In the first in a new series, John Twidell explains the fundamentals of wind power technology. He summarizes the engineering and operational principles of wind turbines, and looks at some of the latest developments in the field.

Technology Fundamentals

Wind turbines

After 30 years of modern development, the generation of electricity from wind is now accepted as 'mainstream' grid power generation by utilities in many parts of the world. This is because the technology is reliable, cost-effective, and avoids the environmental disadvantages of fossil- and nuclear-fuelled generation. Large machines (usually now of about 1–3 MW in capacity, with rotor diameters of between 70–100 metres) are used in grid-connected applications, and smaller machines are used for autonomous and remote power.

Wind energy technology has become a most sophisticated and advanced multidisciplinary engineering enterprise, well aware of its environmental obligations and economic benefits. World wind generating capacity is now over 33,000 MWe, increasing exponentially at about 30% per year with a global manufacturing market of €10 billion annually. The energy produced each year equals the essential and sustainable electricity requirements of about 17 million European-style houses, abating about one tonne of fossil fuel per house per year.

Appreciating these machines requires an understanding of their fundamental concept, their environmental impact, and of where they are best located for cost-effectiveness. It is also important to be aware of the materials used for construction, and how turbines are sized. Since the vast majority of wind turbines have a horizontal axis with two or more blades, this is the type covered here.

BLADE ROTATION

To understand why a wind turbine blade rotates, we can start by looking at an aeroplane wing (Figure 1). The air meeting the wing has relative wind speed *v*, at an angle of attack α, of about 5º. The wing profile makes the air pass (in a smooth, laminar flow) over the top of the wing faster than it passes beneath. In accordance with Bernoulli's theory, this causes a lift force on the wing. Since the wing is joined at its root to the fuselage, the aeroplane stays up.

Now, the wing is turned, so it becomes a wind turbine blade. Imagine looking down onto the section of a vertical blade, as in Figure 2 (this figure also applies to all positions of the rotating blade). Because the blade is turning, the wind direction relative to the blade is similar to that relative to an aeroplane wing. The setting of the blade, angle γ, is such that the lift force causes the blade to move in the direction of rotation, and so power is transmitted via the root of the blade to the turbine shaft. Note that the direction of the relative wind, as experienced by the blade because of its own motion, is in a quite different direction from the unperturbed wind. In Figure 2, this direction is at angle ϕ to the plane of rotation, where ϕ is the flow angle, equal to the sum of the angle of attack, α, and the blade setting

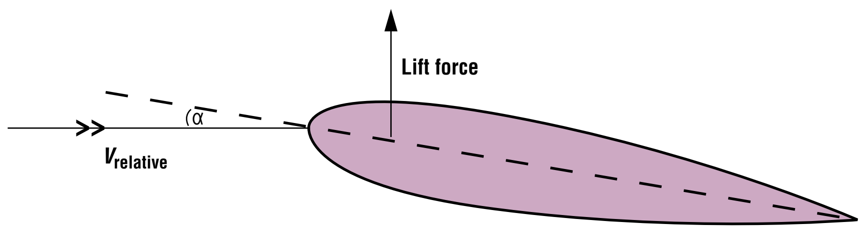

FIGURE 1 **Cross-section of an aeroplane wing. Relative wind speed $v_{relative}$. Angle of attack, α**

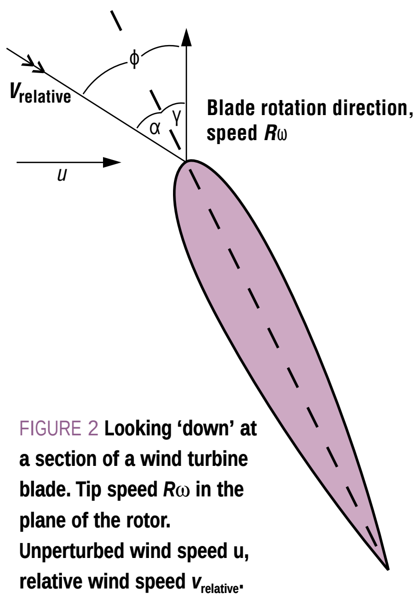

FIGURE 2 **Looking 'down' at a section of a wind turbine blade. Tip speed $R\omega$ in the plane of the rotor. Unperturbed wind speed u, relative wind speed $v_{relative}$. Blade setting angle α, angle of attack γ, flow angle ϕ**

angle γ. The design of the blade profile allows optimum values of angle of attack and blade setting, both of which should remain constant whatever the unperturbed wind speed. Because the relative wind speed increases in amplitude from the blade root to the blade tip, blade section design has improved from standard aeroplane shapes to specialist wind turbine designs. It is also necessary to limit the energy capture from the wind when the machinery has reached its rated (maximum) limits; this also affects blade design.

SPEED OF ROTATION: TIP-SPEED RATIO λ

Therefore, if you understand how aeroplanes fly, or how yachts sail into the wind, you should now understand that Bernoulli's theory of lift also explains why wind turbine blades rotate. Next, we need to know the optimum rotational speed of the blades about the hub for a particular wind speed.

A very slow rotational speed will allow wind to pass unperturbed through the gaps between the blades, and so the rotor will be inefficient. A very high rotational speed will make the rotor appear solid to the wind, the air will become grossly turbulent, and again the wind will not turn the blades efficiently. At some value between very slow and very fast is the optimum rotational speed for transmitting power to the rotor. It is easy to determine this value for a wind of unperturbed speed u arriving at a blade of constant blade setting angle γ, with constant angle of attack α.

Variable speed and fixed speed

Figure 2 shows the relative wind impinging on the rotating blade at an angle of attack α and relative speed v. The tip of the blade moves at a speed $R\omega$, where R is the blade rotor radius (blade length) and ω is the angular speed of rotation (radians/second). If γ and α are constant, then their sum, ϕ, is constant. Thus, the cotangent of ϕ (= $R\omega/u$) is also constant. This dimensionless ratio, $R\omega/u$, is the 'tip-speed ratio', symbol λ, a most important parameter for wind turbines. For each particular shape of wind turbine blade, whatever the size, the tip-speed ratio λ should remain constant, regardless of wind speed. Greatest efficiency is therefore achieved by allowing the rotor to change its rate of rotation as the wind speed changes, so maintaining a constant value for λ; this is called **variable speed** operation.

The latest wind turbines have generators and power electronics that allow variable speed, yet still produce alternating current (AC) electricity at 50 Hz to be produced for export to the utility grid (60 Hz in the US and other parts of the Americas). If traditional generators are used, then the rotor has to remain at a constant rotational rate to export constant frequency (e.g. 50 Hz or 60 Hz) power; called **fixed speed** operation. The components for fixed speed generation are cheaper than for variable speed, so this method was, and still is, used, despite the loss of approximately 20% of energy production by not having variable speed with constant λ.

Tip-speed ratio and turbine design

Both variable and fixed speed turbines reach their maximum, rated, power in strong winds. Therefore the blade has to be designed and adjusted to become inefficient in wind speeds greater than the rated wind speed (usually about 12 metres/second). This value, however, depends on the 'windiness' of the site. Therefore, each turbine has to be designed and tuned to the expected wind conditions of its site. The order of design procedure is as follows:

1. the maximum power of the wind turbine is decided
2. from meteorological information, the most likely wind speed, u', and the distribution of wind speeds, is deduced for the site
3. the length of the blades, R, is calculated to optimize annual energy production at the least cost, remembering that rated power cannot be exceeded
4. the most probable rate of rotation is calculated, so the blade tips have a speed $\lambda u'$, where λ usually has a value of about 7–10
5. an appropriate combination of gearbox (if needed), generator and power electronics is chosen, to produce electricity at 50 Hz or 60 Hz. For a given wind speed, it follows that ω is proportional to $1/R$, i.e. the larger the wind turbine, the slower it should rotate to maintain optimum efficiency.

The need for a blade tip-speed ratio of 7–10, whatever the size of the rotor, fixes the period of rotation at $T = 2\pi/\omega$. Therefore, in a moderate wind speed of about 7 metres/second, a small turbine of rotor diameter 10 metres should have a rotational period of about 0.4 seconds; however, a very large turbine of 100 metres diameter should have a period of about 4 seconds. Thus, the larger the wind turbine, the more slowly it rotates.

> At some value between very slow and very fast is the optimum rotational speed for transmitting power to the rotor

SPEED OF ROTATION AS WIND SPEED VARIES

Fixed speed turbines

Most manufacturers of wind turbines use traditional electricity generators for AC at grid frequency (50 Hz or 60 Hz), and these generators are usually wired directly to the grid. The generators only produce electricity at the grid frequency if rotating at an exactly constant (synchronous generator) speed, or

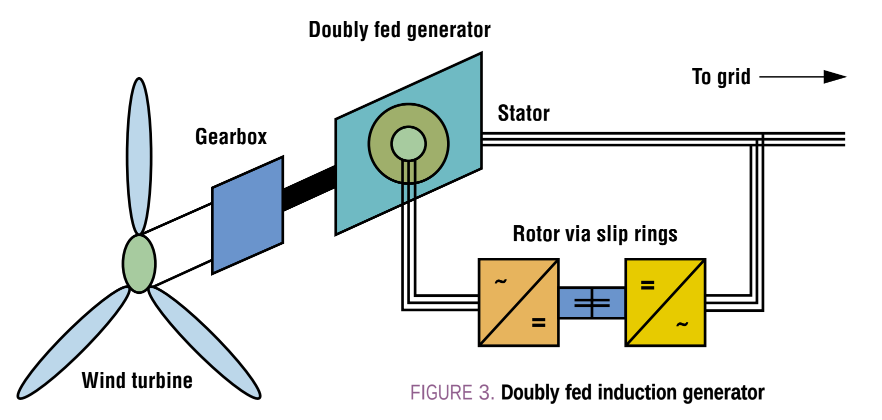

FIGURE 3. **Doubly fed induction generator**

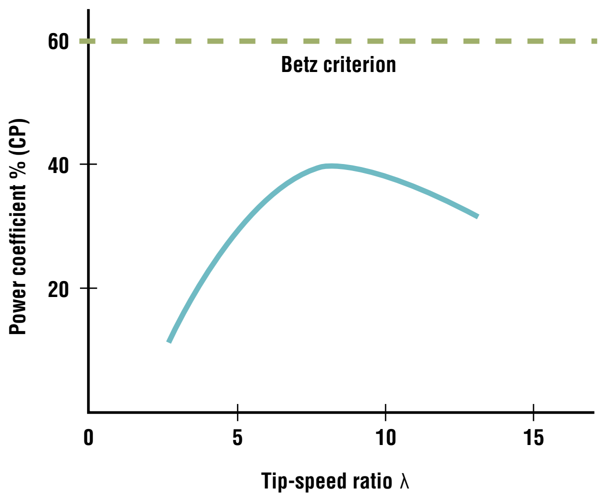

FIGURE 4. **Relationship between non-dimensional scaling factors (power coefficient *Cp* and tip-speed ratio λ) for a typical modern wind turbine generator**

nearly constant (induction generator) speed, of say 1500 rpm. Matching the rotor to this requires a gearbox; for instance, with a generator speed of 1500 rpm, and a rotor shaft at 30 rpm, a gearbox with a ratio of 50:1 is required. If the gearbox has only one speed ratio, then the designer has to design for one wind speed (usually, the 'most probable wind speed'). If there are two speed ratios, it is possible to reduce the rotor speed to match low wind speeds, and then use the increased gearbox ratio for the 50 Hz or 60 Hz electricity generation. When the wind is at speeds other than the design (rated) wind speed, generation can still occur, but the efficiency of energy capture is less. At much larger wind speeds, this inefficiency becomes a benefit, as the generator is then less likely to be overloaded.

Variable speed turbines

Optimum energy capture by the rotor requires a constant tip-speed ratio. Therefore, when the wind speed changes, the rotor speed should change accordingly. This is possible, in two main ways:

1. the wind turbine is entirely 'decoupled' from the grid by the following process:
   - generating AC, with a synchronous generator
   - rectifying all the power to direct current (DC)
   - inverting (converting) the DC to standard 50 HZ or 60 Hz AC for grid connection.

   There are added costs of equipment, and, until recently, some inverters produced unwanted electrical harmonics. However, such AC/DC/AC systems are becoming increasingly common, especially because of the improved energy capture, improved low wind speed efficiency, and better and cheaper power electronics.

2. a 'doubly fed' induction generator is used (see Figure 3), as increasingly developed, especially for wind power. Such generators allow variable speed rotation by controlling and changing the currents in the rotor using power electronics. Power is extracted from the stator (as with a conventional induction generator), and via an AC/DC/AC converter, from the rotor (not conventional). Many companies now use this method, which provides an example of the many improvements in technology that wind turbines have promoted.

Elimination of the gearbox

Moving a wire through a magnetic field generates electricity. Standard commercial electricity generators have the equivalent of four or six magnetic fields from windings (pole-pairs). In all but the smallest wind turbines, a gearbox is needed so the requirement for optimum tip-speed ratio is met. However, if the generator has many more pole-pairs (a multi-pole generator), then the gearbox can be eliminated. This has potential benefits for cost and noise reduction. The necessary 50–100 pole-pair-scale generators have a large diameter, and so become a defining feature (e.g. of the German Enercon turbines). This is an example of how sophisticated electrical engineering and electronic control is reducing the amount – and hence cost – of the mechanical components.

NUMBER OF BLADES

As a blade rotates, it moves into the space occupied by a previous blade. The limit to speed of rotation is that this space should not contain air strongly perturbed by that previous blade; therefore, fast-turning rotors should have few blades. However, having more blades increases torque on the rotor shaft.

The general rule for the optimum number of blades on a rotor depends on its function, and can be outlined as follows:

- electricity generation requires high speed at low torque, so the rotor has few blades
- water pumping (and historic milling) requires large torque at low speed, so this rotor has many blades.

The minimum number of blades is one, which is possible with a dense counterweight; however the rotor motion is very uneven because the wind speed is higher with the blade up than it is with the blade down. Having two blades is common, but motion is still not steady, and the visual impact can be slightly disturbing. A three-bladed rotor has a steady motion, is quieter and is visually the most acceptable. However blades are expensive, so the fewer of them there are, the cheaper the turbine. It is suggested that three-bladed turbines will become the norm on land, but two-bladed machines may become common for offshore wind farms.

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POWER EXTRACTED FROM THE WIND

Interaction of the wind with the blades transmits power to those blades. However, this wind must not stop, otherwise more wind cannot 'arrive'. Therefore, the departing wind takes away kinetic energy, so the extraction of power from the wind by the turbine is less than 100%. The Betz's linear momentum theory concludes that the maximum fractional energy extraction is 16/27, i.e. 60%, which is the benchmark criterion for designers. The dimensionless fraction is called the 'power coefficient', C_p, which is a function of the tip-speed ratio, λ (see Figure 4). In practice, $C_{p,max}$ is less than 60%, and about 40% for a clean blade at optimum tip-speed ratio. Rotors with fewest blades have highest $C_{p,max}$.

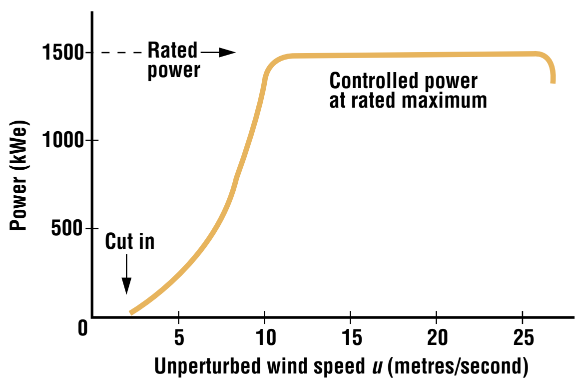

FIGURE 5. **Power vs wind speed characteristic for a typical 1500 kWe-rated wind turbine**

ENERGY IN THE WIND

Let the unperturbed wind speed be u; per second, the wind that imparts energy to the rotor of cross-sectional area A is predominantly in a cylinder of air, of length u and cross-section A. This cylinder, of mass m, has kinetic energy $P_o = mu^2/2$. However, $m = \rho Au$, where ρ is the air density. So $P_o = (\rho Au^3)/2$. The power in the wind varies as the **cube** of the wind speed. This rapid and highly non-linear relationship explains much about wind turbine design, siting and performance.

For example, a doubling of wind speed allows eight times more power capture. The consequences are as follows:

- great care is taken to site machines for strong and steady winds
- since wind speed varies, the design (rated) wind speed is about twice the average wind speed
- by designing for strong winds, turbines may not turn in the frequent low wind speeds
- a rapid increase in wind speed can quickly bring generation to the maximum rated value of the generator, so rapid and efficient control action is required.

POWER CURVE

The main practical characteristic is the change in power production with wind speed. Figure 5 is an example of power vs wind speed for a single speed machine in increasing wind. Generation starts at the cut-in wind speed (about 4 metres/second), increases in proportion to the wind speed cubed until the generator's rated power is reached, then flattens, either because the blades or blade tips are turned for control ('active stall') or the blade is designed to become very inefficient ('passive stall') at the rated condition. The rotor may be stopped and braked ('parked') in gales when the extreme wind turbulence would cause damage.

DESIGN SIZE

At least four factors dominate the design of blades and components:

- the forces from the wind vary as the **square** of the wind speed (as with all moving fluids)
- the rotational frequency and its harmonics cause unwanted, but predictable, vibrations
- unpredictable turbulence in the wind causes persistent, rapid and often violent oscillations
- the rise and fall of the blades (which weigh many tonnes) during rotation means they are subject to gravity stress cycles numbering 100 times more than the equivalent fatigue cycles on aircraft wings.

Therefore, the designer has to work within two different sets of criteria, one time-dependent and the other frequency-dependent.

The limiting factors on machine size relate to:

- the enormous torque on the main shaft at the hub of a slowly rotating rotor with large cross-sectional area
- the gravity- and turbulence-induced fatigue stresses on long blades
- operational experience.

Cost-effectiveness relates to engineering costs being, very roughly, proportional to mass. Starting from a small machine, increasing size has a linear relationship with mass as the blades become longer. However, power capture is proportional to the rotor area and hence the square of linear dimension, so there is considerable benefit in choosing a larger size. Then, as machines are increased in size beyond a 'certain range' of rotor diameters, the power-train torque dominates, and components have to be increased in volume, i.e. as linear dimension cubed. Thus machine cost, per unit of rated electrical capacity, changes from being inversely proportional to linear dimension, to being proportional to the linear dimension squared. The 'certain range' of rotor diameter has increased steadily for commercial machines as manufacturing and operational experience is gained. Ten years ago, this optimum had rotor diameters of about 30 metres (250 kWe-rated turbines); now, this figure is about 100 metres (2000 kWe).

Blades today are always of composite material structure, and of these, wood laminates are the toughest and lightest. Usually, blade angle (pitch) is adjustable at the blade/hub fixing for rotational control. The manufacture of blades is an associated speciality, undertaken by a relatively small number of companies.

Avoiding problems

The dangers of enforced resonance in structures require the designer to avoid vibrational frequencies near to the fundamental rotor frequency and its harmonics. Designers of bridges and aircraft have similar challenges; structures are either stiff (i.e. rigid and heavy) or flexible (i.e. dynamic and lightweight). To date, the great majority of commercial wind turbine towers and structural components are 'stiff' and, hence, more heavy and expensive than otherwise. Cost-effectiveness of future wind turbines may depend more on having dynamic and compliant design than on increased size. Control of rotation is now accurate and reliable, so conditions leading to resonant vibration in blades and other structural components can be avoided, as is particularly required for variable speed turbines.

Remote monitoring and control

The use of information technology and sophisticated communications for real-time monitoring, condition monitoring and control of wind turbines will increase. For instance, this will include the use of meteorological information and subsequent action to increase the accuracy of predicting electricity sales to the grid. It is already common for companies to monitor and, if necessary, control machines worldwide via satellite communication. No other commercial plant is operated in this fashion to such an extent.

OFFSHORE OR ON LAND?

Large structures, for example, 50 metre-long wind turbine blades, are difficult to transport on land. In addition, in the UK (excepting Scotland) and elsewhere in Europe, there are potentially only a few permitted land-based (as opposed to offshore) sites for wind farms comprising such large machines. Therefore, the development of offshore wind farms has increased in recent years,. The benefits of this include the possibility for large-scale implementation, steadier and stronger winds than on the adjacent land, and the opportunity for the wind farm to generate at a scale of 200 MW and be connected directly to national transmission grids. The difficulties include the extremes and dangers of the sea, and the increased cost of foundations, interconnections, installation and maintenance. Acoustic noise is not so important, so the larger tip-speed ratio of two-bladed rotors is permissible, with a consequent gain in efficiency and potential reduction in capital costs. Synergistic development with, amongst others, fisheries, fish protection and leisure facilities is also underdeveloped.

ENVIRONMENTAL IMPACT

In many parts of the world, there is such a dearth of electricity generation that wind turbines are welcomed by the public. Where there are alternative choices, however, environmental impact is of major significance for development – though it should be noted that 'impacts' may be judged as either beneficial or harmful. The impacts of wind turbines and the factors influencing them are:

- visual impact
- acoustics
- bird strike
- electromagnetic interference
- sustainability.

Land area and use

Turbines should be separated by at least five to ten tower heights; this allows the wind strength to re-form, and for air turbulence created by one rotor not to adversely affect another downwind. Consequently, only about 1% of land area is actually taken out of use by the towers and the access tracks. The taller and larger the turbines, the greater the separation. Megawatt-sized machines should be spaced between 0.5 km and 1 km apart. Neither buildings nor commercial forestry can be established between, so the land is thereafter safeguarded against such development, and can remain for agricultural use, leisure activities or natural ecology.

Visual impact

Wind turbines are always visible from places in clear line of sight; however, as noted before, the larger the machines, the greater the distance between them. The need for a long 'fetch' of undisturbed wind, and the economic bias towards large machines, means that turbines will be potentially visible from distances of tens of kilometres. However, at such distances, the majority of the public will have their sight obscured by features such as hills or trees, or by buildings. The people most likely to notice the machines on land are walkers and pilots. For the former, it is an aesthetic matter – 'beauty is in the eye of the beholder'; for the latter, it can present a danger, if flying an aircraft at exceptionally low levels. For offshore machines, visual impact is as yet largely unassessed.

> The environmental impact of wind turbines is of major significance for development

Acoustics

Noise is generated mostly from blade tips (high frequencies), from blades passing towers and perturbing the wind (low frequencies), and from machinery, especially gearboxes. Since noise is essentially a sign of inefficiency, and also because of complaints, manufacturers have reduced noise generation intensities greatly over the last five years. The critical noise intensity at the nearest building is usually considered to be 40 dBA (acoustic decibels), or less, as judged necessary for sleeping. This level of acceptance is usually attained at distances of about 250 metres or less. However attitudes to noise are strongly psychological; the owner of a machine probably welcomes the noise as a sign of prosperity, whilst neighbours may be irritated by intrusion of 'their space'.

Bird strike

There have been many independent studies of birds killed by rotating blades. This undoubtedly happens, but perhaps at a similar or smaller frequency than strikes by a car, against the windows of a building or by grid transmission cables; every death is regretted. The counter-argument, again attested by experts, is that land around wind turbines may provide excellent breeding conditions. The exception to this argument is the possibility of strikes by large migratory birds flying in the dark, or by raptors intent on their prey.

Electromagnetic interference

TV, FM and radar waves are perturbed in line of sight by electrically conducting materials. Therefore, the metallic parts of rotating blades can produce dynamic interference in signals. It is easy, but not necessarily cheap; to install TV and FM repeater stations to provide another direction of signal for receivers. Radar interference is, as yet, a largely undocumented effect, of most concern to the military; however, wind turbines are a fact of life, one which has to be accepted by the military on an international scale. There are many sites of wind turbines close to airfields, and no significant difficulties occur.

Sustainability

There is a scientific need for sustainable and zero-emission technology. Wind turbines generate power with no chemical emissions, and therefore abate the unacceptable pollution from fossil and nuclear generation. As humans we are part of an ecology, and so should preserve and improve conditions for all species. Wind turbines are key components of such a sustainable lifestyle.

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