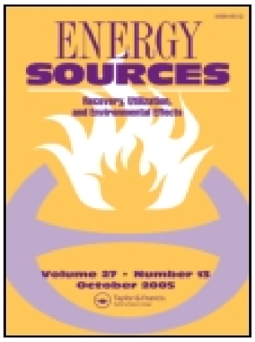

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A Review of Modern Wind Turbine Technology

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Abstract *This article deals with a review of modern wind turbine technology. Wind energy for electricity production today is a mature, competitive, and virtually pollution-free technology widely used in many areas of the world. Wind technology converts the energy available in wind to electricity or mechanical power through the use of wind turbines. A wind turbine is a machine for converting the mechanical energy in wind into electrical energy. Wind turbines capture the power from the wind by means of aerodynamically designed blades and convert it into rotating mechanical power. Wind turbine blades use airfoils to develop mechanical power. Recent advances in technology and performance have resulted in current wind turbine designs being increasingly efficient, cost effective, and reliable.*

Keywords control of turbines, electricity, turbine desing, wind energy, wind turbine

Introduction

In recent years, there has been growing interest in renewable energy systems due to the environmental problem and the economic benefits from fossil fuel savings (Han et al., 2007). Renewable energy sources like wind energy is indigenous and can help in reducing the dependency on fossil fuels. Wind is the indirect form of solar energy and is always being replenished by the sun. Wind is caused by differential heating of the earth's surface by the sun. It has been estimated that roughly 10 million megawatt (MW) of energy are continuously available in the earth's wind (Joselin Herbert et al., 2007). One of the largest problems of wind power, as compared to conventionally generated electricity, is its dependence on the volatility of the wind which is directly related to the meteorological conditions (Marciukaitis et al., 2008).

Wind energy has a lower delivered cost than any other new non-hydroelectric renewable resource (Menz, 2005). During the 1980s, the cost of wind-generated electricity dropped from about 15–20 cents/KWh (EC, 2007) to the current average cost of 3–7 € cents/KWh, as indicated in Table 1. However, the major factor in the reduction of the cost of wind energy over the last 20 years has been the increase in the size of individual wind turbines and wind farm projects together with engineering and design improvements to the blades, electronic controls, and weight reduction of individual components that impacts their manufactured costs (Barthelmie, 2007).

Wind energy for electricity production today is a mature, competitive, and virtually pollution-free technology widely used in many areas of the world (Ottinger, 2005). Global wind electricity production grew from 8.1 terrawatt-hours (TWh) in 1995 to 98.4 TWh in 2005 (Observ'ER, 2006). As can be seen from Figure 1, approximately 0.55% of the

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Table 1
Electricity production costs in 2004

Energy source	€ cents/kWh
Wind	3–7
Biomass	5–8
Geothermal	5–8
Solar thermal	10–20
Ocean	10–25
Photovoltaics	20–42
Coal	3–6
Natural gas	2–4
Nuclear	4–7

Source: Diamantaras, 2005.

world electricity production comes from wind energy. Wind power was second in power capacity added, with 11,500 MW added and existing capacity growing by 24% to reach 59,000 MW in 2005 (REN21, 2006; Balat, 2007). According to the EWEA 2006 figures (EWEA, 2006), there were, at the end of 2005, 47,000 wind power turbines installed throughout the EU with a total output of 40,504 MW (69% of the global total).

Wind technology converts the energy available in wind to electricity or mechanical power through the use of wind turbines (Balat, 2005). Wind turbines have been in use since 1941 when the world's first megawatt-size wind turbine was connected to the local electrical distribution system in Vermont, USA (Drewry and Georgiou, 2007). The innovative 200 kW Gedser wind turbine was built in 1956–1957 by J. Juul for the electricity company SEAS at Gedser coast in the southern part of Denmark (Babu et al., 2006). Since the 1970s, the use of large, modern wind turbines has become popular for

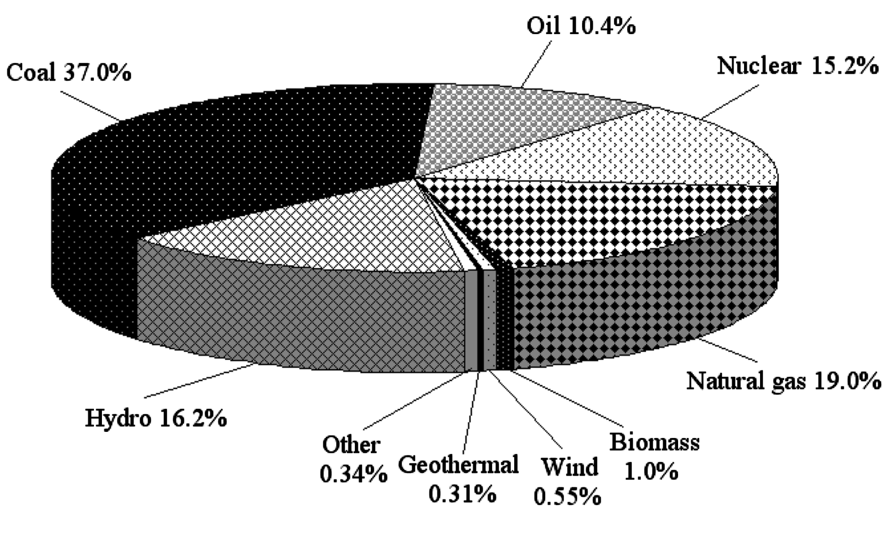

Figure 1. The share of energy sources in world electricity production in 2005. (*Source*: Observ'ER, 2006; Cronshaw, 2006; BGR, 2007.)

electricity generation in some places (Courtney, 2006). Modern wind turbine generators, which in the United States have traditionally been utilized in large wind farms, are now being sited at individual facilities in a number of distributed generation applications (duPont, 2003). Modern wind turbines are large to maximize interaction with the air and, thus, gain efficiency (Courtney, 2006). Modern wind technology takes advantage of advances in materials, engineering, electronics, and aerodynamics (Demirbas, 2006).

Modern Wind Turbines

Modern wind turbines fall into two basic groups: the horizontal-axis variety and the vertical-axis design (Demirbas, 2006). Turbines that rotate around a horizontal axis are most common. Vertical axis turbines are less frequently used (Drewry and Georgiou, 2007). Both types use aerodynamic lift to extract power from the wind. They also have the same sub-systems, as illustrated in Figure 2 (Rizk and Nagrial, 2000).

Horizontal Axis Wind Turbines

Horizontal axis wind turbines (HAWTs) have the main rotor shaft running horizontally and the generator at the top of a tower, and must be pointed into the wind by some means (Babu et al., 2006). Many of these turbines also support independent blade pitch action—each of the blades of the turbine can be pitched about its longitudinal axes (Suryanarayanan and Dixit, 2005). Typical large wind turbines today are massive 3-bladed, horizontal-axis structures with enormous blade spans (70–100 m diameter), tall towers (60–100 m in height), and power ratings in the range 1–5 MW (Suryanarayanan and Dixit, 2007).

Vertical Axis Wind Turbines

Vertical axis wind turbines (VAWTs) have the potential to produce more power than the common HAWT based on their structural superiority (DeCoste et al., 2006). VAWT's

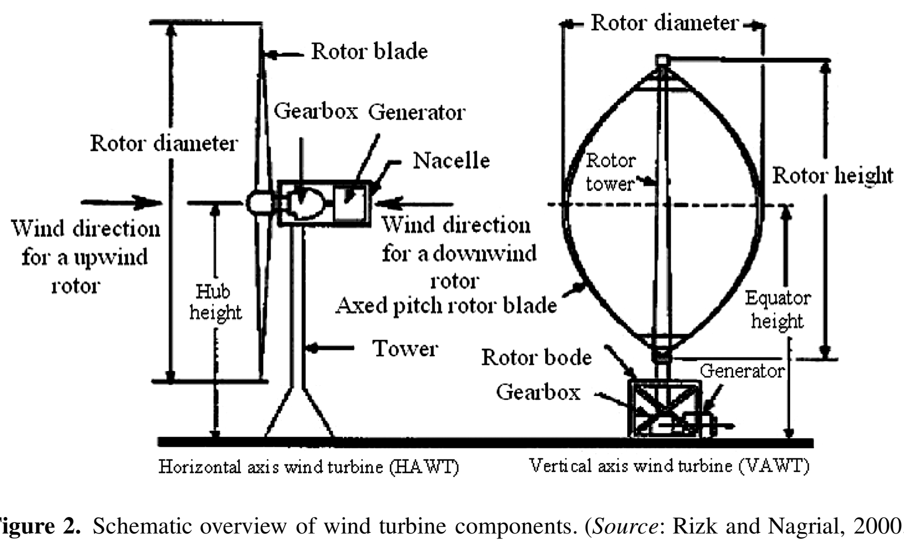

Figure 2. Schematic overview of wind turbine components. (*Source*: Rizk and Nagrial, 2000.)

rotating axis is vertical to the wind direction, and there are two types of VAWT: Savonius type using drag force and Darrieus type using lift force (Hwang et al., 2006). VAWTs have several advantages in comparison with the conventional propeller type, HAWTs. For example, the conventional wind turbines have to be set into the wind direction to operate at the maximum efficiency point; however, VAWT operates independently of the wind direction (Fukudome et al., 2005). VAWT capacities are comparable to HAWT, and with a possible shift in technology from horizontal to vertical designs, the potential for VAWT to reach a higher capacity than the HAWT are plausible. Other advantages of the VAWT are that the mechanical power generation equipment can be located at ground level, which makes for easy maintenance (DeCoste et al., 2006).

Producing Electricity Using Wind Turbines

A wind turbine is a machine for converting the mechanical energy in wind into electrical energy (Babu et al., 2006). A typical wind turbine can produce 1.5 to 4.0 million kWh of electricity a year (Courtney, 2006). At a reasonable wind site, a typical wind turbine will produce electricity 70–85% of the time (Barthelmie, 2007).

The function of a wind turbine is to convert the motion of the wind into rotational energy that can be used to drive a generator, as illustrated in Figure 3. Wind turbines capture the power from the wind by means of aerodynamically designed blades and convert it into rotating mechanical power. Wind turbine blades use airfoils to develop mechanical power (Blaabjerg et al., 2004).

The cross-sections of wind turbine blades have the shape of airfoils as the one shown in Figure 4. Airflow over an airfoil produces a distribution of forces along the airfoil surface. The resultant of all these pressure and friction forces is usually resolved into two forces and a moment, lift force, drag force, and pitching moment, as shown in Figure 4 (Blaabjerg et al., 2004).

Wind turbines are relatively simple systems that generate electricity when wind conditions are between 3 and 4 meters per second (m/s), the speed at which the turbine blades experience sufficient lift to begin rotating, and 25 to 30 m/s, depending on the manufacturer and model (Fitch, 2006). The highest wind speed at which a wind turbine generates electricity is called its furling speed. A wind turbine only provides power when the wind speed is high enough and not too high. The precise values of the lowest and highest wind speeds for power generation depend on the design of wind turbine (Courtney, 2006). The power (P) is related to the air density (ρ) and is proportional to

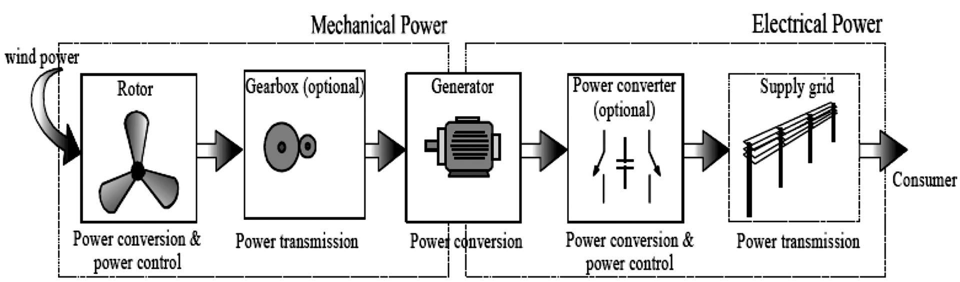

Figure 3. Conversion from windpower to electrical power in a wind turbine. (*Source*: Blaabjerg et al., 2004.)

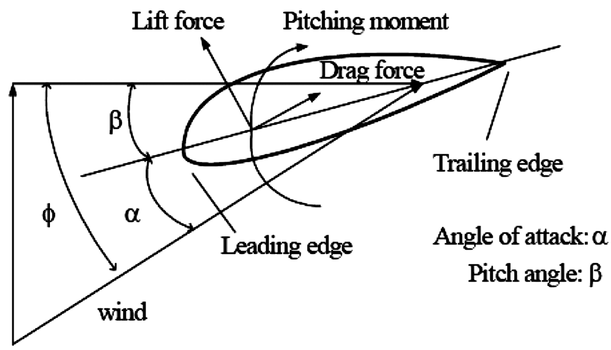

Figure 4. A simple airfoil used in wind turbines. (*Source*: Blaabjerg et al., 2004.)

the cube of the wind speed (U) and the square of the rotor radius (r) (Barthelmie, 2007):

$$P = \frac{1}{2}\rho\pi r^2 U^3 \tag{1}$$

The exact amount of electricity produced depends on the wind turbine according to its individual power curve (Figure 5). Once the wind speed increases above the cut-in wind speed, the electricity output increases quickly until the wind speed reaches the "rated wind speed" when the turbine reaches its rated power output and the electricity production is no longer a function of wind speed. For the current generation of wind turbines installed in a commercial context by a utility company (or other wind farm operator) this will be of the order 1.5 MW at about 12 m/s and above (Barthelmie, 2007). The two-parameter probability density function is used to represent the wind speed probability distribution (Pryor et al., 2005):

$$P(U) \equiv \frac{k}{A}\left[\frac{U}{A}\right]^{k-1} \exp\left[-\left[\frac{U}{A}\right]^{k}\right] for\ U \geq 0, A > 0, k > 0 \tag{2}$$

where k is the dimensionless shape parameter (a measure of the peakedness of the distribution), A is the scale parameter (a measure of the central tendency), and $P(U)$ is the probability density function.

As an approximation, the scale parameter is related to the annual mean wind speed as follows (Morthorst and Andersen, 2005):

$$\overline{U} = \frac{1}{T}\int_0^T U(t)dt = \int_0^\infty UP(U)dU \approx 0.89A \tag{3}$$

where T is the time over which the average is taken. T should be large, such as one year, or even better, 10–20 years. This is because wind speed varies significantly during the year, and even the annual average wind speed may vary by up to 10–20% between different years.

In the example depicted in Figure 5, the wind speed distribution has a shape parameter (related to the variability) of 2.0 and a scale parameter (related to the mean wind speed) of 8.0 m/s. Shape parameters can be between about 1 and 4 but are typically between 2 and 3. For the same scale parameter, a larger shape parameter indicates a wider wind speed distribution (Barthelmie, 2007).

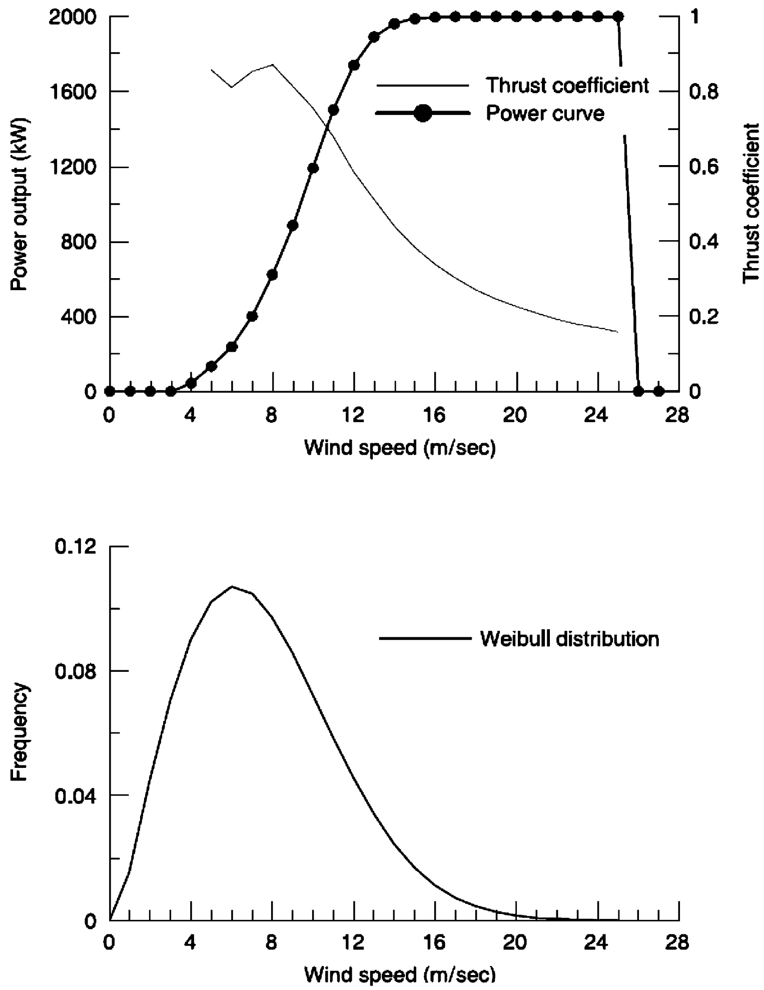

Figure 5. An example power curve for a Bonus 2 MW wind turbine (top) and an example Weibull distribution where the shape parameter, which is related to the variability, is 2.0 and the scale parameter, which is related to the mean, is 8.0 m/sec. (*Source*: Barthelmie, 2007.)

The "availability" of wind turbines (i.e., the percentage of the time when wind speeds meant that electricity production was possible to the amount of time the turbines were actually operating) typically exceeds 98% for onshore wind farms (Barthelmie, 2007). Future major developments of wind power capacities are likely to take place offshore. As for onshore wind parks, short-term wind power prediction up to 48 h ahead is expected to be of major importance for the management of offshore farms and their secure integration to the grid (Pinson et al., 2004). Higher and more regular wind speeds, as well as the possibility to install numerous and powerful (multi-megawatt) wind turbines, are the main advantages of going offshore to produce electricity. Wind speeds in the power production classes in the offshore environment are more persistent than those onshore. Calms are less frequent and less persistent (Kariniotakis et al., 2004). When inspecting offshore wind power production data averaged at a few-minute rate, one observes variations that are due to slower local atmospheric changes, e.g., frontline passages and rain showers (Pinson et al., 2007).

Wind Turbine Design Characteristics

Most wind turbines have upwind rotors that are actively yawed to preserve alignment with wind direction. The three-bladed rotor is the most popular and, typically, has a separate front bearing with a low-speed shaft connected to a gearbox which provides an output speed suitable for a four-pole generator (Figure 6) (Drewry and Georgiou, 2007). The design life-time of modern wind turbines is normally thought to be 20 years, and the corresponding number of rotations is of the order 10^8 to 10^9. The basic design aspects for a rotor blade are the selection of material and shape. The material should be stiff, strong, and light. The challenge for the designers is thus to go beyond the simple plank and the shape of the blade with pre-twist into a design of the blade structure that is optimized with respect to materials selection and cost-effective production (Babu et al., 2006).

The blades convert the wind energy into rotational forces that drive the generator. Although these blades are rigidly attached to the generator, the pitch angle of the blades is variable. The blades change pitch during operation by passively twisting. The blades start at pitch-up position and flatten-out as the turbine speed increases. This makes the pitch angle be adjusted in such a way as to operate the wind turbine at its optimal performance. Hence, the power extracted from the wind turbine is being maximized in a wide variety of wind speed (Han et al., 2007). The characteristic parameters of a wind turbine are given in Table 2.

Recent advances in technology and performance have resulted in current wind turbine designs being increasingly efficient, cost effective, and reliable. The popular size of machines has moved from the small-medium range, 50–100 kW, to much larger 200 kW to 1 MW systems. In the period from the mid 1970s to the mid 1980s, the average power (kWh) per swept area (m^2) increased approximately 40% (Lee and Flay, 1999).

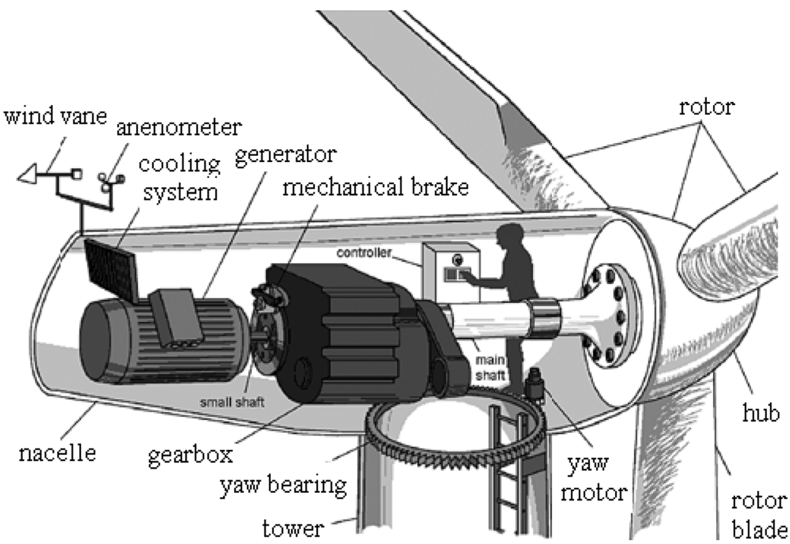

Figure 6. Wind turbine open nacelle. (*Source*: Drewry and Georgiou, 2007.)

Table 2
The characteristic parameters of wind turbine

Radius of turbine	24 m
Rated power	750 kW
Cut-in wind speed	4 m/s
Cut-out wind speed	25 m/s
Rated wind speed	16 m/s

Source: Han et al., 2007.

Control of Wind Turbines

Control applications for wind turbines have received increased attention in the past decade (Barbu and D'Amato, 2006). Reliable and powerful control strategies are needed for wind energy conversion systems to achieve maximum performance (Boukhezzar et al., 2007). Wind turbines can operate either with a fixed speed or a variable speed. Variable speed control of wind turbines is of practical interest (Song, 2000). Typically, variable-speed turbines use aerodynamic controls in combination with power electronics to regulate torque, rotational speed (RPM), and power (Muljadi et al., 1998). Generally, power electronics are used to command generator torque to change the rotor speed as the wind speed fluctuates, thus tracking peak power. Using generator torque to influence the blade-bending loads, however, is not practical because cyclic torque would be transmitted through the drive-train, which would compromise one of the main benefits of variable-speed operation. Also, only symmetric loads would be influenced. A more direct and effective method is individual blade pitch (Stol, 2003). From a system theoretic perspective (Figure 7), the power production mode control problems may be cast as (Suryanarayanan and Dixit, 2007):

$$\min_{\tau,\beta_i} \| T_{\delta v \to \delta w} \| \tag{4}$$

where δv, δw, β_i, and τ, respectively denote the deviation in wind velocity from a reference, the deviation in the vector of output variables of interest from a reference,

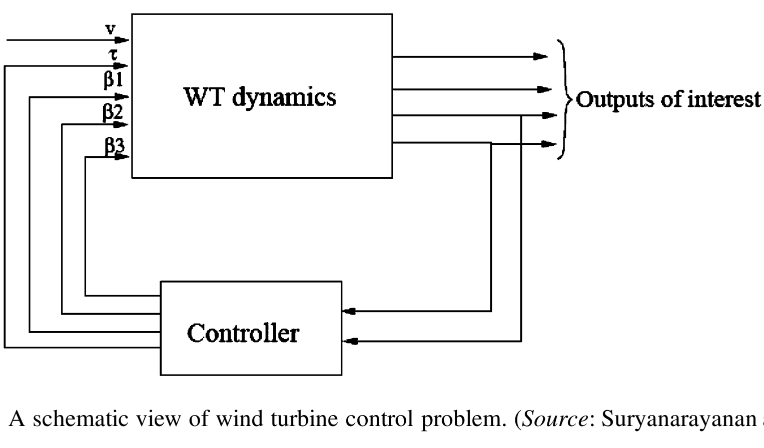

Figure 7. A schematic view of wind turbine control problem. (*Source*: Suryanarayanan and Dixit, 2007.)

the blade pitch angles, and the generator torque demand and $\|.\|$ denotes an appropriate norm.

For a variable speed wind turbine with a pitch control system, which regulates the effective rotor blade angle, optimum power can be obtained using appropriate control methods (Sharma et al., 2001). The blade pitch control is relatively fast, however, and can be better used to regulate power flow especially when near the high speed limit (Muljadi and Butterfield, 1999). In low to moderate wind speeds, the turbine should simply try to produce as much power as possible, so there is generally no need to vary the pitch angle. The pitch angle should only be at its optimum value to produce maximum power. In high wind speeds, pitch control provides a very effective means of regulating the aerodynamic power and loads produced by the rotor so that design limits are not exceeded (Sun et al., 2004). The commonly used pitch control techniques are classified as passive and active pitch control. In passive regulation, the turbine blades are stalled at a certain wind speed higher than the rated wind speed to keep the power constant at rated value. Some systems use hydraulic actuators or separate electric actuators for each blade. In active pitch control, the blade pitch angle is continuously adjusted based on the measured parameters to generate the required power output. In some cases, it has been observed that the active pitch regulation sometimes can make the system unstable during highly variable wind conditions (Sharma et al., 2001). A pitch angle controller will limit the power when the turbine reaches nominal power. The generated electrical power is done by controlling the doubly-fed generator through the rotor-side converter. The control of the grid-side converter is simply just keeping the dc-link voltage fixed. Internal current loops in both converters are used, which typically are linear PI-controllers, as it is illustrated in Figure 8a. The power converters to the grid-side and the rotor-side are voltage source inverters (Blaabjerg et al., 2004).

Another solution for the electrical power control is to use the multi-pole synchronous generator. A passive rectifier and a boost converter are used to boost the voltage at low speed. The system is industrially used today. It is possible to control the active power from the generator. The topology is shown in Figure 8b. A grid inverter is interfacing the dc-link to the grid. Here it is also possible to control the reactive power to the grid. Common for both systems are that they are able to control reactive and active power very fast, and thereby, the turbine can take an active part in the power system control (Blaabjerg et al., 2004).

Conclusions

Modern wind turbines are large to maximize interaction with the air and, thus, gain efficiency. Modern wind technology takes advantage of advances in materials, engineering, electronics, and aerodynamics. A typical wind turbine can produce 1.5 to 4.0 million kWh of electricity a year. Wind turbines are relatively simple systems that generate electricity when wind conditions are between 3 and 4 meters per second (m/s), the speed at which the turbine blades experience sufficient lift to begin rotating, and 25 to 30 m/s, depending on the manufacturer and model.

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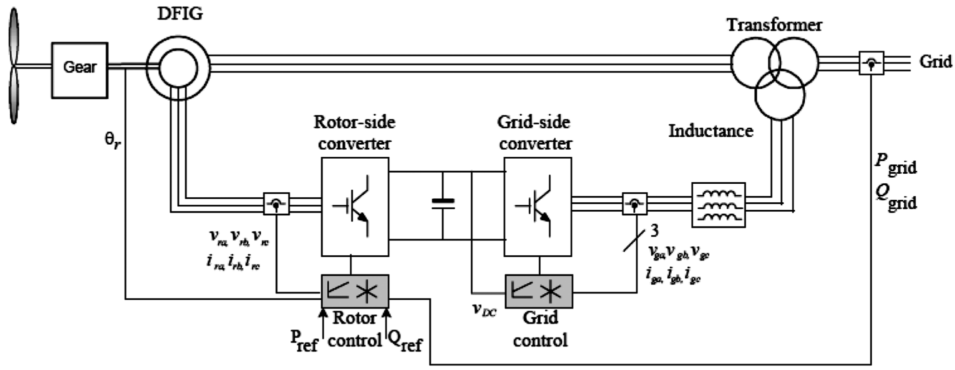
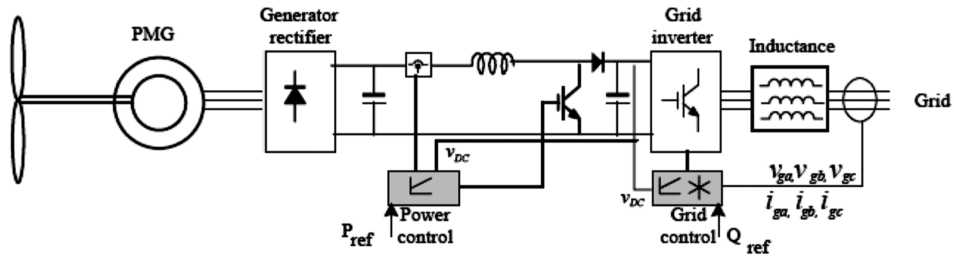


(a)



(b)

Figure 8. Basic control of active and reactive power in a wind turbine: (a) Doubly-fed induction generator system and (b) multi-pole synchronous generator system. (*Source*: Blaabjerg et al., 2004.)

Reliable and powerful control strategies are needed for wind energy conversion systems to achieve maximum performance. Wind turbines can operate either with a fixed speed or a variable speed. Variable speed control of wind turbines is of practical interest. For a variable speed wind turbine with a pitch control system, which regulates the effective rotor blade angle, optimum power can be obtained using appropriate control methods. The blade pitch control is relatively fast, however, and can be better used to regulate power flow especially when near the high speed limit.

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