CHAPTER 1

Fundamentals of wind energy

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The rising concerns over global warming, environmental pollution, and energy security have increased interest in developing renewable and environmentally friendly energy sources such as wind, solar, hydropower, geothermal, hydrogen, and biomass as the replacements for fossil fuels. Wind energy can provide suitable solutions to the global climate change and energy crisis. The utilization of wind power essentially eliminates emissions of CO_2, SO_2, NO_x and other harmful wastes as in traditional coal-fuel power plants or radioactive wastes in nuclear power plants. By further diversifying the energy supply, wind energy dramatically reduces the dependence on fossil fuels that are subject to price and supply instability, thus strengthening global energy security. During the recent three decades, tremendous growth in wind power has been seen all over the world. In 2009, the global annual installed wind generation capacity reached a record-breaking 37 GW, bringing the world total wind capacity to 158 GW. As the most promising renewable, clean, and reliable energy source, wind power is highly expected to take a much higher portion in power generation in the coming decades.

The purpose of this chapter is to acquaint the reader with the fundamentals of wind energy and modern wind turbine design, as well as some insights concerning wind power generation.

1 Wind energy

Wind energy is a converted form of solar energy which is produced by the nuclear fusion of hydrogen (H) into helium (He) in its core. The H $\rightarrow$ He fusion process creates heat and electromagnetic radiation streams out from the sun into space in all directions. Though only a small portion of solar radiation is intercepted by the earth, it provides almost all of earth's energy needs.

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Wind energy represents a mainstream energy source of new power generation and an important player in the world's energy market. As a leading energy technology, wind power's technical maturity and speed of deployment is acknowledged, along with the fact that there is no practical upper limit to the percentage of wind that can be integrated into the electricity system [1]. It has been estimated that the total solar power received by the earth is approximately 1.8×10^{11} MW. Of this solar input, only 2% (i.e. 3.6×10^9 MW) is converted into wind energy and about 35% of wind energy is dissipated within 1000 m of the earth's surface [2]. Therefore, the available wind power that can be converted into other forms of energy is approximately 1.26×10^9 MW. Because this value represents 20 times the rate of the present global energy consumption, wind energy in principle could meet entire energy needs of the world.

Compared with traditional energy sources, wind energy has a number of benefits and advantages. Unlike fossil fuels that emit harmful gases and nuclear power that generates radioactive wastes, wind power is a clean and environmentally friendly energy source. As an inexhaustible and free energy source, it is available and plentiful in most regions of the earth. In addition, more extensive use of wind power would help reduce the demands for fossil fuels, which may run out sometime in this century, according to their present consumptions. Furthermore, the cost per kWh of wind power is much lower than that of solar power [3].

Thus, as the most promising energy source, wind energy is believed to play a critical role in global power supply in the 21st century.

2 Wind generation

Wind results from the movement of air due to atmospheric pressure gradients. Wind flows from regions of higher pressure to regions of lower pressure. The larger the atmospheric pressure gradient, the higher the wind speed and thus, the greater the wind power that can be captured from the wind by means of wind energy-converting machinery.

The generation and movement of wind are complicated due to a number of factors. Among them, the most important factors are uneven solar heating, the Coriolis effect due to the earth's self-rotation, and local geographical conditions.

2.1 Uneven solar heating

Among all factors affecting the wind generation, the uneven solar radiation on the earth's surface is the most important and critical one. The unevenness of the solar radiation can be attributed to four reasons.

First, the earth is a sphere revolving around the sun in the same plane as its equator. Because the surface of the earth is perpendicular to the path of the sunrays at the equator but parallel to the sunrays at the poles, the equator receives the greatest amount of energy per unit area, with energy dropping off toward the poles. Due to the spatial uneven heating on the earth, it forms a temperature gradient from the equator to the poles and a pressure gradient from the poles to the equator. Thus, hot air with lower air density at the equator rises up to the high atmosphere and moves towards the poles and cold air with higher density flows from the poles towards the equator along the earth's surface. Without considering the earth's self-rotation and the rotation-induced Coriolis force, the air circulation at each hemisphere forms a single cell, defined as the meridional circulation.

Second, the earth's self-rotating axis has a tilt of about 23.5° with respect to its ecliptic plane. It is the tilt of the earth's axis during the revolution around the sun that results in cyclic uneven heating, causing the yearly cycle of seasonal weather changes.

Third, the earth's surface is covered with different types of materials such as vegetation, rock, sand, water, ice/snow, etc. Each of these materials has different reflecting and absorbing rates to solar radiation, leading to high temperature on some areas (e.g. deserts) and low temperature on others (e.g. iced lakes), even at the same latitudes.

The fourth reason for uneven heating of solar radiation is due to the earth's topographic surface. There are a large number of mountains, valleys, hills, etc. on the earth, resulting in different solar radiation on the sunny and shady sides.

2.2 Coriolis force

The earth's self-rotation is another important factor to affect wind direction and speed. The Coriolis force, which is generated from the earth's self-rotation, deflects the direction of atmospheric movements. In the north atmosphere wind is deflected to the right and in the south atmosphere to the left. The Coriolis force depends on the earth's latitude; it is zero at the equator and reaches maximum values at the poles. In addition, the amount of deflection on wind also depends on the wind speed; slowly blowing wind is deflected only a small amount, while stronger wind deflected more.

In large-scale atmospheric movements, the combination of the pressure gradient due to the uneven solar radiation and the Coriolis force due to the earth's self-rotation causes the single meridional cell to break up into three convectional cells in each hemisphere: the Hadley cell, the Ferrel cell, and the Polar cell (Fig. 1). Each cell has its own characteristic circulation pattern.

In the Northern Hemisphere, the Hadley cell circulation lies between the equator and north latitude 30°, dominating tropical and sub-tropical climates. The hot air rises at the equator and flows toward the North Pole in the upper atmosphere. This moving air is deflected by Coriolis force to create the northeast trade winds. At approximately north latitude 30°, Coriolis force becomes so strong to balance the pressure gradient force. As a result, the winds are defected to the west. The air accumulated at the upper atmosphere forms the subtropical high-pressure belt and thus sinks back to the earth's surface, splitting into two components: one returns to the equator to close the loop of the Hadley cell; another moves along the earth's surface toward North Pole to form the Ferrel Cell circulation, which lies between north latitude 30° and 60°. The air circulates toward the North Pole along the earth's surface until it collides with the cold air flowing from the North Pole at approximately north latitude 60°. Under the influence of Coriolis force, the moving air in this zone is deflected to produce westerlies. The Polar cell circulation lies between the North Pole and north latitude 60°. The cold air sinks down at the

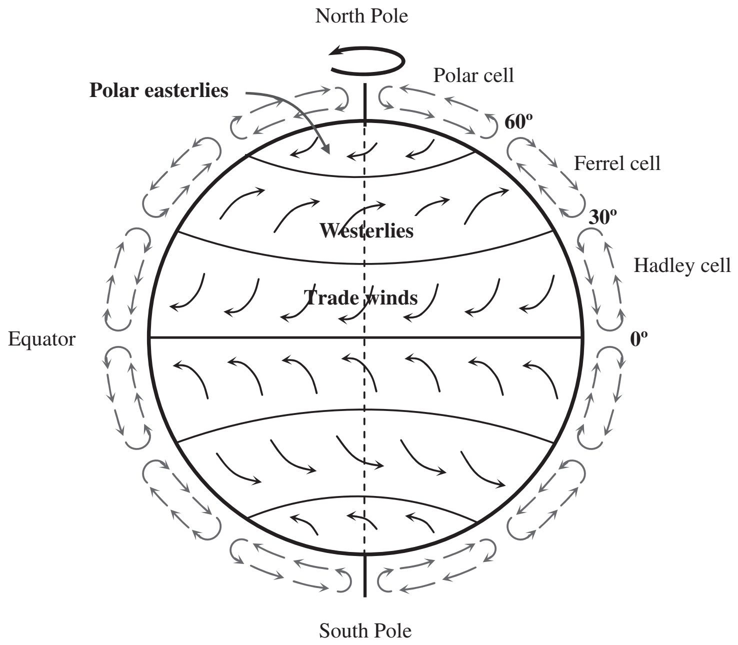


Figure 1: Idealized atmospheric circulations.

North Pole and flows along the earth's surface toward the equator. Near north latitude 60°, the Coriolis effect becomes significant to force the airflow to southwest.

2.3 Local geography

The roughness on the earth's surface is a result of both natural geography and manmade structures. Frictional drag and obstructions near the earth's surface generally retard with wind speed and induce a phenomenon known as wind shear. The rate at which wind speed increases with height varies on the basis of local conditions of the topography, terrain, and climate, with the greatest rates of increases observed over the roughest terrain. A reliable approximation is that wind speed increases about 10% with each doubling of height [4].

In addition, some special geographic structures can strongly enhance the wind intensity. For instance, wind that blows through mountain passes can form mountain jets with high speeds.

3 History of wind energy applications

The use of wind energy can be traced back thousands of years to many ancient civilizations. The ancient human histories have revealed that wind energy was discovered and used independently at several sites of the earth.

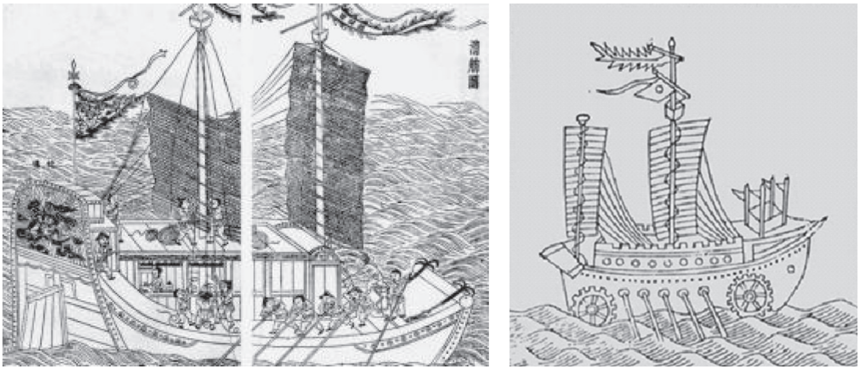
3.1 Sailing

As early as about 4000 B.C., the ancient Chinese were the first to attach sails to their primitive rafts [5]. From the oracle bone inscription, the ancient Chinese scripted on turtle shells in Shang Dynasty (1600 B.C.–1046 B.C.), the ancient Chinese character "凡" (i.e., "凡", sail - in ancient Chinese) often appeared. In Han Dynasty (220 B.C.–200 A.D.), Chinese junks were developed and used as ocean-going vessels. As recorded in a book wrote in the third century [6], there were multi-mast, multi-sail junks sailing in the South Sea, capable of carrying 700 people with 260 tons of cargo. Two ancient Chinese junks are shown in Figure 2. Figure 2(a) is a two-mast Chinese junk ship for shipping grain, quoted from the famous encyclopedic science and technology book *Exploitation of the works of nature* [7]. Figure 2(b) illustrates a wheel boat [8] in Song Dynasty (960–1279). It mentioned in [9] that this type of wheel boats was used during the war between Song and Jin Dynasty (1115–1234).

Approximately at 3400 BC, the ancient Egyptians launched their first sailing vessels initially to sail on the Nile River, and later along the coasts of the Mediterranean [5]. Around 1250 BC, Egyptians built fairly sophisticated ships to sail on the Red Sea [9]. The wind-powered ships had dominated water transport for a long time until the invention of steam engines in the 19th century.

3.2 Wind in metal smelting processes

About 300 BC, ancient Sinhalese had taken advantage of the strong monsoon winds to provide furnaces with sufficient air for raising the temperatures inside furnaces in excess of 1100°C in iron smelting processes. This technique was capable of producing high-carbon steel [10].



(a) (b)

Figure 2: Ancient Chinese junks (ships): (a) two-mast junk ship [7]; (b) wheel boat [8].

The double acting piston bellows was invented in China and was widely used in metallurgy in the fourth century BC [11]. It was the capacity of this type of bellows to deliver continuous blasts of air into furnaces to raise high enough temperatures for smelting iron. In such a way, ancient Chinese could once cast several tons of iron.

3.3 Windmills

China has long history of using windmills. The unearthed mural paintings from the tombs of the late Eastern Han Dynasty (25–220 AD) at Sandaohao, Liaoyang City, have shown the exquisite images of windmills, evidencing the use of windmills in China for at least approximately 1800 years [12].

The practical vertical axis windmills were built in Sistan (eastern Persia) for grain grinding and water pumping, as recorded by a Persian geographer in the ninth century [13].

The horizontal axis windmills were invented in northwestern Europe in 1180s [14]. The earlier windmills typically featured four blades and mounted on central posts – known as Post mill. Later, several types of windmills, e.g. Smock mill, Dutch mill, and Fan mill, had been developed in the Netherlands and Denmark, based on the improvements on Post mill.

The horizontal axis windmills have become dominant in Europe and North America for many centuries due to their higher operation efficiency and technical advantages over vertical axis windmills.

3.4 Wind turbines

Unlike windmills which are used directly to do work such as water pumping or grain grinding, wind turbines are used to convert wind energy to electricity. The first automatically operated wind turbine in the world was designed and built by Charles Brush in 1888. This wind turbine was equipped with 144 cedar blades having a rotating diameter of 17 m. It generated a peak power of 12 kW to charge batteries that supply DC current to lamps and electric motors [5].

As a pioneering design for modern wind turbines, the Gedser wind turbine was built in Denmark in the mid 1950s [15]. Today, modern wind turbines in wind farms have typically three blades, operating at relative high wind speeds for the power output up to several megawatts.

3.5 Kites

Kites were invented in China as early as the fifth or fourth centuries BC [11]. A famous Chinese ancient legalist Han Fei-Zi (280–232 BC) mentioned in his book that an ancient philosopher Mo Ze (479–381 BC) spent three years to make a kite with wood but failed after one-day flight [16].

4 Wind energy characteristics

Wind energy is a special form of kinetic energy in air as it flows. Wind energy can be either converted into electrical energy by power converting machines or directly used for pumping water, sailing ships, or grinding gain.

4.1 Wind power

Kinetic energy exists whenever an object of a given mass is in motion with a translational or rotational speed. When air is in motion, the kinetic energy in moving air can be determined as

$$E_k = \tfrac{1}{2} m\bar{u}^2 \tag{1}$$

where m is the air mass and $\bar{u}$ is the mean wind speed over a suitable time period. The wind power can be obtained by differentiating the kinetic energy in wind with respect to time, i.e.:

$$P_w = \frac{dE_k}{dt} = \frac{1}{2}\dot{m}\bar{u}^2 \tag{2}$$

However, only a small portion of wind power can be converted into electrical power. When wind passes through a wind turbine and drives blades to rotate, the corresponding wind mass flowrate is

$$\dot{m} = \rho A \bar{u} \tag{3}$$

where ρ is the air density and A is the swept area of blades, as shown in Fig. 3. Substituting (3) into (2), the available power in wind P_w can be expressed as

$$P_w = \tfrac{1}{2}\rho A \bar{u}^3 \tag{4}$$

An examination of eqn (4) reveals that in order to obtain a higher wind power, it requires a higher wind speed, a longer length of blades for gaining a larger swept area, and a higher air density. Because the wind power output is proportional to the cubic power of the mean wind speed, a small variation in wind speed can result in a large change in wind power.

4.1.1 Blade swept area

As shown in Fig. 3, the blade swept area can be calculated from the formula:

$$A = \pi\left[(l+r)^2 - r^2\right] = \pi l\,(l+2r) \tag{5}$$

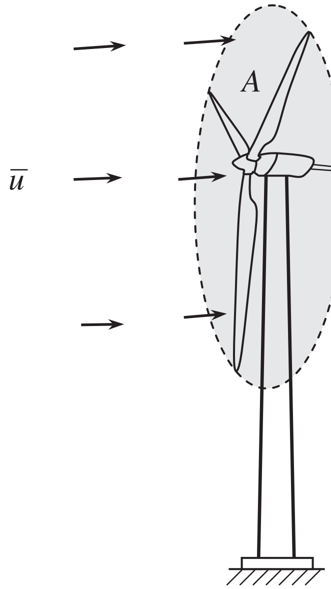


Figure 3: Swept area of wind turbine blades.

where l is the length of wind blades and r is the radius of the hub. Thus, by doubling the length of wind blades, the swept area can be increased by the factor up to 4. When $l >> 2r$, $A \approx \pi\, l^2$.

4.1.2 Air density

Another important parameter that directly affects the wind power generation is the density of air, which can be calculated from the equation of state:

$$\rho = \frac{p}{RT} \tag{6}$$

where p is the local air pressure, R is the gas constant (287 J/kg-K for air), and T is the local air temperature in K.

The hydrostatic equation states that whenever there is no vertical motion, the difference in pressure between two heights is caused by the mass of the air layer:

$$\mathrm{d}p = -\rho g\,\mathrm{d}z \tag{7}$$

where g is the acceleration of gravity. Combining eqns (6) and (7), yields

$$\frac{\mathrm{d}p}{p} = -\frac{g}{RT}\mathrm{d}z \tag{8}$$

The acceleration of gravity g decreases with the height above the earth's surface z:

$$g = g_0\left(1 - \frac{4z}{D}\right) \tag{9}$$

where g_0 is the acceleration of gravity at the ground and D is the diameter of the earth. However, for the acceleration of gravity g, the variation in height can be ignored because D is much larger than $4z$.

In addition, temperature is inversely proportional to the height. Assume that $dT/dz = c$, it can be derived that

$$p = p_0 \left(\frac{T}{T_0} \right)^{-g/cR} \tag{10}$$

where p_0 and T_0 are the air pressure and temperature at the ground, respectively.

Combining eqns (6) and (10), it gives

$$\rho = \rho_0 \left(\frac{T}{T_0} \right)^{-(g/cR+1)} = \rho_0 \left(1 + \frac{cz}{T_0} \right)^{-(g/cR+1)} \tag{11}$$

This equation indicates that the density of air decreases nonlinearly with the height above the sea level.

4.1.3 Wind power density

Wind power density is a comprehensive index in evaluating the wind resource at a particular site. It is the available wind power in airflow through a perpendicular cross-sectional unit area in a unit time period. The classes of wind power density at two standard wind measurement heights are listed in Table 1.

Some of wind resource assessments utilize 50 m towers with sensors installed at intermediate levels (10 m, 20 m, etc.). For large-scale wind plants, class rating of 4 or higher is preferred.

Table 1: Classes of wind power density [17].

	10 m height		50 m height	
Wind power class	Wind power density (W/m^2)	Mean wind speed (m/s)	Wind power density (W/m^2)	Mean wind speed (m/s)
1	<100	<4.4	<200	<5.6
2	100–150	4.4–5.1	200–300	5.6–6.4
3	150–200	5.1–5.6	300–400	6.4–7.0
4	200–250	5.6–6.0	400–500	7.0–7.5
5	250–300	6.0–6.4	500–600	7.5–8.0
6	300–350	6.4–7.0	600–800	8.0–8.8
7	>400	>7.0	>800	>8.8

4.2 Wind characteristics

Wind varies with the geographical locations, time of day, season, and height above the earth's surface, weather, and local landforms. The understanding of the wind characteristics will help optimize wind turbine design, develop wind measuring techniques, and select wind farm sites.

4.2.1 Wind speed

Wind speed is one of the most critical characteristics in wind power generation. In fact, wind speed varies in both time and space, determined by many factors such as geographic and weather conditions. Because wind speed is a random parameter, measured wind speed data are usually dealt with using statistical methods.

The diurnal variations of average wind speeds are often described by sine waves. As an example, the diurnal variations of hourly wind speed values, which are the average values calculated based on the data between 1970 and 1984, at Dhahran, Saudi Arabia have shown the wavy pattern [18]. The wind speeds are higher in daytime and the maximum speed occurs at about 3 p.m., indicating that the daytime wind speed is proportional to the strength of sunlight. George *et al.* [19] reported that wind speed at Lubbock, TX is near constant during dark hours, and follows a curvilinear pattern during daylight hours. Later, George *et al.* [20] have demonstrated that diurnal wind patterns at five locations in the Great Plains follow a pattern similar to that observed in [19].

Based on the wind speed data for the period 1970–2003 from up to 66 onshore sites around UK, Sinden [21] has concluded that monthly average wind speed is inversely propositional to the monthly average temperature, i.e. it is higher in the winter and lower in the summer. The maximum wind speed occurs in January and the minimum in August. Hassanm and Hill have reported that the month-to-month variation of mean wind speed values over the period of 1970–1984 at Dhahran, Saudi Arabia has shown the wavy pattern [13]. However, because the variation in temperature at Dhahran is small over the whole year, there is no a clear correlation between wind speed and temperatures.

The year-to-year variation of yearly mean wind speeds depends highly on selected locations and thus there is no common correlation to predict it. For instance, except for several years, the annual mean wind speeds decrease all the way from 1970 to 1983 at Dhahran, Saudi Arabia [18]. In UK, this variation displays in a more fluctuated matter for the period 1970–2003 [21]. Similarly, a significant variation in the annual mean wind speed over 20-year period (1978–1998) is reported in [22], with maximum and minimum values ranging from less than 7.8 to nearly 9.2 m/s. The long-term wind data (1978–2007) obtained from automated synoptic observation system of meteorological observatories were analyzed and reported by Ko *et al.* [23]. The results show that fluctuation in yearly average wind speed occurs at the observed sites; it tends to slightly decrease at Jeju Island, while the other two sites have random trends.

4.2.2 Weibull distribution

The variation in wind speed at a particular site can be best described using the Weibull distribution function [24], which illustrates the probability of different mean wind speeds occurring at the site during a period of time. The probability density function of a Weibull random variable $\bar{u}$ is:

$$f(\bar{u},k,\lambda)=\begin{cases}\frac{k}{\lambda}\left(\frac{\bar{u}}{\lambda}\right)^{k-1}\exp\left(-\left(\frac{\bar{u}}{\lambda}\right)^{k}\right) & \bar{u}\geq 0\\ 0 & \bar{u}<0\end{cases} \tag{12}$$

where λ is the scale factor which is closely related to the mean wind speed and k is the shape factor which is a measurement of the width of the distribution. These two parameters can be determined from the statistical analysis of measured wind speed data at the site [25]. It has been reported that Weibull distribution can give good fits to observed wind speed data [26]. As an example, the Weibull distributions for various mean wind speeds are displayed in Fig. 4.

4.2.3 Wind turbulence

Wind turbulence is the fluctuation in wind speed in short time scales, especially for the horizontal velocity component. The wind speed $u(t)$ at any instant time t can be considered as having two components: the mean wind speed $\bar{u}$ and the instantaneous speed fluctuation $u'(t)$, i.e.:

$$u(t)=\bar{u}+u'(t) \tag{13}$$

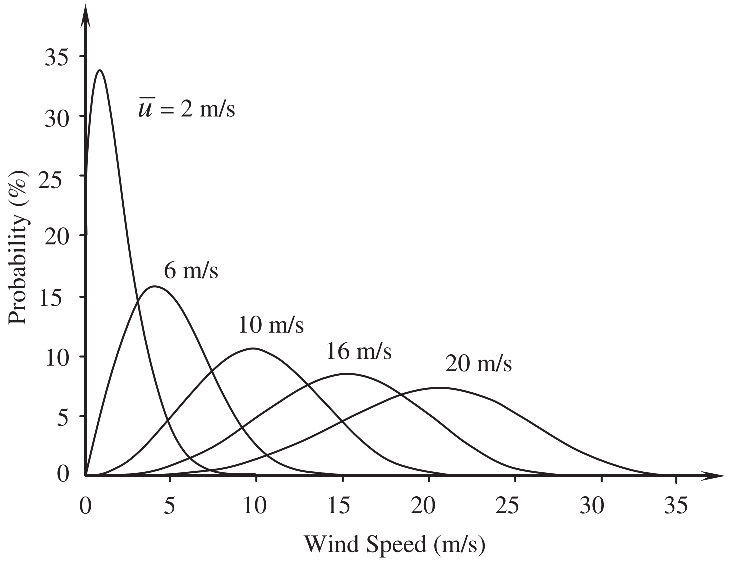


Figure 4: Weibull distributions for various mean wind speeds.

Wind turbulence has a strong impact on the power output fluctuation of wind turbine. Heavy turbulence may generate large dynamic fatigue loads acting on the turbine and thus reduce the expected turbine lifetime or result in turbine failure.

In selection of wind farm sites, the knowledge of wind turbulence intensity is crucial for the stability of wind power production. The wind turbulence intensity I is defined as the ratio of the standard deviation σ_u to the mean wind velocity $\bar{u}$:

$$I = \frac{\sigma_u}{\bar{u}} \tag{14}$$

where both σ_u and $\bar{u}$ are measured at the same point and averaged over the same period of time.

4.2.4 Wind gust

Wind gust refers to a phenomenon that a wind blasts with a sudden increase in wind speed in a relatively small interval of time. In case of sudden turbulent gusts, wind speed, turbulence, and wind shear may change drastically. Reducing rotor imbalance while maintaining the power output of wind turbine generator constant during such sudden turbulent gusts calls for relatively rapid changes of the pitch angle of the blades. However, there is typically a time lag between the occurrence of a turbulent gust and the actual pitching of the blades based upon dynamics of the pitch control actuator and the large inertia of the mechanical components. As a result, load imbalances and generator speed, and hence oscillations in the turbine components may increase considerably during such turbulent gusts, and may exceed the maximum prescribed power output level [27]. Moreover, sudden turbulent gusts may also significantly increase tower fore-aft and side-to-side bending moments due to increase in the effect of wind shear.

To ensure safe operation of wind farms, wind gust predictions are highly desired. Several different gust prediction methods have been proposed. Contrary to most techniques used in operational weather forecasting, Brasseur [29] developed a new wind gust prediction method based on physical consideration. In another study [30], it reported that using a gust factor, which is defined as peak gust over the mean wind speed, could well forecast wind gust speeds. These results are in agreement with previous work by other investigators [31].

4.2.5 Wind direction

Wind direction is one of the wind characteristics. Statistical data of wind directions over a long period of time is very important in the site selection of wind farm and the layout of wind turbines in the wind farm.

The wind rose diagram is a useful tool of analyzing wind data that are related to wind directions at a particular location over a specific time period (year, season, month, week, etc.). This circular diagram displays the relative frequency of wind directions in 8 or 16 principal directions. As an example shown in Fig. 5, there are 16 radial lines in the wind rose diagram, with 22.5° apart from each other. The length of each line is proportional to the frequency of wind direction. The frequency

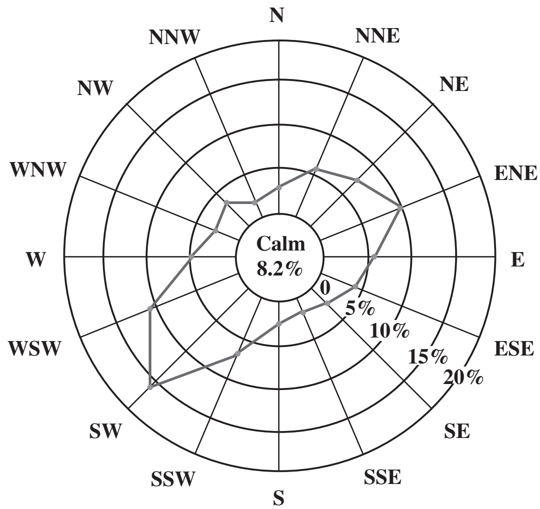


Figure 5: Wind rose diagram for wind directions.

of calm or near calm air is given as a number in the central circle. Some wind rose diagrams may also contain the information of wind speeds.

4.2.6 Wind shear

Wind shear is a meteorological phenomenon in which wind increases with the height above the ground. The effect of height on the wind speed is mainly due to roughness on the earth's surface and can be estimated using the Hellmann power equation that relates wind speeds at two different heights [33]:

$$u(z) = u(z_0)\left(\frac{z}{z_0}\right)^{\alpha} \tag{15}$$

where z is the height above the earth's surface, z_0 is the reference height for which wind speed $u(z_0)$ is known, and α is the wind shear coefficient. In practice, α depends on a number of factors, including the roughness of the surrounding landscape, height, time of day, season, and locations. The wind shear coefficient is generally lower in daytime and higher at night. Empirical results indicate that wind shear often follows the "1/7 power law" (i.e. α = 1/7). The values of wind shear coefficient for different surface roughness are provided in [34].

Because the power output of wind turbine strongly depends on the wind speed at the hub height, modern wind turbines are built at the height greater than 80 m, for capturing more wind energy and lowering cost per unit power output.

5 Modern wind turbines

A modern wind turbine is an energy-converting machine to convert the kinetic energy of wind into mechanical energy and in turn into electrical energy. In the recent three decades, remarkable advances in wind turbine design have been achieved along with modern technological developments. It has been estimated that advances in aerodynamics, structural dynamics, and micrometeorology may contribute to a 5% annual increase in the energy yield of wind turbines [35].

Various wind turbine concepts have been developed and built for maximizing the wind energy output, minimizing the turbine cost, and increasing the turbine efficiency and reliability.

5.1 Wind turbine classification

Wind turbines can be classified according to the turbine generator configuration, airflow path relatively to the turbine rotor, turbine capacity, the generator-driving pattern, the power supply mode, and the location of turbine installation.

5.1.1 Horizontal-axis and vertical-axis wind turbines

When considering the configuration of the rotating axis of rotor blades, modern wind turbines can be classified into the horizontal-axis and vertical-axis turbines. Most commercial wind turbines today belong to the horizontal-axis type, in which the rotating axis of blades is parallel to the wind stream. The advantages of this type of wind turbines include the high turbine efficiency, high power density, low cut-in wind speeds, and low cost per unit power output.

Several typical vertical-axis wind turbines are shown in Fig. 6. The blades of the vertical-axis wind turbines rotate with respect to their vertical axes that are perpendicular to the ground. A significant advantage of vertical-axis wind turbine is that the turbine can accept wind from any direction and thus no yaw control is needed. Since the wind generator, gearbox, and other main turbine components can be set up on the ground, it greatly simplifies the wind tower design and construction, and consequently reduces the turbine cost. However, the vertical-axis wind turbines must use an external energy source to rotate the blades during initialization. Because the axis of the wind turbine is supported only on one end at the ground, its maximum practical height is thus limited. Due to the lower wind power efficiency, vertical-axis wind turbines today make up only a small percentage of wind turbines.

5.1.2 Upwind and downwind wind turbines

Based on the configuration of the wind rotor with respect to the wind flowing direction, the horizontal-axis wind turbines can be further classified as upwind and downwind wind turbines. The majority of horizontal-axis wind turbines being used today are upwind turbines, in which the wind rotors face the wind. The main advantage of upwind designs is to avoid the distortion of the flow field as the wind passes though the wind tower and nacelle.

For a downwind turbine, wind blows first through the nacelle and tower and then the rotor blades. This configuration enables the rotor blades to be made more flexible without considering tower strike. However, because of the influence of the distorted unstable wakes behind the tower and nacelle, the wind power output

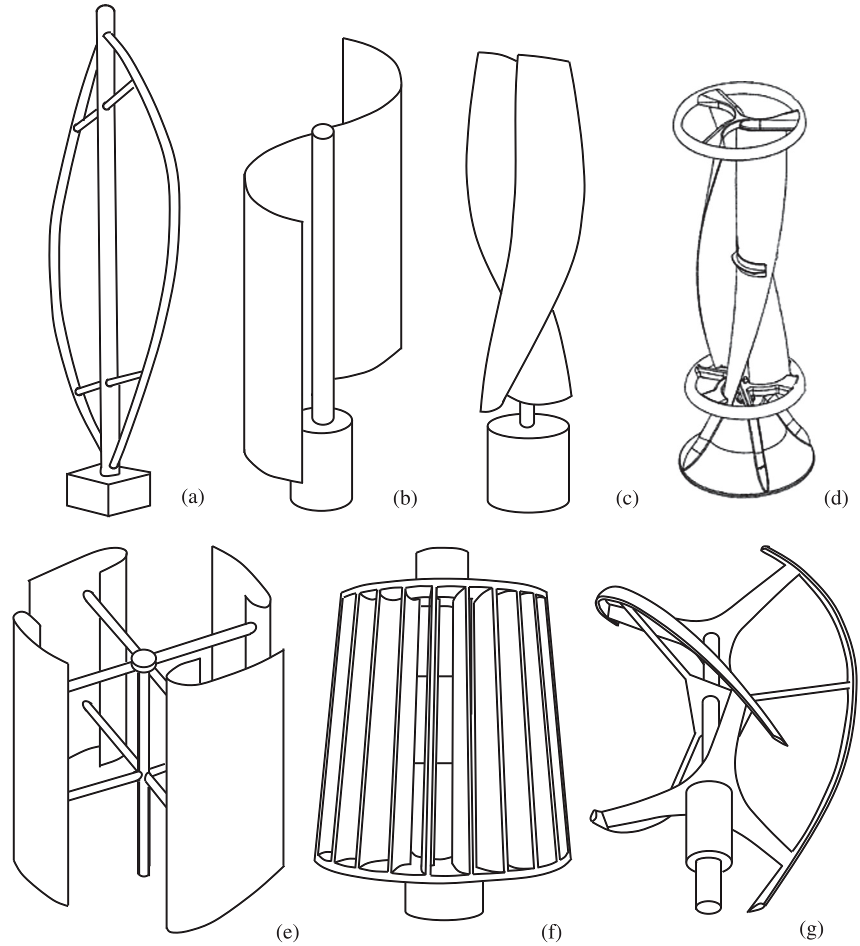


Figure 6: Several typical types of vertical-axis wind turbines: (a) Darrius; (b) Savonius; (c) Solarwind™ [36]; (d) Helical [37]; (e) Noguchi [38]; (f) Maglev [39]; (g) Cochrane [40].

generated from a downwind turbine fluctuates greatly. In addition, the unstable flow field may result in more aerodynamic losses and introduce more fatigue loads on the turbine. Furthermore, the blades in a downwind wind turbine may produce higher impulsive or thumping noise.

5.1.3 Wind turbine capacity

Wind turbines can be divided into a number of broad categories in view of their rated capacities: micro, small, medium, large, and ultra-large wind turbines. Though a restricted definition of micro wind turbines is not available, it is accepted that a turbine with the rated power less than several kilowatts can be categorized as micro wind turbine [41]. Micro wind turbines are especially suitable in locations where the electrical grid is unavailable. They can be used on a per-structure basis, such as street lighting, water pumping, and residents at remote areas, particularly in developing countries. Because micro wind turbines need relatively low cut-in speeds at start-up and operate in moderate wind speeds, they can be extensively installed in most areas around the world for fully utilizing wind resources and greatly enhancing wind power generation availability.

Small wind turbines usually refer to the turbines with the output power less than 100 kW [42]. Small wind turbines have been extensively used at residential houses, farms, and other individual remote applications such as water pumping stations, telecom sites, etc., in rural regions. Distributed small wind turbines can increase electricity supply in the regions while delaying or avoiding the need to increase the capacity of transmission lines.

The most common wind turbines have medium sizes with power ratings from 100 kW to 1 MW. This type of wind turbines can be used either on-grid or off-grid systems for village power, hybrid systems, distributed power, wind power plants, etc.

Megawatt wind turbines up to 10 MW may be classified as large wind turbines. In recent years, multi-megawatt wind turbines have become the mainstream of the international wind power market. Most wind farms presently use megawatt wind turbines, especially in offshore wind farms.

Ultra-large wind turbines are referred to wind turbines with the capacity more than 10 MW. This type of wind turbine is still in the earlier stages of research and development.

5.1.4 Direct drive and geared drive wind turbines

According to the drivetrain condition in a wind generator system, wind turbines can be classified as either direct drive or geared drive groups. To increase the generator rotor rotating speed to gain a higher power output, a regular geared drive wind turbine typically uses a multi-stage gearbox to take the rotational speed from the low-speed shaft of the blade rotor and transform it into a fast rotation on the high-speed shaft of the generator rotor. The advantages of geared generator systems include lower cost and smaller size and weight. However, utilization of a gearbox can significantly lower wind turbine reliability and increase turbine noise level and mechanical losses.

By eliminating the multi-stage gearbox from a generator system, the generator shaft is directly connected to the blade rotor. Therefore, the direct-drive concept is more superior in terms of energy efficiency, reliability, and design simplicity.

5.1.5 On-grid and off-grid wind turbines

Wind turbines can be used for either on-grid or off-grid applications. Most medium-size and almost all large-size wind turbines are used in grid tied applications. One of the obvious advantages for on-grid wind turbine systems is that there is no energy storage problem.

As the contrast, most of small wind turbines are off-grid for residential homes, farms, telecommunications, and other applications. However, as an intermittent power source, wind power produced from off-grid wind turbines may change dramatically over a short period of time with little warning. Consequently, off-grid wind turbines are usually used in connection with batteries, diesel generators, and photovoltaic systems for improving the stability of wind power supply.

5.1.6 Onshore and offshore wind turbines

Onshore wind turbines have a long history on its development. There are a number of advantages of onshore turbines, including lower cost of foundations, easier integration with the electrical-grid network, lower cost in tower building and turbine installation, and more convenient access for operation and maintenance.

Offshore wind turbines have developed faster than onshore since the 1990s due to the excellent offshore wind resource, in terms of wind power intensity and continuity. A wind turbine installed offshore can make higher power output and operate more hours each year compared with the same turbine installed onshore. In addition, environmental restrictions are more lax at offshore sites than at onshore sites. For instance, turbine noise is no long an issue for offshore wind turbines.

5.2 Wind turbine configuration

Most of the modern large wind turbines are horizontal-axis turbines with typically three blades. As shown in Fig. 7, a wind turbine is comprised of a nacelle, which

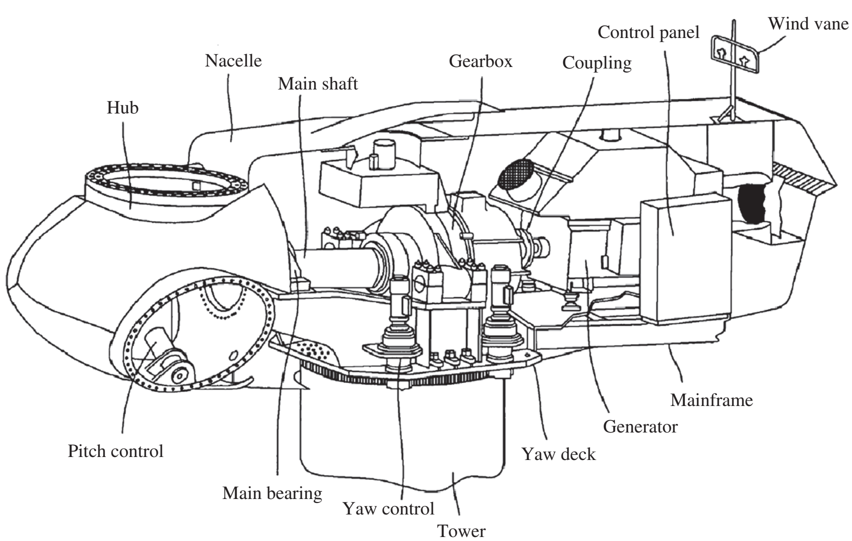


Figure 7: A horizontal-axis wind turbine configuration. Courtesy of the US Patent & Trademark Office.

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is positioned on the top of a wind tower, housing the most turbine components inside. Three blades (not shown) mounted on the rotor hub, which is connected via the main shaft to the gearbox. The rotor of the wind generator is connected to the output shaft of the gearbox. Thus, the slow rotating speed of the rotor hub is increased to a desired high rotating speed of the generator rotor.

Using the pitch control system, each blade is pitched individually to optimize the angle of attack of the blade for allowing a higher energy capture in normal operation and for protecting the turbine components (blade, tower, etc.) from damaging in emergency situations. With the feedback information such as measured instantaneous wind direction and speed from the wind vane, the yaw control system provides the yaw orientation control for ensuring the turbine constantly against the wind.

5.3 Wind power parameters

5.3.1 Power coefficient

The conversion of wind energy to electrical energy involves primarily two stages: in the first stage, kinetic energy in wind is converted into mechanical energy to drive the shaft of a wind generator. The critical converting devices in this stage are wind blades. For maximizing the capture of wind energy, wind blades need to be carefully designed.

The power coefficient C_p deals with the converting efficiency in the first stage, defined as the ratio of the actually captured mechanical power by blades to the available power in wind:

$$C_p = \frac{P_{me,out}}{P_w} = \frac{P_{me,out}}{(1/2)\rho A\bar{u}^3} \tag{16}$$

Because there are various aerodynamic losses in wind turbine systems, for instance, blade-tip, blade-root, profile, and wake rotation losses, etc., the real power coefficient C_p is much lower than its theoretical limit, usually ranging from 30 to 45%.

5.3.2 Total power conversion coefficient and effective power output

In the second stage, mechanical energy captured by wind blades is further converted into electrical energy via wind generators. In this stage, the converting efficiency is determined by several parameters

- Gearbox efficiency η_{gear} – The power losses in a gearbox can be classified as load-dependent and no-load power losses. The load-dependent losses consist of gear tooth friction and bearing losses and no-load losses consist of oil churning, windage, and shaft seal losses. The planetary gearboxes, which are widely used in wind turbines, have higher power transmission efficiencies over traditional gearboxes.

- Generator efficiency η_{gen} – It is related to all electrical and mechanical losses in a wind generator, such as copper, iron, load, windage, friction, and other miscellaneous losses.
- Electric efficiency η_{ele} – It encompasses all combined electric power losses in the converter, switches, controls, and cables.

Therefore, the total power conversion efficiency from wind to electricity η_t is the production of these parameters, i.e.:

$$\eta_t = C_p \eta_{gear} \eta_{gen} \eta_{ele} \quad (17)$$

The effective power output from a wind turbine to feed into a grid becomes

$$P_{eff} = C_p \eta_{gear} \eta_{gen} \eta_{ele} P_w = \eta_t P_w = \tfrac{1}{2}(\eta_t \rho A \bar{u}^3) \quad (18)$$

5.3.3 Lanchester–Betz limit

The theoretical maximum efficiency of an ideal wind turbomachine was derived by Lanchester [43] in 1915 and Betz [44] in 1920. It was revealed that no wind turbomachines could convert more than 16/27 (59.26%) of the kinetic energy of wind into mechanical energy. This is known as Lanchester–Betz limit (or Lanchester–Betz law) today.

As shown in Fig. 8, $\bar{u}_1$and $\bar{u}_4$ are mean velocities far upstream and downstream from the wind turbine; $\bar{u}_2$ and $\bar{u}_3$ are mean velocities just in front and back of the wind rotating blades, respectively. By assuming that there is no change in the air velocity right across the wind blades (i.e. $\bar{u}_2 = \bar{u}_3$) and the pressures far upstream and downstream from the wind turbine are equal to the static pressure of the undisturbed airflow (i.e. $p_1 = p_4 = p$), it can be derived that

$$p_2 - p_3 = \tfrac{1}{2}\rho(\bar{u}_1^2 - \bar{u}_4^2) \quad (19)$$

and

$$\bar{u}_2 = \bar{u}_3 = \tfrac{1}{2}(\bar{u}_1 + \bar{u}_4) \quad (20)$$

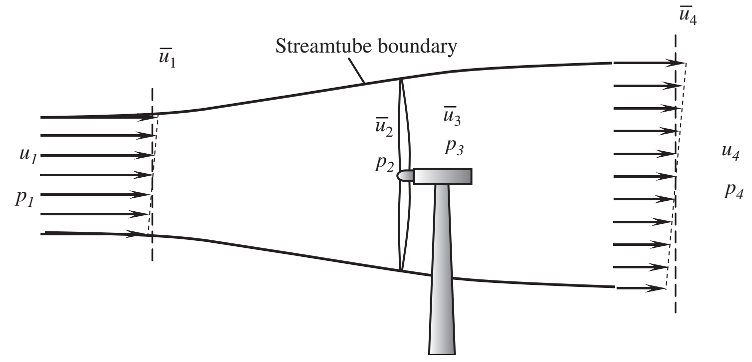

Figure 8: Airflow through a wind turbine.

Thus, the power output of mechanical energy captured by wind turbine blades is

$$P_{\text{me,out}} = \tfrac{1}{2}\rho A\overline{u}_2(\overline{u}_1^2 - \overline{u}_4^2) = \tfrac{1}{2}\rho A\overline{u}_1^3 4a(1-a)^2 \tag{21}$$

where a is the axial induction factor, defined as

$$a = \frac{\overline{u}_1 - \overline{u}_2}{\overline{u}_1} \tag{22}$$

Substitute eqn (21) into (16) (where $\overline{u}_1 = \overline{u}$), yields

$$C_{\text{p}} = 4a(1-a)^2 \tag{23}$$

This indicates that the power coefficient is only a function of the axial induction factor a. It is easy to derive that the maximum power coefficient reaches its maximum value of 16/27 when $a = 1/3$ (see Fig. 9).

5.3.4 Power curve

As can be seen from eqn (18), the effective electrical power output from a wind turbine P_{eff} is directly proportional to the available wind power P_{w} and the total effective wind turbine efficiency η_{t}.

The power curve of a wind turbine displays the power output (either the real electrical power output or the percentage of the rated power) of the turbine as a function of the mean wind speed. Power curves are usually determined from the field measurements. As shown in Fig. 10, the wind turbine starts to produce usable power at a low wind speed, defined as the cut-in speed. The power output increases continuously with the increase of the wind speed until reaching a saturated point, to which

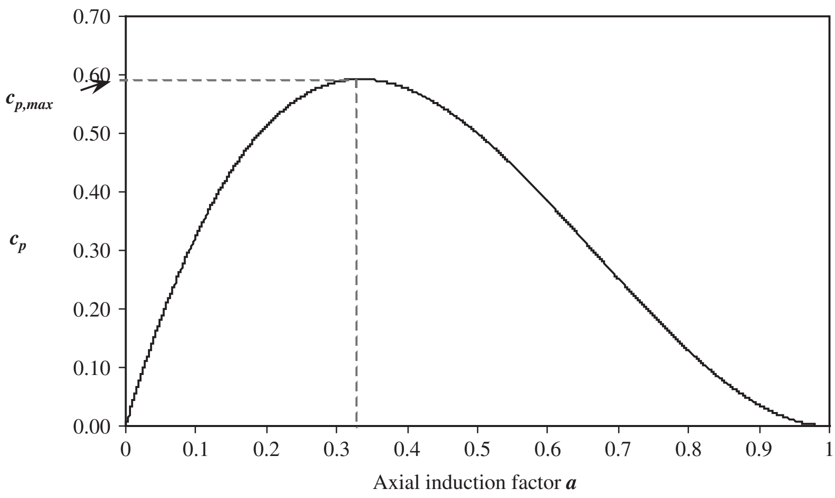

Figure 9: Power coefficient as a function of axial induction factor a.

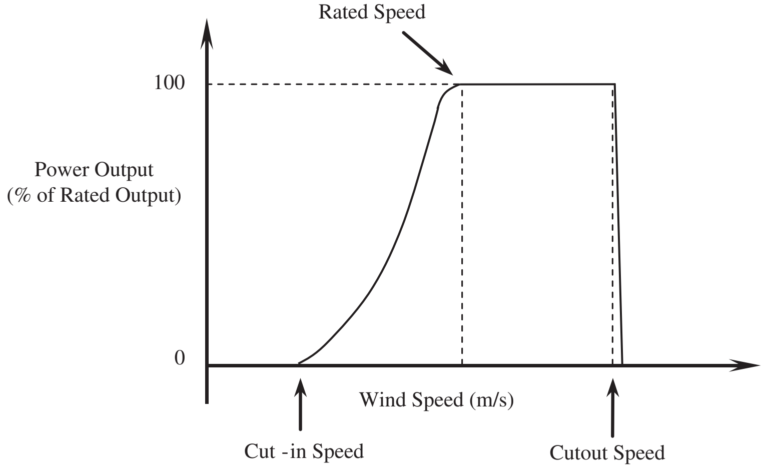

Figure 10: Typical wind turbine power curve.

the power output reaches its maximum value, defined as the rated power output. Correspondingly, the speed at this point is defined as the rated speed. At the rated speed, more increase in the wind speed will not increase the power output due to the activation of the power control. When the wind speed becomes too large to potentially damage the wind turbine, the wind turbine needs to shut down immediately to avoid damaging the wind turbine. This wind speed is defined as the cut-out speed. Thus, the cut-in and cut-out speeds have defined the operating limits of the wind turbine.

There are a number of methods available for forecasting the wind turbine power performance curves. Based on statistical tools, a comparison of five different methods has been performed by Cabezon *et al.* [45]. The best results were obtained when the fuzzy logic tool and tuning over the transfer functions were applied for wind turbines. More recently, based on a stochastic model for the power conversion process, Gottschall and Peinke [46] proposed a dynamic method for estimating the power performance curves and the dynamic approach has verified to be more accurate than the common IEC standard [47]. A novel method, based on the stochastic differential equations of diffusive Markov processes, was developed to characterize wind turbine power performance directly from high-frequency fluctuating measurements [48].

5.3.5 Tip speed ratio

The tip speed ratio is an extremely important factor in wind turbine design, which is defined as the ratio of the tangential speed at the blade tip to the actual wind speed, i.e.:

$$\lambda = \frac{(l+r)\omega}{\overline{u}} \tag{24}$$

where l is the length of the blade, r is the radius of the hub, and ω is the angular speed of blades.

If the blade angular speed ω is too small, most of the wind may pass undisturbed though the blade swept area making little useful work on the blades. On the contrary, if ω is too large, the fast rotating blades may block the wind flow reducing the power extraction. Therefore, there exists an optimal angular speed at which the maximum power extraction is achieved. For a wind turbine with n blades, the optimal angular speed can be approximately determined as [49]:

$$\omega_{\text{opt}} \approx \frac{2\pi}{n}\frac{\bar{u}}{L} \tag{25}$$

where L is the length of the strongly disturbed air stream upwind and downwind of the rotor.

Substituting eqn (25) into (24), the optimal tip speed ratio becomes

$$\lambda_{\text{opt}} \approx \frac{2\pi}{n}\left(\frac{l+r}{L}\right) \tag{26}$$

Empirically, the ratio $(l + r)/L$ is equal to about 2. Thus, for three-blade wind turbines (i.e. $n = 3$), $\lambda_{\text{opt}} \approx 4\pi/3$.

If the aerofoil blade is designed with care, the optimal tip speed ratio may be about 25–30% higher than the calculated optimal values above. Therefore, a wind turbine with three blades would have an optimal tip speed ratio [49]:

$$\lambda_{\text{opt}} = \frac{4\pi}{3}(1.25 \sim 1.30) \approx 5.24 \sim 5.45 \tag{27}$$

5.3.6 Wind turbine capacity factor

Due to the intermittent nature of wind, wind turbines do not make power all the time. Thus, a capacity factor of a wind turbine is used to provide a measure of the wind turbine's actual power output in a given period (e.g. a year) divided by its power output if the turbine has operated the entire time. A reasonable capacity factor would be 0.25–0.30 and a very good capacity factor would be around 0.40 [50]. In fact, wind turbine capacity factor is very sensitive to the average wind speed.

5.4 Wind turbine controls

Wind turbine control systems continue to play important roles for ensuring wind turbine reliable and safe operation and to optimize wind energy capture. The main control systems in a modern wind turbine include pitch control, stall control (passive and active), yaw control, and others.

Under high wind speed conditions, the power output from a wind turbine may exceed its rated value. Thus, power control is required to control the power output within allowable fluctuations for avoiding turbine damage and stabilizing the power output. There are two primary control strategies in the power control: pitch control and stall control. The wind turbine power control system is used to control the power output within allowable fluctuations.

5.4.1 Pitch control

The pitch control system is a vital part of the modern wind turbine. This is because the pitch control system not only continually regulates the wind turbine's blade pitch angle to enhance the efficiency of wind energy conversion and power generation stability, but also serves as the security system in case of high wind speeds or emergency situations. It requires that even in the event of grid power failure, the rotor blades can be still driven into their feathered positions by using either the power of backup batteries or capacitors [51] or mechanical energy storage devices [52].

Early techniques of active blade pitch control applied hydraulic actuators to control all blades together. However, these collective pitch control techniques could not completely satisfy all requirements of blade pitch angle regulation, especially for MW wind turbines with the increase in blade length and hub height. This is because wind is highly turbulent flow and the wind speed is proportional to the height from the ground. Therefore, each blade experiences different loads at different rotation positions. As a result, more superior individual blade pitch control techniques have been developed and implemented, allowing control of asymmetric aerodynamic loads on the blades, as well as structural loads in the non-rotating frame such as tower side-side bending. In such a control system, each blade is equipped with its own pitch actuator, sensors and controller.

In today's wind power industry, there are primarily two types of blade pitch control systems: hydraulic controlled and electric controlled systems. As shown in Fig. 11, the hydraulic pitch control system uses a hydraulic actuator to drive the blade rotating with respect to its axial centreline. The most significant advantages of hydraulic pitch control system include its large driving power, lack of a gearbox, and robust backup power. Due to these advantages, hydraulic pitch control systems historically dominate wind turbine control in Europe and North America for many years.

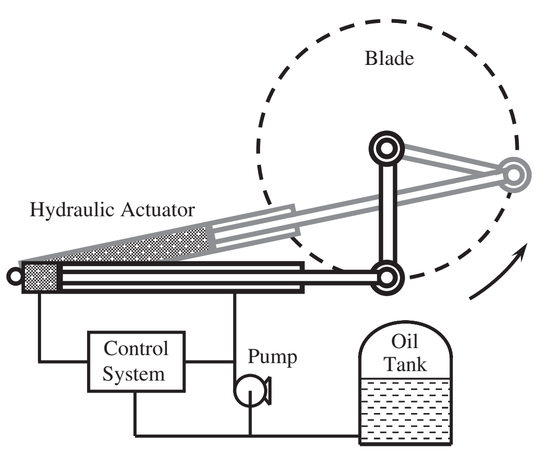

Figure 11: Hydraulic pitch control system.

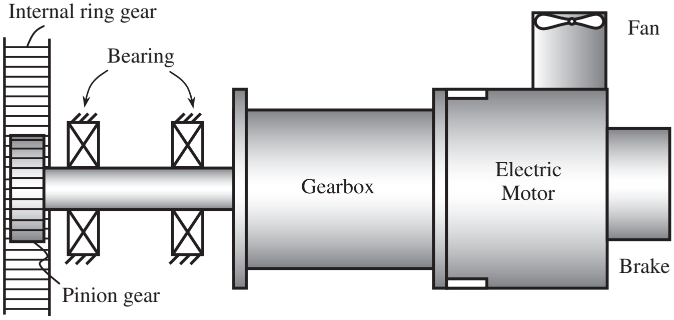

Figure 12: Electric pitch control system.

The electric pitch control systems have been developed alternatively with the hydraulic systems. This type of control system has a higher efficiency than that of hydraulic controlled systems (which is usually less than 55%) and avoids the risk of environmental pollution due to hydraulic fluid being split or leaked.

In an electric pitch control system as shown in Fig. 12, the motor connects to a gearbox to lower the motor speed to a desired control speed. A drive pinion gear engages with an internal ring gear, which is rigidly attached to the roof of the rotor blade. Alternatively, some wind turbine manufacturers use the belt-drive structure adjusting the pitch angle. The use of electric motors can raise the responsiveness rate and sensitivity of blade pitch control. To enhance operation reliability, the use of redundant pitch control systems was proposed to be equipped in large wind turbines [53].

5.4.2 Stall control

Besides pitch control, stall control is another approach for controlling and protecting wind turbines. The concept of stall control is that the power is regulated through stalling the blades after rated speed is achieved.

Stall control can be further divided into passive and active control approaches. Passive stall control is basically used in wind turbines in which the blades are bolted to the hub at a fixed installing angle. In a passive stall-regulated wind turbine, the power regulation relies on the aerodynamic features of blades. In low and moderate wind speeds, the turbine operates near maximum efficiency. At high wind speeds, the turbine is automatically controlled by means of stalled blades to limit the rotational speed and power output, protecting the turbine from excessive wind speeds.

Compared with pitch control, a passive stall control system has a simple structure and avoids using a complex control system, leading to high reliability of the control system. In addition, the power fluctuations are lower for stall-regulated turbines. However, this control method has some disadvantages, such as lower efficiency, the requirement of external equipment at the turbine start, larger dynamic loads acting on the blades, nacelle, and tower, dependence on reliable brakes for the operation safety. Therefore, this control technique has been primarily used for small and medium wind turbines. Since the capacity of wind turbines has entered the multi-megawatt power range in recent years, pitch control has become dominant in the wind power market.

The active stall control technique has been developed for large wind turbines. An active stall wind turbine has stalling blades together with a blade pitch system. Since the blades at high wind speeds are turned towards stall, in the opposite direction as with pitch-control systems, this control method is also referred to as negative pitch control. Compared with passive stall control, active control provides more accurate control on the power output and maintains the rated power at high wind speeds. However, with the addition of the pitch-control mechanism, the active stall control mode increases the turbine cost and decreases operation reliability.

With megawatt wind turbines becoming the mainstream in the wind power industry from the late 1990s, pitch control is more favorable than stall control. It has been reported that the number of pitch-regulated turbines is four times higher than that of stall-regulated turbines and the trend is going to continue in coming decades [41].

5.4.3 Yaw control

In order to maximize the wind power output and minimize the asymmetric loads acting on the rotor blades and the tower, a horizontal-axis wind turbine must be oriented with rotor against the wind by using an active yaw control system. Like wind pitch systems, yaw systems can be driven either electrically or hydraulically. Generally, hydraulic yaw systems were used in the earlier time of the wind turbine development [54]. In modern wind turbines, yaw control is done by electric motors. The yaw control system usually consists of an electrical motor with a speed reducing gearbox, a bull gear which is fixed to the tower, a wind vane to gain the information about wind direction, a yaw deck, and a brake to lock the turbine securely in yaw when the required position is reached. For a large wind turbine with high driving loads, the yaw control system may use two or more yaw motors to work together for driving a heavy nacelle (see Figure 7).

In practice, the yaw error signals obtained from the wind vane are used to calculate the average yaw angle in a short interval. When this average yaw angle exceeds the preset threshold, the yaw motor is activated to align the turbine with the wind direction. Thus, with heavily filtered wind direction measurements, the actions of yaw control are rather limited and slow.

5.4.4 Other control approaches

In the early time of wind turbine design, ailerons were once used to control the power output. This method involves placing moveable flaps on the trailing edge of rotor blades [55]. The ailerons change the lift and drag characteristics of the blades and eventually change the rotor torque, which enable to regulate rotor speed and rotor power output. However, this method was less successful and was soon abandoned.

Another possibility is to yaw the rotor partly out of the wind to decrease power. This technique of yaw control is in practice used only for tiny wind turbines (>1 kW) [56].

6 Challenges in wind power generation

While wind power generation offers numerous benefits and advantages over conventional power generation, there are also some challenges and problems need to be seriously addressed. The wide range of challenges and problems, from long-term environmental influences to thermal management of wind turbines, must be carefully considered in response to the rapid growth of wind power generation.

6.1 Environmental impacts

Modern wind farms today may contain a large number of large-size wind turbines. Therefore, their impacts on the environment cannot be ignored. One of the impacts is that poorly sited wind energy facilities may block bird migration routes and hurt or kill birds.

Though blade rotation speeds are rather low for large wind turbines at their normal operation, the tangential speeds at the blade tips could be higher than 70 m/s. At such high speeds, birds flying through the blade sweeping areas may be easily hurt or killed by colliding with blades. It has been reported by the US National Academy of Science that wind turbines may kill up to 40,000 birds per year in US [57]. Though this number is much smaller than the 80 million birds killed by cars each year, it is important to evaluate the long-term influence on local geography, seasonal bird abundance and the species at risk. To reduce the bird death, using bird scares to drive birds away from wind farms has been considered. A more recent study has revealed that fossil-fuelled power stations appear to pose a much greater threat to avian wildlife than wind and nuclear power technologies [58].

Today, this problem becomes less important. Before building a wind farm, a series of environmental assessments have to be completed to avoid bird migration routes and to minimize other environmental impacts. Once the wind farm is built, further monitoring takes place to better understand the ongoing relationship between birds and the wind farm [59].

Building wind farms will change the character of local landscape. Modern large wind turbines are more than 100 m tall and thus can be seen at a far distance. In practice, the visual effect for local residents is a significant consideration and is always scrutinized for wind projects. To minimize the visual effect, wind turbines usually use neutral colors such as light grey or off-white [60]. Strategies to minimize visual effects involve the spacing, design, and uniformity of turbines, markings or lighting, roads and service buildings [61]. There are a number of analytical tools available to assist understanding and testing of the effect of wind farms on visual amenity.

6.2 Wind turbine noise

With the extensive build up of wind power plants and the population growth all over the world, the influence of wind turbine noise to the nearby residents becomes a problem not to be neglected. Wind turbine noise consists of aerodynamic noise from rotating blades and mechanical vibration noise from gearboxes and generators. For a modern large wind turbine, aerodynamic noise from the blades is considered to be the dominant noise source.

A detailed review of available wind turbine noise standards, regulations, and guidelines in Europe, North America, and Australia was made by Ramakrishnan [62]. Though the noise limits vary significantly country to country, the approximate noise level at nighttimes in most European countries and Canada ranges from 35 to 40 dBA.

There are two components in aerodynamic noise: (1) airfoil self noise, that is, the noise produced by the blade in an undisturbed inflow and is caused by the interaction in the boundary layer with the blade trailing edge; and (2) inflow turbulence noise which is caused by the interaction of upstream atmospheric turbulence with the blade and depends on the atmospheric conditions. Both airfoil self noise and inflow turbulence noise mechanisms are dependent on a number of parameters such as wind speed, angle of attack, radiation direction, and airfoil shape.

There are a number of techniques for reducing aerodynamic noise produced by wind turbine blades. One of them is to use serrated blades at their trailing edges. It can improve blade aerodynamic characteristics and reduce the noise induced by Karman vortex street [63]. Another is to use turbulence generating means, placed on the leeward surface side and at the outer section of the blade, to reduce noise [66]. In a recent US patent application, it has reported that with an anti-noise device at the blade trailing edge, it allows altering the characteristics of the boundary layer and therefore modifies emitted noise [67].

The field measurements of GE wind turbines have shown that the use of the optimized blades and the serrated blades can reduce average overall noise by 0.5 and 3.2 dBA, respectively [68]. In a field test of a 2.3 MW wind turbine, the overall noise level reduction provided by blade serrations is over 6 dBA for at least two frequencies [69].

6.3 Integration of wind power into grid

Wind is a highly intermittent energy source for causing overall fluctuation in wind power generation. Electricity generated from wind turbines strongly depends on the local weather and geographic conditions that can fluctuate a great deal more than with some renewable energy sources such as hydropower.

With the increasing share of wind energy in the global power market, a large amount of wind power is integrated into existing grids. Thus, the expected growth in wind power could soon exceed the current capability of grids with today's technology. To prepare this situation in advance, the influence of intermittent wind power on the grid stability and system security must be properly addressed.

The impacts of wind power to a power grid depend on the level of wind power penetration, grid size and generation mix of electricity in the grid. Undoubtedly, there is no problem for low wind power penetration in a large power grid. However, integrating large utility-scale wind power presents unique challenges. These challenges call into questions such as: How to ensure system controllability? How to manage new kinds of variability and uncertainty [70]? The detailed analysis regarding the impacts of wind power on power systems can be found in [71].

6.4 Thermal management of wind turbines

Large wind turbines are usually installed far away from urban areas and often operate under severe climate conditions, thus experiencing large variations in environmental temperatures. As a consequence, there is a need for a wind turbine to have a robust thermal control system for maintaining temperature levels inside the nacelle within specified limits.

During turbine operation, heat is generated from electric/electronic devices and rotating mechanical components (e.g. gearboxes and bearings) as a result of various power losses. For ensuring safe and reliable operation and preventing failure of the turbine, heat generated in the wind turbine must be dissipated efficiently.

Wind turbine cooling includes:

- Wind generator cooling
- Electronic and electric equipment cooling
- Gearbox cooling
- Other components/subsystems cooling

New cooling techniques have continuously been innovated in all cooling modes. A method was proposed to utilize incoming wind to cool the wind turbine. This wind assisted cooling system sucks in wind flow from an air inlet port on the top of the nacelle, fills the received airflow into the generator and finally exhausts at the front of the nacelle [72]. Some large wind generators use water or oil cooling for dealing with high thermal loads [73]. While the turbine benefits high cooling efficiency, it also suffers lower reliability and higher cost for adding such a complex cooling system.

The main challenge for electronic devices in a wind turbine is that they must withstand a wide range of ambient temperatures, usually from –40 to +55°C. In addition, they must be protected from dusts and moisture, as well as electrical shocks from lightning. There are several cooling modes in electronic cooling, including passive or active air cooling, forced single- or multi-phase liquid cooling, and phase change cooling. Under high ambient temperature conditions, a cooling or ventilation system is necessary to prevent overheating of electronic devices.

In cold climates, heating may be required for

- Warming up the lubrication oil in gearboxes
- Heating blades and hub to prevent them from icing over
- Raising the temperature inside the control cabinets toward a desired temperature range to prevent electronic devices from malfunctioning

6.5 Wind energy storage

Today developing advanced, cost-effective storage technologies of electric energy still remains a challenge, which may limit the widespread application of wind energy. The research and development (R&D) of new energy storage systems are highly desired to meet cyclical energy demands and stabilize power output, especially for large-scale wind farms.

The technologies for wind energy storage have been developed over several decades to convert wind energy into various forms of energy, including:

- Electrochemical energy in batteries and super capacitors
- Magnetic energy in superconducting magnetic energy storage (SMES)
- Kinetic energy in rotating flywheels
- Potential energy in pumped water at higher altitudes
- Mechanical energy in compressed air in vast geologic vaults
- Hydrogen energy by decomposing water

Among these techniques, the most popular method is to use batteries. However, there are some drawbacks to regular batteries, such as cost, short lifetime, corrosion, and disposal concerns [74]. Research and development of innovative batteries are underway. It has reported that lithium-ion battery technology is projected to provide stationary electrical energy solutions to enable the effective use in renewable energy sources. It is expected that safe and reliable lithium-ion batteries will soon be connected to solar cells and wind turbines [75]. Sodium-sulfur battery is another promising candidate for energy storage [76]. This type of batteries is preferably used to store renewable energy such as wind, sunlight, and geothermal heat [77]. The detailed review of electrical energy storage can be found in [78].

6.6 Wind turbine lifetime

Modern wind turbines are designed for the lifetime of 20–30 years. A critical challenge facing turbine manufacturers and wind power plants is how to achieve the lifetime goals while at the same time minimize the costs of maintenance and repair. However, improving the operational reliability and extending the lifetime of wind turbines are very difficult tasks for a number of reasons:

- Wind turbines have to be exposed to various hostile conditions such as extreme temperatures, wind speed fluctuations, humidity, dust, solar radiation, lightning, salinity and frequent onslaughts of rain, hail, snow, ice, and sandstorms.
- A modern wind turbine consists of a large number of components and systems; each of them has its own lifetime. According to the Cannikin law, failure must first occur in the component or system with the shortest lifetime.

- A wind turbine is subjected to a large variety of dynamic loads due to wind fluctuations in speed and direction and numerous starts and stops of the system. Some primary parts or components have to withstand heavy fatigue loads [79].
- Advanced high-strength, fatigue-resistant materials are vital to some key components in modern large wind turbines due to the continuous increase in blade length, hub height, and turbine weight.
- As a complex engineering system, a wind turbine must be designed at the system level rather than part/component level as a common practice in some turbine manufacturers.

6.7 Cost of electricity from wind power

Although the wind power industry appears to be booming in recent years worldwide, achieving continuous cost reduction in wind power generation continues to be a challenge and a key focus for the wind industry.

Wind power is characterized by low variable costs and relatively high fixed costs. The main factors governing wind power economics are [80]:

- Investment costs, including wind turbines, foundations, and grid connection
- Operation and maintenance (O&M) costs, including regular maintenance, repairs, insurance, spare parts, and administration
- Wind turbine's electricity production cost, which highly depends on the wind turbine capacity, wind farm size, and average wind speed at the chosen site
- Wind turbine lifetime
- Discount rate

Among these, the most important factors are the wind turbines' electricity production and their investment costs. The trends towards lager wind turbines and larger wind farms help reduce both investment and O&M costs per kilowatt-hour (kWh) produced.

Though the price of electricity from wind has fallen approximately 90% over the last 30 years because of the developments of wind technology, it is still more expensive than those from coal or natural gas. It has been predicted by Electric Power Research Institute that even for plants coming online in 2015, wind energy would cost nearly one-third more than coal and about 14% more than natural gas [81]. This is the greatest obstacle for wind power to increase its share in the electric power market. A recent study [82] indicates that wind energy in US today still depends on federal tax incentives to compete with fossil fuel prices, and technology progress could dominate future cost competitiveness.

The global financial and economic crisis, which started from early 2008, has dramatically altered the pace of wind development. With reduced power consumption, the prices of fossil fuels (e.g. coal and natural gas) have greatly decreased, putting even more pressures on the wind power industry to continuously drive down wind power costs for staying competitive in the present challenging economic times.

7 Trends in wind turbine developments and wind power generation

Wind turbine technology has been developed by continuously optimizing turbine design, improving turbine performance, and enhancing overall turbine efficiency. There have been several generations of development and improvement in wind turbine technology, concentrated on blades, generators, direct drive techniques, pitch and yaw control systems, and so on. To provide more electrical energy from wind technology in the next several decades, it requires

- Developing innovative techniques
- Decreasing wind turbine costs through technology advancement
- Optimizing manufacturing processes and enhancing manufacturing operations
- Improving wind turbine performance and efficiency
- Reducing operating and maintenance costs
- Expanding wind turbine production capacities

The current major trends in the development of wind turbines are towards higher power, higher efficiency and reliability, and lower cost per kilowatt machines.

7.1 High-power, large-capacity wind turbine

One of the significant developments in wind turbine designing and manufacturing in recent years is the increase in the wind turbine capacity of individual wind turbines. From machines of just 25 kW two decades ago, the commercial range of modern wind turbines sold today is typically 1–6 MW. At the same time, 7–10 MW wind turbines are underway in some larger wind turbine OEMs. With this trend, innovative techniques have been developed and new materials have been adopted for optimizing the wind turbine performance and minimizing the operation and manufacturing costs. Enercon has installed the present world's largest wind turbine E-126 in Germany and is in the process of installing more units in Belgium. The E-126 turbine is rated at 6 MW with the rotor diameter of 126 m [83]. Clipper Windpower has announced that it is planning to build a 7.5 MW offshore wind turbine [84].

However, while high-powered wind turbines enable to increase wind power output per unit and lower the cost per kWh, there are some significant challenges facing wind turbine engineers:

a. Failure rates of wind turbines depend not only on turbines' operational age but also their rated power. High-power, large-size wind turbines have shown significant higher annual failure rates due to the primary failures of the control system, drivetrain, and electronic/electrical components. Because most of mega-watt wind turbines were usually among the first models installed, they show high early failure rates that decrease slightly throughout their years of operation [85].

b. Wind velocity is proportional to the height from the earth's surface. With the continuously increasing blade length of large wind turbines, the differences of the dynamic wind loads between the rotating blades become significantly large, resulting in a large resultant unbalanced fatigue load on the turbine blades, and a resultant unbalanced torsional moment on the main shaft, and in turn, on the wind tower.
c. During wind turbine's operation, a minimum clearance must be maintained between the blade tips and the wind tower. Therefore, high blade stiffness is required to avoid the collision between the blades and the tower. In practice, the maximum blade length is constrained by required stiffness and stresses of blades.
d. Large wind turbines become more susceptible to variations in wind speed and intensity across the swept area.
e. Transportation and installation of long-length blades remain challenges to the wind power industry. The length of a blade for a 4.5–5 MW wind turbine ranges 50–70 m. It is very difficult to ship such long blades through current highways and installed on the top of 120–160 m wind towers.
f. The tower strength is another consideration. For a given survivable wind speed, the mass of a wind turbine is approximately proportional to the cube of its blade length and the output power is proportional to the square of it blade length. Typically, the mass of a 4.5–5 MW is of 200–500 tons. It was reported that doubling the tower height generally requires doubling the diameter as well, increasing the amount of material by a factor of 8 [86].

To ensure the sustainability of the increase in power output and turbine size, all these challenges must be carefully and effectively addressed.

7.2 Offshore wind turbine

With several decades of experience with onshore wind technology, offshore wind technology has presently become the focus of the wind power industry. Due to the lower resistance, wind speeds over offshore sea level are typically 20% higher than those over nearby lands. Thus, according to the wind power law, the offshore wind power can capture much more power than the onshore one. This indicates that an offshore wind turbine may gain a higher capacity factor than that of its land-based counterpart. In addition, because the offshore wind speeds are relatively uniform with the lower variations and turbulence, it enables the offshore wind turbines to simplify the control systems and reduces blade and turbine wears.

Sweden installed the first offshore wind turbine in 1990, with the unit capacity of 220 kW. Denmark built its first demonstration offshore wind turbines in 1991, which consists of 11 units, with the unit capacity of 450 kW. With the developments of offshore wind technology in the next several years, offshore wind turbines entered the stage of industrial production in 2001. Today, high capacity wind turbines focus on the offshore application. In 2009, nearly 600 MW offshore wind power were added and connected to electric grids, basically by European countries, bringing the total accumulative installed offshore wind power capacity to more than 2,000 MW. It is expected that in 2010 ten additional European

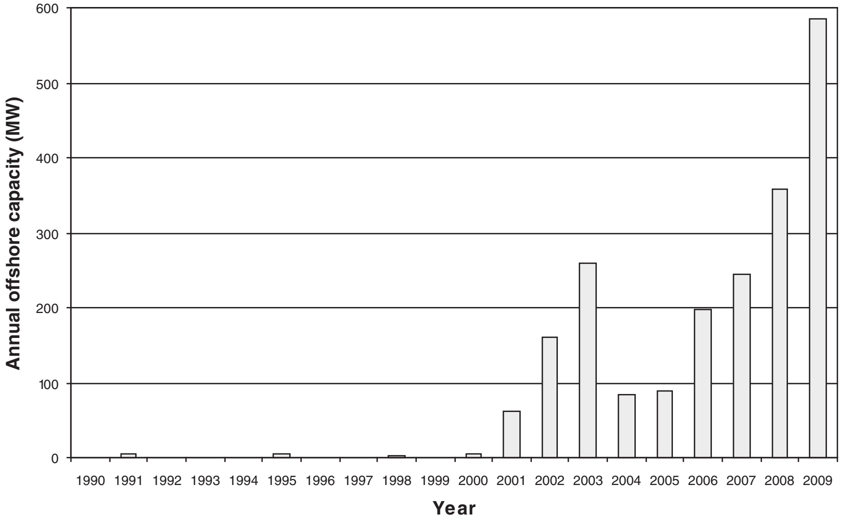

Figure 13: Annual installed offshore wind power capacity (all but 2009 data from [1]).

offshore wind farms will be completed to add approximately 1,000 MW online, which represents a growth rate of 75% compared to 2009. The related foundation technologies for offshore applications are also being developed for the erection of higher capacity wind turbines. The annual installed offshore wind power capacities from 1990 to 2009 are shown in Fig. 13.

Offshore wind turbines are installed in seawater, with greater risks of structural corrosion, particularly under conditions of high wave, sea salt splashing and low temperature. To avoid or at least delay the corrosion to protect wind turbines, a number of techniques have been developed. One of them involves the use of electrochemical reactions to prevent the steel corrosion, known as cathodic protection. This is done using a small negative voltage applied to metal. A new method, called impressed current cathodic protection, was invented by Brown and Hefner [87]. This method includes providing an impressed current anode electrochemically coupled to the wind turbine support structure to the impressed current anode to operate the impressed current anode.

In dealing with corrosion control, coating technology plays an important role in the wind power industry. The adoption of high performance of multi-coating systems has achieved satisfactory results to prevent external and internal corrosions of wind turbines. The coating materials used today include thermally sprayed metal (zinc and aluminum), siloxane, acrylic, epoxy, polyurethane, etc. It is expected to develop inorganic hybrid materials (such as polysiloxane) as super durable finishes to meet more aggressive environments [88].

7.3 Direct drive wind turbine

In a direct drive wind turbine, rotor blades directly drive the rotor of the wind generator. By eliminating the multi-stage gearbox, which is one of the most easily damaged components in a MW wind turbine, the number of rotating parts is greatly reduced and the turbine structure is considerably simplified. As a result, it significantly increases the reliability and efficiency of the wind turbine and reduces turbine noise and maintenance costs. Since direct drive wind generators operate at relative low speeds, it reduces the wear and tear of the generator. In order to identify suitable generator concepts for director drive wind turbines, Bang *et al.* have compared various direct drive generator systems and concluded that direct drive permanent-magnet synchronous machines are more superior in terms of the energy yield, reliability and maintenance costs [89].

Though the concept of direct drive wind turbine has been proposed for a long time, the modern direct drive techniques have become available until recent three decades. Presently, direct drive wind turbines have been manufactured by large wind OEMs. Siemens installed two innovative 3.6 MW direct drive wind turbines at a site in west Denmark in 2008. The feasibility of building 10 MW direct-drive wind turbine was investigated by Polinder *et al.* [90].

However, direct drive wind turbines have some disadvantages in terms of the cost, size, and mass, making them difficult in manufacturing, shipping, and installing. Without a gearbox, the rotor diameter in a direct drive generator must be made larger enough to maintain a relative high rotating speed at the air gap. A lot of structural material must be added to keep the stator and rotor in place for maintaining the air gap. Therefore, the direct drive wind turbine has a larger size and a higher weight. For instance, the Siemens 3.6 MW direct drive wind turbine has a total weight of 265 tons (nacelle 165 tons and rotor 100 tons), as compared with 235 tons for a 3.6 MW geared turbine [91]. This requires the higher strength for the turbine tower. According to Bang *et al.* [89], the cost of a 3 MW direct drive PM synchronous generator system could be 35% higher than that of a 3 MW induction generator system with three stage gearbox. To make the direct drive wind turbines more attractive to the wind market, all these disadvantages must be solved.

7.4 High efficient blade

Rotor blade design can be split into structural and aerodynamic design. During normal wind turbine operation, rotor blades have to withstand enormous dynamic loads. The bending moment due to the gravity load results in up to 10^8 load cycle alternations within the turbine lifetime. In addition, there are stochastic alternating loads caused by wind turbulence and the effects of ageing of the materials due to the weather [92]. As wind turbines become larger and larger, the length, size, and weight of blades increase accordingly. For instance, the blade diameter in a large wind turbine could be longer than 100 m, which is higher than the wingspan and length of Boeing 747-400 at 64.4 and 70.7 m, respectively. There is no doubt that these blades require extremely high fatigue strength.

In the blade structural design, one indicator is the blade weight/swept area ratio (or swept area density in some references). It is highly desired to minimize this ratio while satisfying the blade strength requirements. Most blades used today are made from composite materials such as glass-fibre epoxy, carbon epoxy, fibre-reinforced plastic, etc. With epoxy resin/glass-fibre material, the weight/swept area ratio of 1–1.5 kg/m^2 can be achieved up to a rotor diameter of 62 m [93]. With the trend toward long-length and larger-size blades, high-strength, fatigue-resistant materials such as metallic materials need to be considered.

The aerodynamic design of wind turbine blades is important as it determines the wind energy capture. With advanced CFD tools, the shape of aerodynamic profile and dimensions of blade can be preliminarily determined and the blade optimization can be achieved via field tests. As a good example, a study of aerodynamic and structural design for wind turbines larger than 5 MW was reported by Hillmer *et al.* [94].

There are a number of improvements achieved in the rotor blade design. A new type of wind turbine blades, named “STAR” (Sweep Twist Adaptive Rotor) blades, was specially designed for low-wind-speed regions. The test results have shown that the STAR blades can shed 20% of the root moment via tip twist of about 3° and yield 5–10% annual energy capture than the regular blades [95].

Researchers at Purdue University and Sandia National Laboratory have developed an innovative technique that uses sensors and computational software to constantly monitor forces exerted on wind turbine blades. The data is fed into an active control system that precisely adjusts the shape of rotor blades to respond to changing winds. The technique could also help improve turbine reliability by providing critical real-time information to the control system for preventing damage to blades from high winds [96]. Recent aerodynamic research has revealed that an increase of the aerodynamic efficiency of a wind turbine rotor may be achieved by extending the turbine blades to very close to the wind turbine nacelle [97].

7.5 Floating wind turbine

Dr. Sclavounos at MIT is among the first to develop the concept of floating wind turbines in deep water. He and his team in 2004 integrated a wind turbine with a floater. According to their analysis, the floater-mounted turbines could work in water depths of up to 200 m [98].

The world’s first commercial-scale floating wind turbine has being constructed in deep water far from land [100]. The turbine is mounted on a floating turbine platform on the sea surface and anchored to the seabed with three strong chains. Changing the length of the chains could allow the turbine to operate in water depths between 50 and 300 m, enough to take it far out into the deep ocean. By comparing with existing offshore wind turbines, floating wind turbine is more economic in the installation and shipping. Electricity would be sent ashore using undersea cables.

Sway, a Norwegian company, plans to launch its prototype of floating wind turbines in 2010. The turbine is to be mounted on an elongated floating mast, connected to the seabed by a metal tube. The turbine mast is designed to sway with wind and waves, and can lean at an angle of up to 15° [101].

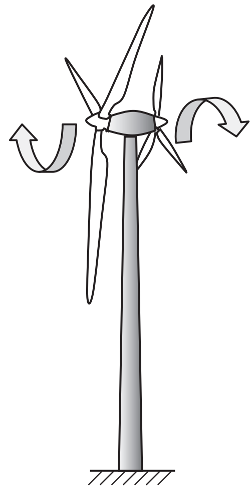

Figure 14: Illustration of a dual-blade set wind turbine.

7.6 Wind turbine with contra-rotating rotors

Coaxial contra-rotating propellers have been widely applied to aircrafts, marines, ships, and torpedoes for improving the propulsion efficiency and offsetting system reactive torques. The efficiency of contra-rotating propellers was found 6–16% higher than that of normal propellers [102]. Late, the contra-rotating concept has been introduced into the wind turbine design. The contra-rotating type of wind turbines has usually two sets of blades that rotate in opposite directions. These two sets of blades can be arranged either one behind another at the turbine front, or separately at the turbine front and rear (see Fig. 14).

Schönball [103] is one of the first to describe a mechanism which composes of two contra-rotating rotors. In the generator, a rotor is driven by one wind wheel and a regular stationary stator driven by another wind wheel. Owing to the opposed rotation of two wind wheels, the relative speed between the two rotors may be doubled and thus the efficiency is correspondingly increased, compared with a conventional generator having one rotor. Similarly, McCombs [104] developed a wind turbine equipped with two sets of blades that propel the rotor and stator directly. More recently, Wachinski [105] proposed a drive device for an improved windmill composed of two counter-rotative sets of blades. In 2005, with two granted US patents [106], Kowintec Inc. successfully built up a 100 kW and 1 MW contra-rotating wind turbine prototypes. The test results have shown that with the dual-blade and dual-rotor, the power production efficiency of the turbine increases 24% and the system cost decreases 20–30%, by comparing with a conventional single rotor unit [108].

The benefits of using contra-rotating wind turbines are:

- Enhancing wind energy capturing capability – A wind turbine with a contra-rotating system can capture more wind energy to convert into electricity, by comparing with a single set of blades. In a contra-rotating win turbine, each set of blades contributes independently to the total power output. Because the length of each set of blades can be made differently, the wind turbine may produce electricity at a lower cut-in speed by the set of blades with a shorter blade length.

- Achieving higher power density – With the increase in power output and the moderate increase in wind turbine volume, the power density becomes higher.
- Reducing wind turbine cost per kWh – Though the total cost of this type of wind turbines increases due to the addition of extra parts, the cost per kWh will decrease for the large increase in power output.
- Increasing wind turbine operation reliability – Some types of contra-rotating wind turbines eliminate gearboxes to simplify the design and increase the turbine operation reliability.

However, this type of wind turbine also has some drawbacks. The main negative effect is the wake vortices created by the first set of blades which can substantially lower the performance of the second set of blades. In fact, the wake vortices will enhance the wind turbulence intensity to strengthen unbalanced dynamic loads on the second set of blades, decreasing the mean wind velocity and the power captured by the second set of blades.

7.7 Drivetrain

In a geared wind turbine, the term “drivetrain” usually encompasses all rotating parts, from the rotor hub, the main gearbox, to the generator. The main gearbox is one of the most important components in the wind turbine, for increasing the slow rotation speed of the blades to the desired high speed of the generator’s rotor. It is also the most expensive component in the turbine and can easily fail before reaching the intended life. With the increase in the turbine size and capacity in the last decade, the gearbox has been subjected to even greater loads and stresses. There are significant challenges presented to gearbox designers and manufacturers.

Wind turbines typically use planetary gears to divide torque along three paths and reduce individual loads on each gear. However, torsional loads twist gears out of alignment, and slight dimensional variation in gearbox components, indicate that planetary gears do not equally share the load. Misaligned gears, shock loads, and uneven forces lead to highly localized stress and eventually fracture along the gear edges. To solve these problems, an innovative type of gearbox has been developed (Fig. 15), using the Integrated Flex-pin Bearing (IFB) to equalize gear loads, eliminate misalignment, and dramatically improve wind turbine reliability. This novel design increases torque capacity of planetary gears up to 50% [109].

Based on the failure analysis of gearboxes, the Gearbox Reliability Collaborative initiated at US National Renewable Energy Laboratory (NREL) provides a fresh approach toward better gearboxes that combines the resources of key members of

Figure 15: Flex-drive planetary gearbox. Courtesy of [109].

the supply chain to investigate design-level root causes of field problems and solutions that will lead to higher gearbox reliability [111].

7.8 Integration of wind and other energy sources

One of the notable characteristics in the wind power generation is its uncertainty due to the sudden change in both wind speed and direction, especially for off-grid wind power generation systems. Therefore, the power output from wind turbines fluctuates from time to time. When wind turbines are connected to a small or isolated grid, the power output from other generators must be varied in response to these variations and fluctuation in order to keep system frequency and voltage within predefined limits. For this purpose, it is beneficial to integrate wind and other complementary energy sources to form hybrid power systems for assuring the stability and reliability of power supply and reducing the requirement for the wind energy storage.

7.8.1 Wind–solar hybrid system

Both wind and solar energy are highly intermittent electricity generation sources. Time intervals within which fluctuations occur span multiple temporal scales, from seconds to years. These fluctuations can be subdivided into periodic fluctuations (diurnal or annual fluctuations) and non-periodic fluctuations related to the weather change.

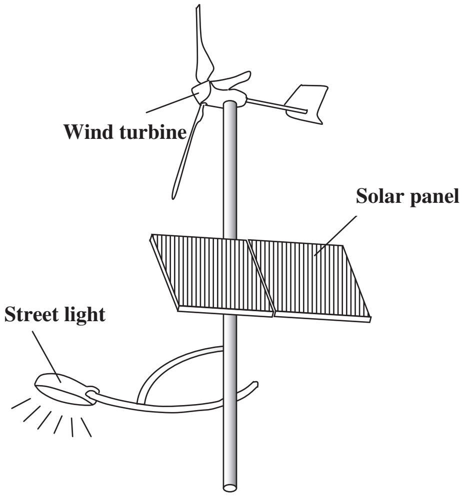

Figure 16: Wind–solar hybrid system for street lights.

Wind and solar energy are complementary to each other in time sequence and regions. In the summer, sunlight is intensive and the sunshine duration is long but there is less wind. In the winter, when less sunlight is available, wind becomes strong. During a day, the sunshine is strong while wind is weak. After sunset, the wind is strengthened due to large temperature changes near the earth's surface. It has been reported that the effects of complementarity are more dramatic in certain periods and locations at Serbia [112]. The analyses and test data of wind–solar hybrid power systems have shown that the optimum combination of the wind–solar hybrid system lies between 0.70 and 0.75 of solar energy to load ratio with the minimized life cycle cost. For all load demands, the leveled energy cost for the wind–solar hybrid system is always lower than that of standalone solar or wind system [113].

Because the major operating time for wind and solar systems occurs at different periods of time, wind–solar hybrid power systems can ensure the reliability of electricity supply. The applications of wind–solar hybrid systems ranges extensively from residential houses to municipal and industrial facilities, either grid-connected or standalone. For instance, as an independent power supply source, wind–solar hybrid systems have been widely used in China for street lighting (see Fig. 16). The world's largest wind–solar power test base, integrating wind power, photovoltaic power and energy storage, is being constructed at Zhangbei, China. The project will have an installed capacity to generate 300 MW of wind power, 100 MW of solar power and 75 MW of chemical energy storage [114].

7.8.2 Wind–hydro hybrid system

Hydropower generation is to convert potential energy in water into electrical energy by means of hydropower generators. As a renewable and clean energy source, hydropower accounts for the dominant portion of electricity generated from all renewable sources.

In many locations of the world, hydropower is complementary with wind power, while the seasonal wind power distribution is higher in winter and spring but lower in summer and fall, hydropower is lower in the dry seasons (winter and spring) but higher in the wet seasons (summer and fall). Thus, the integration of wind and hydropower systems can provide significant technical, economic, and systematic benefits for both systems. Taking a reservoir as a means of energy regulation, "green" electricity can be produced with wind–hydro hybrid systems.

7.8.3 Wind–hydrogen system

Hydrogen is an energy carrier and can be produced from a variety of resources such as water, fossil fuels, and biomass. As a fuel with a high energy density, hydrogen can be stored, transported and then converted into electricity by means of fuel cells at end users. It is widely recognized that wind power, solar power and other renewable energy power generation systems can be integrated with the electrolysis hydrogen production system to produce hydrogen fuel. The largest wind-to-hydrogen power system in the UK has been applied to a building that is fuelled solely by wind and "green" hydrogen power with the developed hydrogen mini-grid system technology. In this system, electricity generated from a wind turbine is mainly used to provide to the building and excess electricity is used to produce hydrogen using a state-of-the-art high-pressure alkaline electrolyser [115].

7.8.4 Wind–diesel power generation system

Wind power can be combined with power produced by diesel engine-generator systems to provide a stable supply of electricity. In response to the variations in wind power generation and electricity consumption, diesel generator sets may operate intermittently to reduce the consumption of the fuel. It was reported that a viable wind–diesel stand-alone system can operate with an estimated 50–80% fuel saving compared to power supply from diesel generation alone [116].

Wind–diesel hybrid power systems have been studied since 1995 in the US. Till now, many new techniques have been developed and a large number of wind–diesel power generation systems have been installed all over the world [117]. According to the proportion of wind use in the system, three different types of wind–diesel systems can be distinguished: low, medium, and high penetration wind–diesel systems. Presently, low penetration systems are used at the commercial level, whereas solutions for high penetration wind–diesel systems are at the demonstration level. The technology trends include the development of robust and proven control strategies [41].

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