence [18, 20].

(A1) *Pitch control*: This also has been present in the market. The main advantage is that it facilitates power control capacity, the start, and emergency stop control. Its main drawback is that, at high wind speeds, even small variations in wind speed result in large variations in output power. The pitch mechanism is not fast enough to avoid such power fluctuations. For releasing the sheet, the slow variations in wind can compensate; nevertheless, this is not possible in the case of gusts [17, 25].

(A2) *Active stall control*: It has recently become popular. This configuration basically maintains all the features of power quality controlled system shutdown. The improvements are in a better utilization of the overall system as a result of using active stall control. The flexible coupling of the

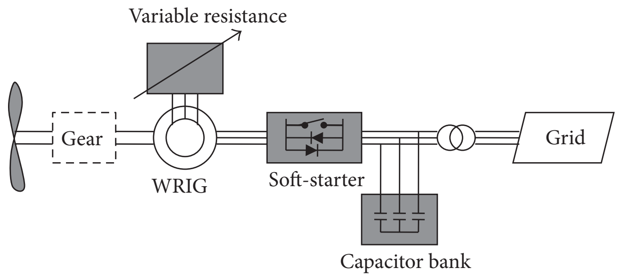

Figure 4: B. Wind Turbine with a Wound Rotor Induction Generator [5].

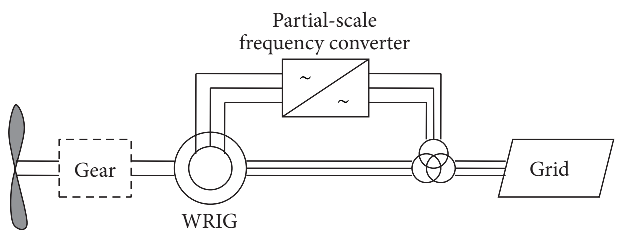

Figure 5: C. Wind Turbine with a Permanent Magnet Synchronous Generator [5].

blades to the hub also facilitates emergency stop and startups. A disadvantage is the highest price that raises the pitch mechanism and controller [15, 24].

(B) *Limited variable speed*: This configuration corresponds to the limited variable speed wind turbine with variable generator rotor resistance. It uses a WRIG [26].

(C) *Variable speed with partial-scale frequency converter*: This configuration, known as the DFIG, corresponds to the limited variable speed of the wind turbine with a WRIG and partial-scale frequency converter on the rotor circuit [19].

(D) *Variable speed with full-scale frequency converter*: This configuration corresponds to the full variable speed wind turbine, with the generator being connected to the grid through a full-scale frequency converter. The frequency converter performs the reactive power compensation and the smoother grid connection. The generator can be excited electrically by a WRSG, WRIG, or PMSG [11].

Therefore, as illustrated in Table 3, Type B0, Type B2, Type C0, Type C2, Type D0, and Type D2 are not used in today's wind turbine industry [5].

2.2. Soft Starter. The soft starter is a component of simple and inexpensive electrical power used in fixed speed wind turbines during grid connection; see Figures 3 and 4. The soft starter function is to reduce the input current, limiting disruptions to the network. Without a smooth start, the input current can be up to 7-8 times of the rated current, which can cause serious disturbances in the network voltage. The soft starter contains two thyristors as switching devices in each phase [5].

They are connected antiparallel to each phase. The smooth connection of the generator to the network over a predefined number of grating periods is accomplished by adjusting the firing angle α of the thyristors. The relationship between the firing angle and the resulting amplification of the soft starter is highly nonlinear and is also a function of the power factor connected element. After the in-rush, thyristors are bridged to reduce overall system losses.

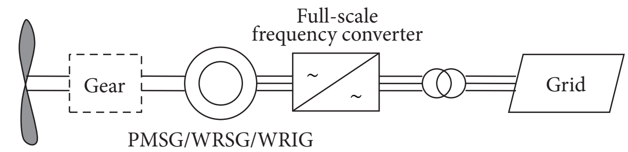

Figure 6: D. Wind Turbine with a Wound Rotor Synchronous Generator [5].

Table 3: Wind turbine classification [5].

Speed control		Power control		
		Passive stall	Pitch	Active stall
Fixed speed	A	A0	A1	A2
Variable speed	B	B0	B1	B2
	C	C0	C1	C2
	D	D0	D1	D2

2.3. Capacitor Bank. The capacitor bank is used in fixed speed wind turbines or limited variable speed; see Figures 3 and 4. It is an electrical component that supplies power to the induction generator reactive. Thus, the reactive power absorbed by the generator of the grid is minimized [27]. The wind turbine generators may have a full load dynamic compensation, where a number of capacitors are connected or disconnected continuously, depending on the reactive power demand of the generator during a predefined time period.

The capacitor banks are usually mounted in the bottom of the tower or the nacelle, that is, at the top of the wind turbine. They can be very charged and damaged in the event of surges on the network and, consequently, it may increase the cost of maintenance.

2.4. Rectifiers and Inverters. Diodes can only be used in the rectification mode, while the electronic switches can be used in the rectification and inversion mode [23, 28]. The most common solution is the rectifier diode rectifier, because of its simplicity, low cost, and low losses. It is nonlinear in nature and accordingly generates harmonic currents. Another drawback is that it permits only unidirectional power flow and cannot control the voltage or current generator [5]. Therefore, it is only used with a generator which can control the tension and with an inverter (e.g., one IGBT) that can control the flow.

The thyristor (grid-commutated) based solution is cheap investor, with low losses, and, as the name suggests, must be connected to the network to be able to operate. Unfortunately, consuming reactive power and harmonics produces a large increasing demand of power quality and makes the self-commutated thyristor less attractive for the investors than the GTO or IGBT converters. The advantage of a GTO inverter is that it can handle more power than the IGBT; nevertheless, this feature is less important in the future due to the rapid development of the IGBT. The disadvantage of this is that the control circuit of the GTO valve is more complicated.

The generator and the rectifier must be selected as a combination (i.e, a solution), while the investor can choose almost independently of the generator and the rectifier. A rectifier diode or a thyristor rectifier can be used only together with a synchronous generator, as it requires no reactive current magnetization. In opposition to this, rectifiers GTO IGBT have to be used with induction generators variable speed because they are able to control the reactive power. However, despite the IGBT is a very attractive option; has the disadvantages of high cost and high losses. The synchronous generator with a diode rectifier, for example, has a much lower total cost than equivalent induction generator IGBT inverter or a rectifier.

2.5. Frequency Converters. A traditional frequency converter, also called an adjustable speed drive, consists of

(i) a rectifier (AC-DC conversion unit) to convert alternating current into direct current, while the energy flows into the DC system;

(ii) energy storage (capacitors);

(iii) an inverter (DC-AC with controllable frequency and voltage) to convert direct current into alternating current, while the energy flows to the AC side.

There are different ways to combine a rectifier and an inverter into a frequency converter. In recent years, different converter topologies have been investigated as to whether it can be applied in wind turbines:

(i) back-to-back converters [26],

(ii) multilevel converters [26],

(iii) tandem converters [11],

(iv) matrix converters [11],

(v) resonant converters [11].

3. Modeling of the Wind Turbine

Since vertical axis wind turbines have very low starting torque, as well as dynamic stability problems they are commonly found in small wind applications. On the other hand, horizontal axis wind turbines are the most common wind turbines and are most commonly used for wind farms, community wind projects, and small wind applications. In this paper, we only discuss the modeling and control methods of horizontal axis wind turbines.

3.1. Modeling Based on the Aerodynamic. The aerodynamic modeling of the wind turbine has been studied and is presented in several research papers as [1, 10, 11, 26, 28–32]. The kinetic energy obtained by the blades of the wind is transformed into mechanical torque at the rotor shaft of the wind turbine the model can be described of in spoiler see Figure 7.

The blades are attached to the rotor with the tip speed $\omega_{\text{rot}} \cdot r$, where r is the length of the blade [33]. The profile of the blade experiences a relative wind speed generated by overlapping the tip speed and wind speed v_w. Wind is introduced from the lift profile (L) and drag forces (D) on the blade, resulting in the movement of these forces blade wind energy which is called the aerodynamic power P_w given as follows [1]:

$$P_w = \frac{1}{2}\rho_{\text{air}} \cdot A_r \cdot c_p(\lambda, \vartheta) \cdot v_w^3, \tag{1}$$

where ρ_{air} is the air density, v_w is the free wind speed experienced by the rotor, A is the swept rotor area, and c_p is the power coefficient.

The power coefficient depends upon the pitch angle ϑ and the tip-speed-ratio λ [1]:

$$\lambda = \frac{\omega_{\text{rot}} \cdot r}{v_w}. \tag{2}$$

The power coefficient c_p is typically given in a form of Figure 8 [30, 34].

The torque on the rotor shaft (see Figure 9), which is important for the axis model, can be calculated from the power with the aid of the rotational speed [33, 35]:

$$T_A = \frac{P_w}{\omega_r}, \tag{3}$$

where ω_r is the wind turbine speed (velocity of the rotor) and T_A is the aerodynamic torque.

3.2. Modeling Based on the Mechanical Property. In the power system analysis, the following four types of drive train models are usually used for the wind turbine available:

(i) six-mass drive train model [29],

(ii) three-mass drive train model [29],

(iii) two-mass shaft model [11],

(iv) one-mass or lumped model [36].

The simplified model of the power train is shown in Figure 9. In this model, all masses are grouped into low and high speed shaft [1, 35]. This model is sufficient for transient stability analysis with a fixed speed. The inertia of the low speed shaft comes mainly from the rotating blades and the inertia of the high speed shaft. It is important to include all small masses of high speed shaft, since they have an important influence on the dynamic system due to the transformation of the transmission ratio. The stiffness and damping of the shaft are combined in equivalent stiffness and damping placed

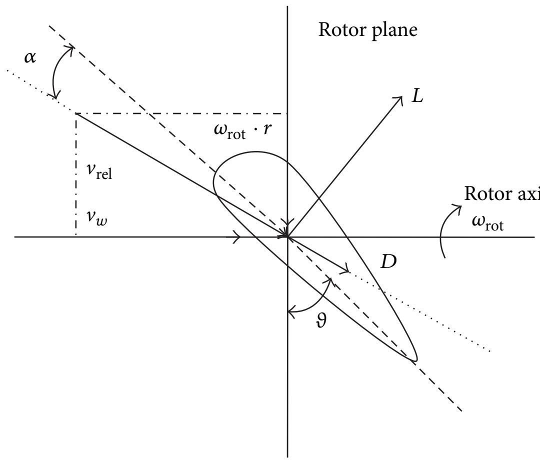

Figure 7: Aerodynamic model [1].

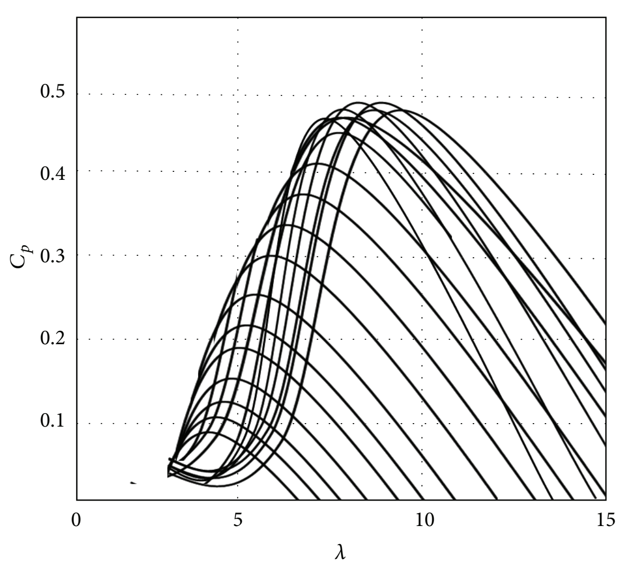

Figure 8: The power coefficient c_p versus the tip speed ratio [34].

on the low speed side. The mass of the gearbox itself is insignificant and abandoned.

The input to the model for a two-mass system is defined as torque T_A, which is obtained by the aerodynamic system and the generator reaction torque T_e. The output is the changes in the rotor speed ω_r and generator speed ω_g.

The dynamic of high speed generator can be expressed as a machine model. The differences in the mechanical drive torque T_m, the generator torque reaction T_e, and torque losses due to friction T_{fric}, cause the change of angular velocity $\dot{\omega}_g$ [29]:

$$\begin{gathered} T_m - T_e - T_{\text{fric}} = J_g \cdot \dot{\omega}_g, \\ \dot{\omega}_g = \ddot{\varphi}_g. \end{gathered} \tag{4}$$

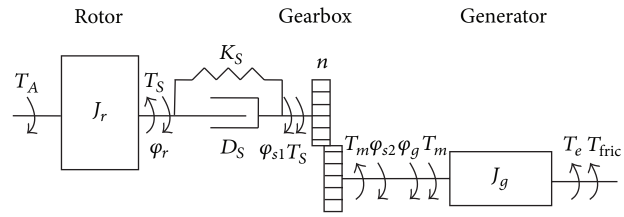

Figure 9: Drive train schematic for the modelling of a wind turbine [34].

The change of the angular speed $\dot{\omega}_r$ is caused by the difference of the aerodynamic torque T_A and shaft torque T_s at the low speed [29]:

$$\begin{gathered} T_A - T_S = J_r \cdot \dot{\omega}_r, \\ \dot{\omega}_r = \ddot{\varphi}_r. \end{gathered} \tag{5}$$

The mechanical driving torque T_m and shaft torque T_s are connected by the gear ratio [29]:

$$T_m = \frac{T_s}{n}. \tag{6}$$

The dynamics of the shaft can be described by [29]:

$$\begin{gathered} T_s = K_s \cdot \Delta\varphi + D_s \cdot \Delta\dot{\varphi}, \\ \Delta\dot{\varphi} = \dot{\varphi}_r - \frac{\dot{\varphi}_g}{n} = \omega_r - \frac{\omega_g}{n}. \end{gathered} \tag{7}$$

The final drive train dynamics is as follows [29]:

$$\begin{aligned} \dot{\omega}_r &= \frac{1}{J_r}\left(T_A - D_S \cdot \omega_r + \frac{D_s}{n}\omega_g - K_s \int \left(\omega_r - \frac{\omega_g}{n}\right) dt\right), \\ \dot{\omega}_g &= \frac{1}{J_g}\left(-T_e - \left(D_g + \frac{D_s}{n^2}\right)\omega_g \right. \\ &\qquad \left. + \frac{D_s}{n}\omega_r - \frac{K_s}{n}\int \left(\omega_r - \frac{\omega_g}{n}\right) dt\right), \end{aligned} \tag{8}$$

where K_s is the stiffness constant and D_s is the damping constant of the shaft. To obtain the stiffness constant, the eigen frequency of the drive train has to be known. Consider a two-mass free swinging system; the eigen frequency is as follows [29]:

$$\omega_{0S} = 2\pi f_{0S} = \sqrt{\frac{K_s}{J_{\text{ges}}}}. \tag{9}$$

The total inertia of the free swinging system on the low speed is calculated by [29]:

$$J_{\text{ges}} = \frac{J_r \cdot J_g \cdot n^2}{J_r + J_g \cdot n^2}. \tag{10}$$

Consequently, the stiffness constant of the low speed shaft is [29]:

$$K_s = J_{\text{ges}} \cdot \left(2\pi f_{0S}\right)^2. \tag{11}$$

The damping constant D_s can be calculated by [29]:

$$D_s = 2\xi_s \cdot \sqrt{\frac{K_s \cdot J_{\mathrm{ges}}}{\xi_s^2 + 4\pi^2}}, \quad (12)$$

where ξ_s is the logarithmic decrement.

3.3. Linearized Model. The aerodynamic torque, T_A,must be opposed by an equal and opposite load torque, T_L, for the turbine to operate at steady speed. If T_A is greater than T_L, the turbine will accelerate, while if T_A is less than T_L, the turbine will decelerate. Equation (13) gives this mathematical description where J_T is the equivalent combined moment of inertia of the rotor, gear reducer and both the low speed and high speed shafts [37]:

$$J_T \dot{\omega}_T = T_A - T_L. \quad (13)$$

T_L is the mechanical torque necessary to turn the generator and was assumed to be a constant value derived from the wind turbine plant physical properties. The aerodynamic torque, T_A, is represent by (5). The power extracted from the wind is shown in (1). This equation is nonlinear, because the power coefficient c_p is highly nonlinear [37]. To simplify the analysis and design linear controllers, we should linearize this model.

Assuming $T_A|_{OP} \approx T_L|_{OP}$, the linearization of (1) is [37]

$$J_T \dot{\omega} = J_T \left.\frac{\partial \dot{\omega}}{\partial u}\right|_{OP} \Delta u + J_T \left.\frac{\partial \dot{\omega}}{\partial \omega}\right|_{OP} \Delta \omega + J_T \left.\frac{\partial \dot{\omega}}{\partial \beta}\right|_{OP} \Delta \beta. \quad (14)$$

In a simple form (14) becomes [37]:

$$\dot{\omega} = \alpha \Delta u + \gamma \Delta \omega + \delta \Delta \beta, \quad (15)$$

where $\Delta\omega_T$, Δu, and $\Delta\beta$ are the derivations at the operating points ω_{TOP}, u_{OP}, and β_{OP}. The parameters α, γ, and δ are coefficients.

α, γ, and δ represent the wind turbine dynamics at the linearization point. Their quantities depend on the wind speed and the partial derivatives of the coefficient of torque c_p with respect to λ and β. The magnitudes of α and δ are the relative weight of the effect wind speed u and pitch angle β on the wind turbine angular speed, respectively. Equation (15) is the linear equation describing the wind turbine dynamics.

The linear model (15) can be transformed by the Laplace transformation as follows [37]:

$$\Delta \omega (s) = \left[\alpha \Delta u (s) + \delta \Delta \beta (s)\right] \frac{1}{s - \gamma}. \quad (16)$$

The linearized model is at the angular rotation speed ω_{TOP}, the wind speed u_{OP}, and the pitch angle β_{OP}. It represents the change of rotor speed $\Delta\omega$ with respect to the inputs Δu and $\Delta\beta$. Therefore, the wind turbine is represented by the first order transfer function $G_p(s)$ [37]:

$$G_p (s) = \frac{\Delta \omega (s)}{\alpha \Delta u + \delta \Delta \beta} = \frac{\Delta \omega (s)}{(\Delta T_A / J_T)} = \frac{1}{s - \gamma}. \quad (17)$$

4. Control of the Wind Turbine

There are many results on wind turbines control from the aerodynamic to generator energy. In this paper, we only discuss the horizontal axis wind turbine and doubly fed induction generator (DFIG). This type of wind turbine is the most used in the market [1].

The performance of the wind turbine depends not only on hardware, also on the wind turbine control technique [38]. The main control objectives of the wind turbine are as follows [39, 40]:

(i) capture the wind power as possible as it can,

(ii) maximize the wind harvested power in partial load zone,

(iii) guarantee a certain level of resilience of the mechanical parts by alleviating the variable loads,

(iv) meet strict power quality standards (power factor, harmonics, flicker, etc.),

(v) transfer the electrical power to the grid at an imposed level in wide range of wind velocities.

The control system has three subsystems: aerodynamic control, variable speed control, and grid connection control; see Figure 10. In the following sections several popular control techniques will be discussed [41].

4.1. Aerodynamic Control. The wind turbine aerodynamics are very similar to the airplane. The blade rotates in the wind, because the air flowing along the surface moves faster than the upwind surface. This creates a lifting force to remove the sheet to rotate [30]. The attack angle of the blade plays a critical role in determining the amount of force and torque generated by the turbine. Therefore, it is an effective means to control the amount of power. There are three methods to aerodynamically control for large wind turbines: passive stall, active stall, and pitch control.

(i) Passive stall control: the blade is fixed on the rotor hub in an optimum (nominal) attack angle. When the wind speed is less than or equal to the nominal value, the turbine blades with the nominal attack angle capture the maximum possible power wind. With wind speed above the nominal value, the strong wind can cause turbulence on the surface of the blade, which faces away from the wind. As a result, the lifting force is reduced and eventually disappears with increasing wind speed by reducing the speed of rotation of the turbine. This phenomenon is called stall. The passive stall control does not need complex pitch mechanisms; however, the blades need a good aerodynamic design.

(ii) Active stall control: the stall phenomenon can be induced not only by higher wind speeds, but also by increasing the attack of the blade. Thus, active stall wind turbines have blades with adjustable pitch control mechanism. When the wind speed exceeds the rated value, the blades are controlled towards the

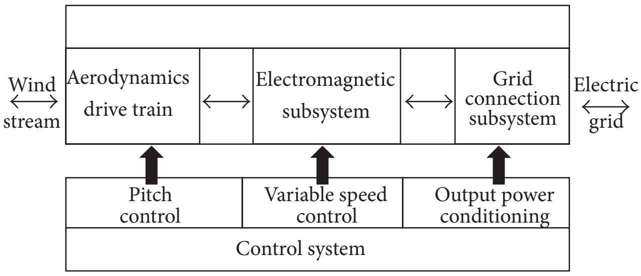

Figure 10: Main control subsystems of a wind turbine [38].

wind to reduce the captured power. Consequently, the captured power can remain at the nominal value by adjusting the blade angle of attack.

(iii) Pitch control: for the light and medium wind, the pitch control can optimize the operation of the wind turbine in the sense of maximizing rotor power. For the strong wind that exceeds the nominal level, pitch control maintains a desired operating condition [26]. The optimization operation by the pitch control can increase rotor power up to 2% [42]. This accuracy of the pitch angel is important but is not relevant for the stability investigations of short-term stress. Therefore, the steady-state angle of inclination can be adjusted to zero when the incoming wind is below the normal level. For strong wind, the steady-state angle is greater than zero and increases with increasing wind speed. Similar to the active stall control, the wind turbines with pitch control have adjustable blade in the rotor hub. When wind speed exceeds nominal value, the pitch controller reduces the attack angle, turning the blades (pitching) from wind gradually. The difference pressure in front and in the rear of the blade is reduced. The pitch control reacts faster than active stall control and provides better controllability.

4.2. Linear Control. Since the drive train is very rigid, its train dynamics do not need to be included. Furthermore, the drive system used in the turbine pitch is very fast. The actuator dynamics are not required. Without considering viscous damping, the dynamic of the direct drive turbine is as follows [1, 29, 37]:

$$T_{\text{aero}} - T_{\text{gen}} = I\dot{\omega}, \tag{18}$$

where T_{aero} is the aerodynamic torque generated by the rotor, T_{gen} is the generator torque, I is the inertia of the rotating system, and $\dot{\omega}$ is the rate of change of rotor speed.

Considering T_{gen} as a constant in the power regulation region, the derivative of (18) is [1, 29, 37]

$$\dot{T}_{\text{aero}} = I\ddot{\omega}. \tag{19}$$

The aerodynamic torque change depends on the change in wind speed, the change in the pitch angle of the rotor blades, and also the change at the current operating point of the turbine. For this representation of the turbine dynamics, the transfer function of the change rate of aerodynamic torque to the rotor speed is a double integrator. It is scaled by the inverse of the rotational inertia. Thus, this linear system is the control model.

The proportional integral derivative technique (PID) is the most popular and powerful linear control, because it is robust with respect to uncertainties and it has a simple form. PID control for the rotational speed error is [37]

$$u = K_p e(t) + K_i \int_0^t e(\tau)\, d\tau + K_d \frac{de(t)}{dt}, \tag{20}$$

where $e(t)$ is the rotational speed error and K_p, K_i, and K_d are the proportional, integral, and derivative gains of the PID controller, respectively.

Wind turbine PID control works quite well for speed regulation in low winds and has oscillations in pitch control of high winds [37]. To realize linear PID control, a traditional approach is to linearize the nonlinear turbine dynamics in a specified operating point [43]. The transfer function $G_C(s)$ for the PID controller between the input rotational speed error and the output pitch angle is [37]

$$G_c(s) = \frac{\Delta\beta_c(s)}{\Delta\omega(s)} = \frac{k_d s^2 + k_p s + k_i}{s}. \tag{21}$$

How to select the PID gains is not an easy job. In [37] a systematic approach with a visualization of the potential performance is presented. However, it still relies on the experience and the intuition of control engineers.

In certain operating points, a set of controllers can now be determined using LQ control [44]. To have a good tracking performance for both DC tracking problems in each integrator, the tracking error is included; see Figure 11. Here the controller gain K is calculated at each operating point for minimizing the cost J_c of [37]:

$$\begin{gathered} J_c = \int_{t=0}^{\infty} z(t)^T Q z(t) + u(t)^T R u(t)\, dt, \\ z = \left[Q_{\text{sh}} \;\; x_\omega \;\; x_Q\right]^T, \\ u = \left[\beta_{\text{ref}} \;\; Q_{g,\text{ref}}\right]^T, \end{gathered} \tag{22}$$

where β_{ref} is the pitch reference, ω_r is the velocity of the rotor, Q_g is the generator torque, ω_g is the output angular on the high speed side, and Q_{sh} is the torsion between the two inertias [37].

It should be noted that with the approach of interpolating controller gains, a good behavior cannot be guaranteed in terms of stability and performance for intermediate operating conditions. In practice, however, the method has shown various application areas [44]. One way of overcoming this problem is to apply LPV technique, such that the model is provided in a time-varying parameter, which is a prior unknown and measurable.

4.3. Nonlinear Control. Sliding mode control is a robust nonlinear feedback control technique. It can be applied for the wind turbine control [45, 46]; see Figure 12.

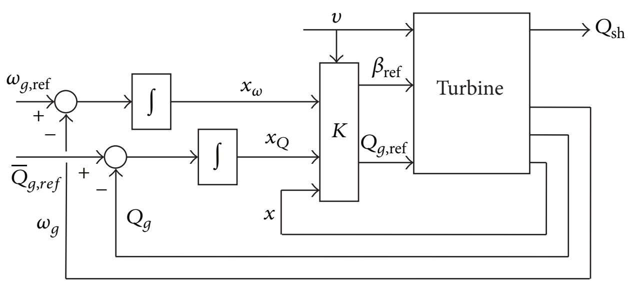

Figure 11: Block diagram of controller formulation [37].

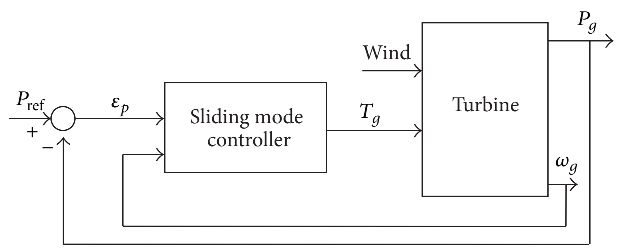

Figure 12: Sliding mode control for wind turbine [45].

The tracking error ε_p is defined as $\varepsilon_p = P_{\text{ref}} - P_w$, where P_w is the aerodynamic power (rotor power) defined in (1) and (3)and P_{ref} is the reference power. The derivative of ε_p is [45]

$$\dot{\varepsilon}_p = \dot{P}_{\text{ref}} - T_A\dot{\omega}_r - \dot{T}_A\omega_r. \quad (23)$$

The dynamic sliding mode controller is defined as follows [45]:

$$\dot{T}_A = \frac{(B+\lambda)}{\omega_r}\operatorname{sgn}\left(\varepsilon_p\right), \quad (24)$$

where $\dot{B}= |\varepsilon_p|$, λ is the tip-speed-ratio defined in (2) and ω_r is the wind turbine speed (velocity of the rotor) defined in (3):

$$\operatorname{sgn}(s) = \begin{cases} 1 & \text{if } s > 0, \\ -1 & \text{if } s < 0. \end{cases} \quad (25)$$

The closed-loop system is [45]

$$\dot{\varepsilon}_p = \dot{P}_{\text{ref}} - T_A\dot{\omega}_r - (B+\lambda)\operatorname{sgn}\left(\varepsilon_p\right). \quad (26)$$

The uncertainty is defined as $d = \dot{P}_{\text{ref}} - T_A\dot{\omega}_r$, and it is bounded as $|d| < B_1$; B_1 is a positive constant. Then, (26) is rewritten as follows [45]:

$$\dot{\varepsilon}_p = -(B+\lambda)\operatorname{sgn}\left(\varepsilon_p\right) + d. \quad (27)$$

A Lyapunov function is defined as follows [45]:

$$V = \frac{1}{2}\varepsilon^2 + \frac{1}{2}\left(B - B_1\right)^2. \quad (28)$$

It is not difficult to see that its time derivative satisfies [45]

$$\dot{V} \le -\lambda\,|\varepsilon|\,. \quad (29)$$

By the LaSalle theorem, it is concluded that the tracking error converges asymptotically to zero.

Since the sliding mode control system provides dynamic invariant property with uncertainties, it has to increase gains when tracking error is not zero. The main problem of the sliding mode control is the chattering. To decrease this behavior the sign function can be approximated as $\operatorname{sgn}(\varepsilon_p) \approx \varepsilon_p/(|\varepsilon_p|+a_0)$; a_0 is small positive constant. This prevents from increased mechanical stress due to strong torque variations. Another chattering reduction method is to use the boundary layer $m\operatorname{sgn}(s)$ around the switching surface as follows [45]:

$$m\operatorname{sgn}(s) = \begin{cases} \operatorname{sgn}(s) & \text{if } s \ge \delta, \\ \dfrac{s}{\delta} & \text{if } s = \delta. \end{cases} \quad (30)$$

4.4. Intelligent Control. Neural control for the wind turbine is shown in Figure 13. Here the adaptive controller has the learning ability [50–53]. The objective is to train the neural network so that the controller will allow the plant to produce the desired result [47]. To accomplish this, the neural network must be trained so that the input error $\varepsilon_p = e(t) = P_{\text{ref}} - P_w = x_d(t) - x_n(t)$ produces the proper control parameter $T_A = u(t)$ to be applied to the plant to produce the aerodynamic power $P_w = x_n(t)$ [54].

Fuzzy control for the wind turbine is shown in Figure 14. $\varepsilon_p = \Delta Q = P_{\text{ref}} - P_w = Q^* - Q$ is the tracking error, $P_{\text{ref}} = Q^*$ is the reference, $P_w = Q$ is the aerodynamic power, and $T_A = Vdr^*$ is the control input. Here each input is evaluated by the triangular or trapezoidal membership functions [48, 55–57]. The degree of membership of the fuzzy sets is associated with each input. The defuzzification is obtained by averaging each output membership function [58, 59].

In [48], each input/output variable that is used in the controller design is expressed in fuzzy set using linguistic variables. Seven linguistic variable are used for LLP, CII, and the flow change rate. The rules are expressed by IF-THEN rules. The defuzzification uses the center gravity technique.

4.5. Generalized Predictive Control. Model predictive control (MPC) usually represents the behavior of complex dynamic systems. It is also applied to the wind turbines [60, 61]. It appears in the form of generalized predictive control (GPC) [62] and bias estimation model (BEM) [49].

GPC uses the estimations of future output to calculate current control [38]. A discrete model of wind turbine is shown in Figure 15. It is a finite difference approximation of the double integrator model. Here Δ_p is the change in the angle of the blade pitch, Δ_v is the wind speed change, and ω is the rotor speed. The coefficients b and c are obtained by a recursive least squares filter.

This model can predict the rotor speed with varying ratios and wind speed. The coefficients b and c increase with the wind speed increasing. The GPC method can be summarized as follows.

The cost function J is [49]

$$J = \left(W - W_D\right)^T Q\left(W - W_D\right) + \sigma u^T u, \quad (31)$$

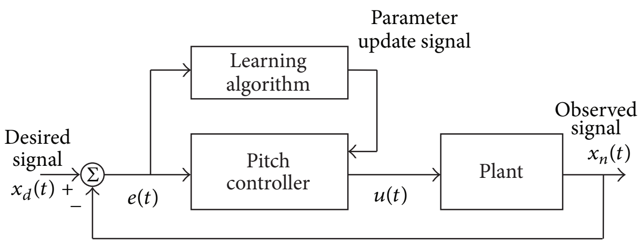

Figure 13: Neural network controller [47].

where Q is the weighting matrix, W_D is the desired response vector, which is known for all time from the desired rotor speed, and σ is the deciding factor that weights the use of control against error in the desired response. For positive semidefinite cost function Q, the control law u is [49]

$$u = \left(\sigma I + G^T Q G\right)^{-1} G^T Q \left(W_D - F\right). \tag{32}$$

To calculate the inverse, Q is chosen as a diagonal matrix. The above can be written as follows [49]:

$$W = Gu + F, \tag{33}$$

where

$$W = \begin{pmatrix} \omega(n+1) \\ \omega(n+2) \\ \Delta\omega(n+1) \\ \Delta\omega(n+1) \end{pmatrix},$$

$$u = \begin{pmatrix} \Delta u(n) \\ \Delta u(n+1) \end{pmatrix},$$

$$G = \begin{pmatrix} 0 & 0 \\ b & 0 \\ 0 & 0 \\ b & 0 \end{pmatrix},$$

$$F = \begin{pmatrix} 2\omega(n) + \omega(n-1) + b\Delta p(n+1) + c\Delta v(n+1) \\ 2F(1) - G\omega(n) + c\Delta v(n) \\ \Delta\omega(n) + b\Delta p(n+1) + c\Delta v(n+1) \\ F(3) + c\Delta v(n) \end{pmatrix}. \tag{34}$$

The transient response of this method is not good, because of the double integrator and short control horizon. The term $\Delta\omega$ is added to provide derivative-type control to improve the transient response.

The desired change in the pitch for the current time step is given by the first element of u. The GPC method is able to adjust the control system as the coefficients vary with changing conditions. However, the change in control is not the preferred change. As wind speed and b increase, the method utilizes the additional gain to obtain a more accurate rotor speed. To enable the system to perform similarly for all wind speeds, the deciding factor σ is scaled by $b, \sigma = \sigma_0 b$, where σ_0 is a constant.

BEM can estimate the unmodelled disturbances acting on the system with additional equations. This method is

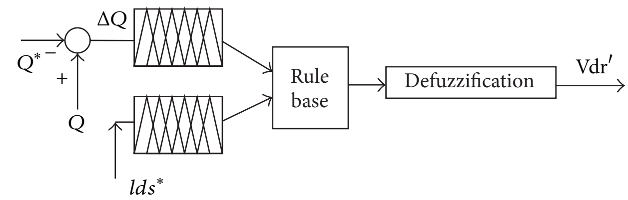

Figure 14: The block diagram of reactive power fuzzy logic controller [48].

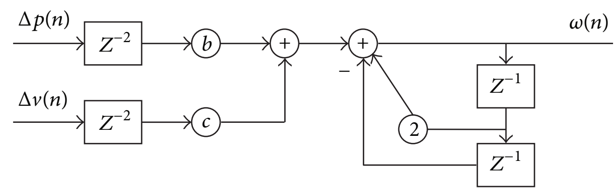

Figure 15: Wind turbine model [49].

investigated because the wind speed over the rotor disk cannot be measured exactly [38]. Consequently, the bias term estimation is useful for the effect of changes in wind speed acting on the turbine.

BEM uses the same model as GPC; see Figure 16. Here the coefficients b and c are determined for 12 m/s wind speed and the average values of b_M and c_M. The estimate of Δ_v is included in the control law to cancel the disturbance.

5. Offshore Floating Wind Turbines

The growing demand for wind energy offshore installed in recent years has been motivated primarily by reduced space for installation in the land and the great advantages to mention a few [63]:

(i) better energy production,
(ii) reduced turbulence intensity,
(iii) higher capacity factor,
(iv) avoids size limits.

Currently investigating this type of turbine is focused not only on controlling wind energy production, but also in three groups, namely, the design [64, 65], installation, and electrical infrastructure and maintenance [66]. This is because the material from which the turbine should be constructed to be resistant to salinity and big changes suffered from the sea climate; secondly because there is no restriction on the dimensions of the turbine, the installation makes it expensive and difficult because it is in the sea; once installed, the turbine in the sea faces another major challenge which is the operation of the network generation; this is done at long distance including wiring, substations, and connecting to the network. Once designed, installed, and put into operation only a challenge remains to cover which is maintenance; this maintenance is usually very expensive due to the conditions under which it is done in some cases in the depth of the sea in other weather conditions [67].

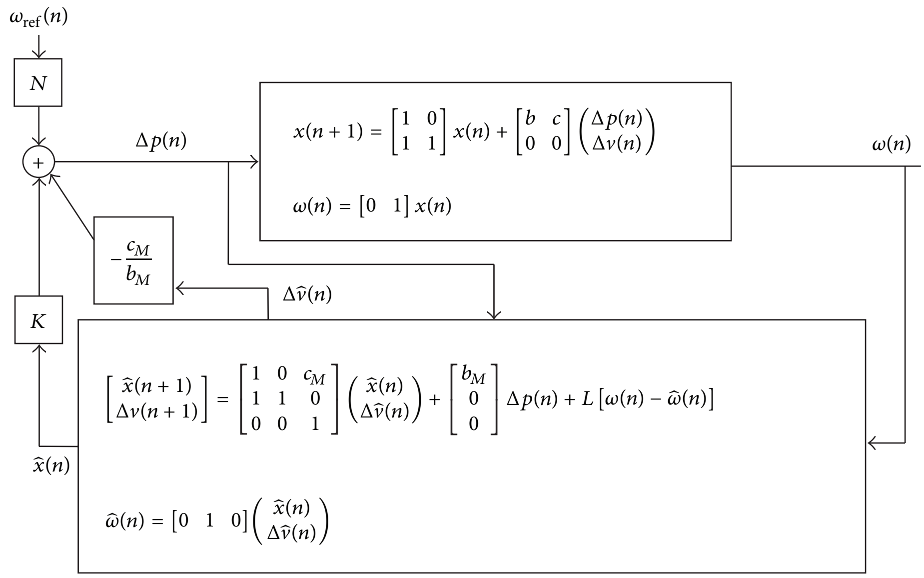

FIGURE 16: BEM control system [38].

6. Conclusions

Green energy has opened an important branch and shows in the rise of technology. The wind turbines and related techniques, environment, structure, and control methodology, are paid more attention recently. This paper presents the most common used wind turbine models which are classified with respect to different objectives as are more production energy, safety of turbine, connection to grid; consequently, the wind turbine dimensions are increased and the control methods are required to respond quickly and effectively to the important task of the power generation. The previous fact results in high cost of the sensors as well as the instability of the system; therefore, more complex identification techniques are required to help the control.

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