WIND POWER PLANTS

Windmills have been used for many centuries for grinding corn and pumping water. Before the invention of the steam engine they were of primary economic importance. However, with the industrial revolution and then the widespread availability of cheap electricity produced from large fossil-fired or hydropower stations, the use of wind power declined. Pioneering work was carried out to investigate the use of wind power for the generation of electricity some 50 years ago (1,2) but this was discontinued due to the then low cost of fossil fuel. However, with the first oil shock of the early 1970s there was a reawakening of interest in wind power; it is from this time that the development of modern electricity generating wind turbines may be traced.

In response to the sudden increase in the price of oil, a number of countries, including the United States and the United Kingdom, initiated major government-funded research and development programs to develop very large wind turbines. Prototype turbines of up to 4 MW output and 100 m in rotor diameter were constructed. Unfortunately, the difficulties of building reliable wind turbines of this size were underestimated and, in almost all cases, the prototypes failed to give satisfactory long-term service. At the same time, many private companies developed small wind turbines, with out-

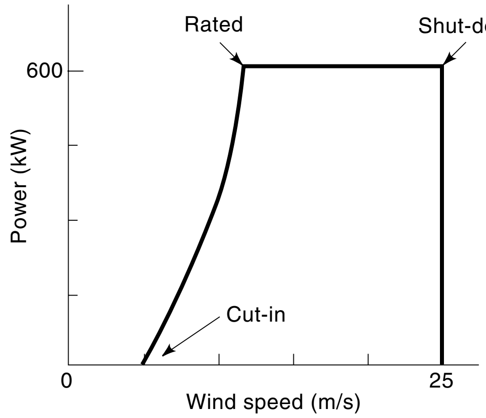

Figure 1. Power curve of a 600 kW wind turbine showing: (1) cut-in wind speed of 5 m/s; (2) rated conditions of 12 m/s and 600 kW; and (3) shut-down wind speed of 25 m/s.

puts of, say, 50 kW and rotor diameters of 15 to 17 m. These small wind turbines were installed in large numbers in the United States in California and in Denmark where particular financial and administrative arrangements had been made to encourage electricity generation by wind power. Although many of these small turbines also failed to work properly, over the next 20 years, the development of wind turbine technology was such that by the end of 1997 some 7500 MW of wind turbine capacity had been successfully installed worldwide, and a number of wind farms with turbines of rotor diameters up go 45 m and with outputs of 600 kW had given satisfactory service for several years. The first units of the next generation of wind turbines with rotor diameters of up to 60 m and rated outputs of 1.5 MW had also been constructed.

There are two basic architectures of a wind turbine: (1) the horizontal axis or propeller type, and (2) the vertical axis, Darrieus or "egg beater" type. Although there are some wind farms of small vertical axis turbines in California and there is limited continuing interest in the technology, this architecture is not of commercial significance. Modern horizontal axis wind turbines usually employ three blades as this is the most aesthetically pleasing arrangement. The rotor is located upwind of the tower to reduce torque pulsations and noise due to the blades passing through the wind shadow of the tower.

The power curve of a wind turbine (Fig. 1) shows the relationship between the wind speed some distance upsteam of the rotor and the electrical output from the turbine generator. At wind speeds below cut-in (5 m/s in this case) there is not enough power in the wind to overcome the frictional losses of the turbine drive train and the rotor is kept parked. Between cut-in and rated wind speed the output power rises very rapidly. The power available in the wind is proportional to the cube of the wind speed. However, with a fixed-speed wind turbine the aerodynamic efficiency of the rotor varies with wind speed and thus the power between cut-in and rated wind speed does not follow the cubic relationship precisely. At rated power and wind speed (600 kW and 12 m/s in this example) the power developed by the rotor is limited either by changing the pitch angle of the blades (pitch control) or by allowing the blades to enter aerodynamic stall (stall control). The choice of rated power and wind speed is made by the designer of the turbine. At shut-down wind speed the turbine rotor is parked and turned out of the wind in order to reduce mechanical loading on the rotor and tower.

Wind speeds vary continuously with both time and place and it is clearly important to ensure that any wind turbine is located in an area of high wind speed if maximum energy output is required.

For assessment of the annual energy that will be obtained from a wind turbine it is usual to use hourly mean wind speeds. A typical example of a discrete probability distribution of hourly mean wind speeds over a year is shown in Fig. 2. This shows the number of hours in the year when the hourly mean wind speed was in a 1 m/s bin centered on the integer wind speed. The continuous form of these probability distributions is conventionally described using Weibull parameters (3). The annual energy yield of a turbine can be calculated simply by summing the product of the power curve and wind speed distribution for each wind speed bin, that is,

$$E = \sum_{i=1}^{i=n} H_i W_i$$

where E is the annual energy yield in kilowatts per hour, H is the hours in wind speed bin i and W is the output power at that wind speed in kilowatts; n is the cut-out wind speed or maximum wind speed of the probability distribution.

OPERATING EXPERIENCE OF WIND POWER PLANTS

Wind power plants, or wind farms as they are often called, operate as unmanned, automatic systems. The wind turbines generate electricity automatically, provided that the wind speed is within the operating limits for the wind turbines and that there are no equipment faults. Manual intervention is only required for routine maintenance and fault correction operations.

Modern wind farms all have a supervisory, control and data acquisition (SCADA) system that allows an operator to monitor the performance of the wind farm remotely and to identify any faults that require manual intervention. Each wind turbine operates autonomously under the control of its own computer-based controller and the SCADA system interrogates each controller in turn to monitor its operation and any alarm conditions.

A typical example of the performance of a wind farm is shown in Fig. 3. The upper trace shows the wind speed measured by an anemometer located on a mast, at the hub height of the turbines, and in the middle of the site. However, as the wind farm was several kilometers in size and located in hilly terrain, each turbine would be subject to a different wind speed. The lower trace shows the output power of the plant measured at the point of connection with the distribution system of the public utility. With the measured wind speed above, say, 15 m/s, the wind farm produced its rated output of 7.2 MW while when the wind speed dropped below approximately 5 m/s no power was produced.

Due to the intermittent nature of the wind resource it is not viable for the power output from a wind farm to be scheduled or dispatched by the electricity utility responsible for operating the generators of the power system. Hence the power output from a wind power plant is exported to the local electricity system on a "take all" basis. Appropriate energy pur-

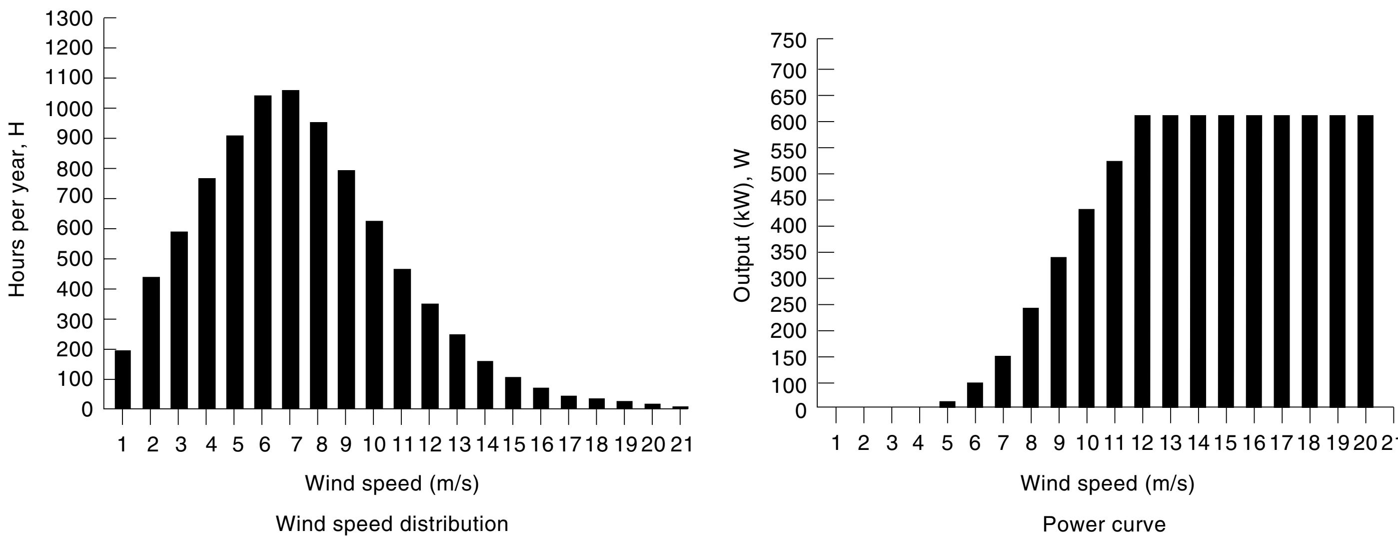

Figure 2. Hourly mean wind speed distribution of a site and power curve of a turbine each in 1 m/s bins.

chase and generation connection agreements are established between the owner/operator of the wind power plant and the electricity utility to facilitate the operating regime at a particular location.

Wind turbines are required to be highly reliable and this is usually expressed in terms of *availability*. Availability is defined as the fraction of time that a wind turbine is available to generate within a time period, irrespective of the wind conditions. Modern commercial wind turbines can achieve annual availabilities of well above 95%. For example, the annual availabilities averaged over all wind turbines for two typical wind farms in the United Kingdom for the years 1994, 1995, and 1996 were above 97%. During these periods one operator visit a week to the sites was required on average to meet both planned and unplanned maintenance requirements.

The impetus behind the requirements for high reliability and availability is twofold: (1) that the wind turbines operate automatically, often at remote locations; and (2) that the wind turbines can only generate within certain wind speeds. It would not be practical to have frequent fault correction visits by maintenance teams. Also, any reduction in availability would compromise the revenue generated by the power plant. The high reliability of modern wind turbines reflects the design and development process that has taken place since the 1970s. High reliability is achieved in part by the design and specification of components such as gearboxes, generators and

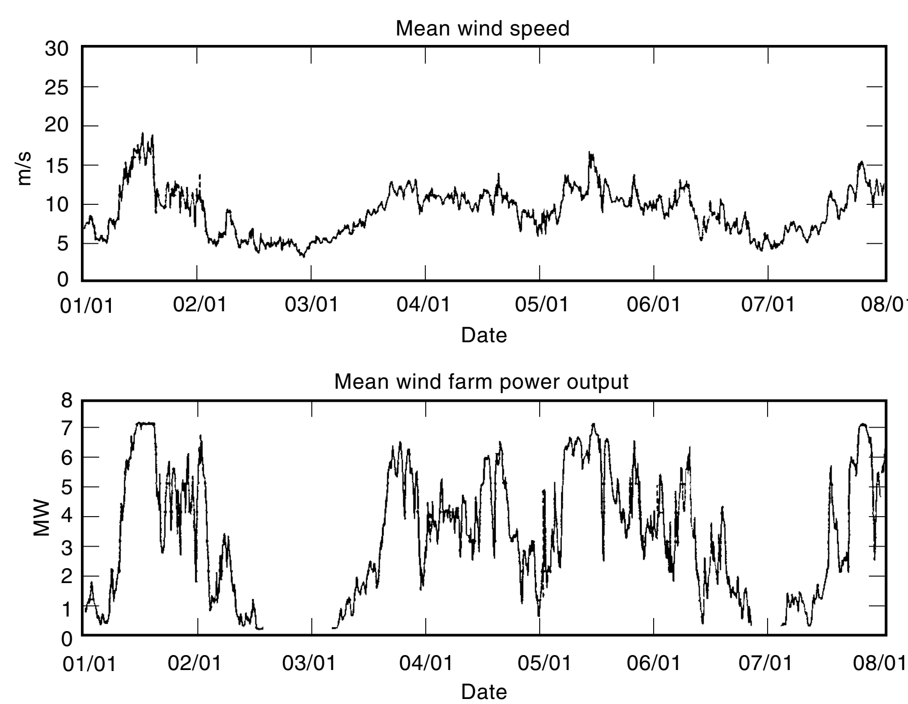

Figure 3. Mean wind speed and output power of a 7.2 MW wind power plant in Wales during January. The power plant consisted of 24 of the 300 kW turbines, each of rotor diameter 33 m.

rotors. In addition, site-specific factors are incorporated into the specification of wind turbines for a wind farm such as the predicted wind loadings, the likelihood of lightning damage to rotors and towers, and the risk of icing of rotors and meteorological instruments used for the control of the wind turbines. The wind turbines are then designed appropriately for the specific site.

It is common to refer to an annual capacity factor of a power plant. This is simply the annual mean output divided by the rated output. Unlike availability, the capacity factor of a wind power plant depends on the wind conditions at the site. Typical capacity factors for wind farms on good sites in the United Kingdom are 30–35%.

WIND POWER PLANT DESIGN

An assessment of the site wind resource is an essential part of the information required by the designer of a wind farm. A comprehensive knowledge of the wind resource enables the developer to predict the annual energy production from a wind farm with various configurations of wind turbines and site layout. The site wind-resource assessment will also assist the developer in predicting the highest wind speeds (usually quoted as 2 or 5 s gust values) at which the wind turbine must be designed to survive. It is common practice in Europe for wind turbines to have their design certified by certifying organizations independent of the wind turbine designers and manufacturers.

The wind resource at a site is essentially assessed by a measure-correlate-predict technique whereby on-site wind speed and direction measurements are collected for at least one year, usually at the hub height of the proposed wind turbines. The measurements are made by erecting meteorological mast(s) with appropriate instruments and data recording equipment. The wind speed data at the site are then compared with data covering a similar period collected at a nearby national meteorological service station. The results of this comparison are applied to the long-term (i.e., longer than ten years) wind speed distribution at the meteorological station to produce an effective long-term wind speed distribution for the wind farm site.

Predictions for the energy output from a wind farm are based on the wind-resource assessment for the site established using the measure-correlate-predict technique. However, the predicted wind speed distribution will be for the points on the site where the meteorological masts are installed. A developer then assesses the topographical effect on the wind speed distribution at other positions on the site away from the meteorological mast positions. Computer modeling can be used for this process and the more advanced codes can also include the effects of the reduced wind speeds caused by the wakes of other wind turbines. The estimated wind speed distributions at each wind turbine site are then combined with the wind turbine power curve as shown in Fig. 2. The power curve for a wind turbine will be supplied by the wind turbine manufacturer based on type tests, and will vary according to the configuration of the wind turbine. A developer will chose a configuration of wind turbine (variable factors include rotor diameter, tower height and generator capacity) that produces a power curve maximizing energy production for a particular site.

In general, energy production will be maximized for sites with strongly directionally biased wind speed distributions by wind turbine configurations where the wind turbines are arranged closely spaced in strings perpendicular to the prevailing wind direction. Sites with less directionally biased wind speed distributions will have energy production maximized using wind turbines arranged in grid layout with larger spacings between wind turbines.

When selecting a site for the construction of a wind farm there are many factors other than energy production that must be taken into consideration before the site layout is determined. The final layout will be a compromise between these factors.

Designated Areas. Most countries will have areas designated by regulatory authorities for such reasons as landscape value and interest of flora and fauna; often it will not be permissible to construct wind farms in these areas. Many wind farms will have areas of high ecological or archaeological interest within the sites where it will not be possible to position wind turbines.

Geotechnical Assessment. A detailed geotechnical assessment of a site will provide information on areas where it would be difficult to position wind turbines because of unsuitable ground conditions.

Visual Impact. The visual effect of a proposed wind farm is often a key factor in the decision of the relevant planning authorities to give consent for the construction of the wind farm. Various techniques exist to predict the visual effects of proposed wind farms, including photomontages and computer-generated "zone of visual intrusion" plots. Wind turbine positions will be moved within a site to produce an acceptable visual effect.

Audible Noise. Many wind farms in Europe are positioned in relatively quiet areas with nearby residential dwellings. The generation of noise by wind turbines is an issue that will normally be addressed by the relevant planning authorities; planning consents will include limits on the sound power levels and tonal content of the sound at points adjacent to the wind turbines.

Other Land Usage. Often wind turbines will be installed on land that will continue to be farmed or used for other purposes. The positions of wind turbines will be varied to accommodate these continuing uses.

Recently, there has been increasing interest in the siting of wind turbines offshore with three wind farms having been installed in shallow European waters by 1997. Installation offshore offers the possibility of constructing very large wind farms with only limited environmental impact and so is being considered seriously in a number of countries. Initially, offshore installation is likely to be more expensive than on land, but the additional costs are partly offset by the larger energy yields available from the higher wind speeds found over the sea.

WIND TURBINE ELECTRICAL SYSTEMS (4)

The drive train of a conventional fixed-speed wind turbine consists essentially of the blades and hub, a main shaft and gearbox, and an induction generator (Fig. 4). The drive train

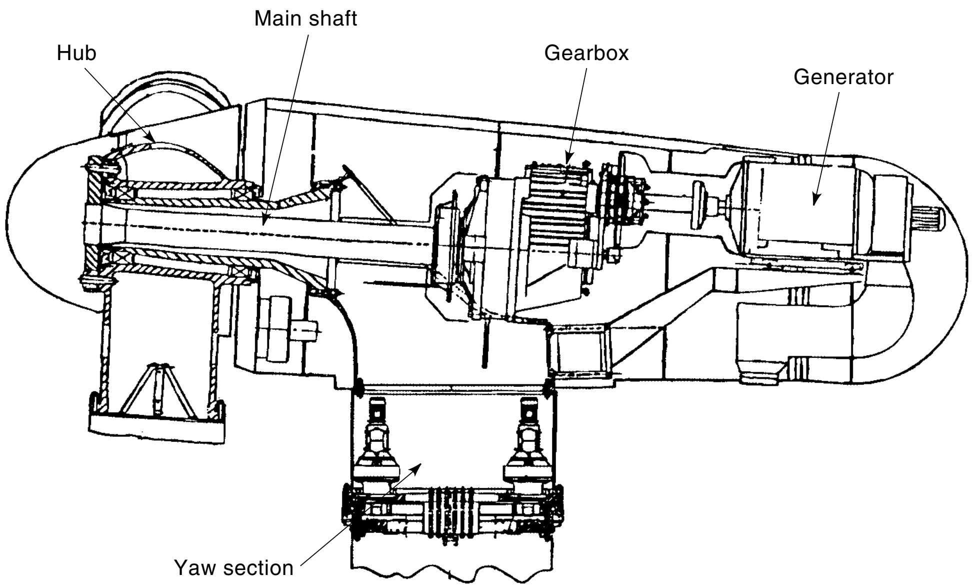

Figure 4. Cross section of the nacelle of a modern three-bladed stall-regulated wind turbine. Access is by a ladder through the yaw section. The nacelle roof opens to allow maintenance staff to stand.

is located on a bed plate, which forms the base of the nacelle at the top of the tower. The bed plate is mounted on the tower by a yaw bearing which allows it to be orientated into the wind by a yaw drive mechanism. The electrical output of the generator is taken to the base of the tower by flexible pendant cables. These are arranged to allow the nacelle to rotate several turns before needing to be unwound. At the base of the tower an electrical cabinet houses the power factor correction capacitors, the electrical switchgear, including the soft-start unit, and the wind turbine computer based controller. A transformer is located either inside the tower base or adjacent to it to transform the generator output to a higher voltage more appropriate for collection of the power throughout the wind farm. Figure 5 is a schematic representation of a fixed-speed wind turbine.

Some early fixed-speed wind turbines used synchronous generators as is common with other prime mover types. However, wind turbines experience cyclic torque pulsations of up to 20% of the mean torque as the blades rotate in the nonuniform wind field. It is extremely difficult to build adequate damper windings on to the pole faces of synchronous generators to damp these torque variations; thus if synchronous generators are to be used, then additional mechanical damping arrangements (e.g., a fluid coupling) are required in the drive train of the turbine. Hence, synchronous generators are now hardly used on fixed-speed wind turbines as it appears to be more cost effective to use induction or asynchronous generators that have an intrinsic damping capability.

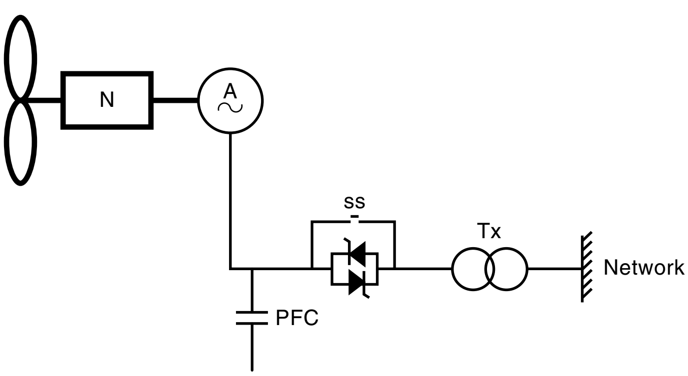

Figure 5. Schematic representation of a fixed-speed wind turbine. (1) N represents the gearbox; (2) A represents the induction generator; (3) PFC represents the power factor correction capacitors; (4) ss represents the antiparallel thyristor soft-start unit; and (5) Tx represents the turbine transformer.

Induction generators are not commonly used for large-scale generation of electricity as they have a number of disadvantages that follow from the fact that it is not possible to control their excitation. When an induction machine is connected to the electrical supply it takes a large transient inrush of magnetizing current as the magnetic circuits are energized. In modern wind turbines this is controlled by ramping the applied voltage using a soft-start device. Usually, this anti-parallel thyristor voltage regulator is not left in service continuously but is shorted out by a bypass contactor once the induction generator is fully fluxed. Because its excitation cannot be controlled, an induction generator operates on a fixed locus of exporting real power (P) while importing reactive power (Q). This is the well-known circle diagram (5) of any induction machine; the generating quadrant for a 600 kW unit is shown in Fig. 6. Once the generator is fully fluxed and connected to the network by the soft-start device, local power factor correction capacitors are connected in order to reduce the reactive power demand from the network and to shift the operating locus as shown.

Fixed-speed wind turbines, as their name implies, operate at a rotational speed fixed by the frequency of the electrical network apart from the very small change in speed caused by the slip of the induction generator. However, some manufacturers prefer a variable speed concept where the rotational

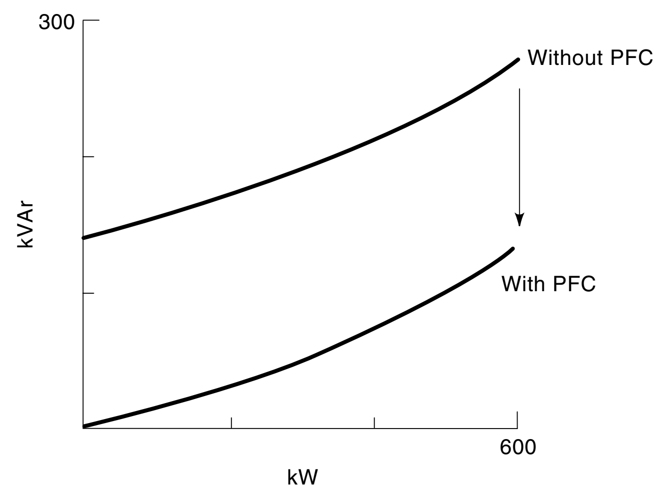

Figure 6. Part of the circle diagram of an induction generator. The active power is exported and the reactive power is absorbed. The effect of the power factor correction capacitors (PFC) in moving the operating characteristic may be seen.

speed of the aerodynamic rotor is allowed to vary. Although this does allow higher aerodynamic efficiencies, these gains tend to be offset by the increased losses in the power electronic equipment required to convert the varying generator output frequency to that of the network. The main advantage of variable speed operation is that the transient torques caused by the blades cutting the changing wind field can be absorbed by rotor speed changes rather than having to be reacted by the wind turbine. This becomes particularly significant at large ratings where the damping provided by induction generators ceases to be adequate. Thus, with variable speed operation, savings can be made in the mechanical strength of the turbine to offset the cost of the power electronics. Some of the more innovative variable speed designs use large diameter multipole synchronous generators that do not require a gearbox. Figure 7 shows this arrangement with a voltage source converter providing the change in frequency. Both the machine side and network side converters use insulated gate bipolar transistor (IGBT) bridges with a pulsewidth modulation (PWM) switching pattern. This allows the power to be fed into the network without low-order harmonics and at any power factor within the rating of the converter.

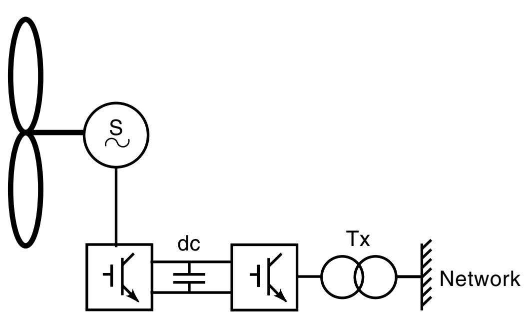

Figure 7. Schematic representation of a variable speed wind turbine. (1) S represents a multipole synchronous generator; (2) DC represents the dc busbar of the IGBT based voltage source converters, and (3) Tx represents the turbine transformer.

WIND FARM ELECTRICAL SYSTEMS (6)

In almost all cases the power collection systems within wind farms in Europe and North America use underground cable. This is to reduce visual impact of the wind farm and to avoid the hazards associated with the large cranes required for erection of the turbines operating in the vicinity of overhead lines. The voltage of the main power collection circuits depends on the size of the wind farm and the voltage at the point of connection to the utility network but is typically in the range of 10 to 35 kV.

The generator voltage of even quite large wind turbines (600 to 800 kW) is usually 690 V, 3-phase, 3 wire. This results in rather high currents in the pendant cables but appears to be the most cost-effective choice for the wind turbine manufacturer. However, it is clearly not sensible to transmit such currents any distance and thus each turbine has its own transformer. These are conventional, oil-filled distribution transformers usually with the 690 V star winding earthed. The electrical energy generated from a wind farm is generally able to attract a premium price because of its environmental benefits. Therefore it is often economic to oversize both transformers and cables in order to reduce electrical losses.

The electrical protection of a wind farm is generally straightforward. An induction generator cannot contribute sustained fault current to a three-phase short-circuit and will only make a modest sustained contribution to unbalanced faults. Therefore all the current-operated protection on a wind farm relies on fault current from the utility distribution network. Each turbine has over/undervoltage and frequency protection built into its controller; this determines if the electrical system is outside its normal operating limits and, if so, the turbine will then be shut down. In the event of a short-circuit on the wind farm electrical system the current-operated protection isolates the wind farm from the network, the generators will then lose their load and overspeed, and be tripped out either by the over-frequency protection or, more probably, by the faster-acting mechanical overspeed protection of the rotor.

A simple induction generator is not able to supply an isolated load because it requires a source of reactive power to operate. However, if reactive power is supplied by power factor correction capacitors, then it is possible to operate in the so-called "self-excited" condition. Figure 8 shows the usual positive phase-sequence equivalent circuit of an induction machine with power factor correction capacitors connected at its terminals (7). It may be seen that, if the rotor circuit and all resistance is ignored and X_m is much greater than X_1, then

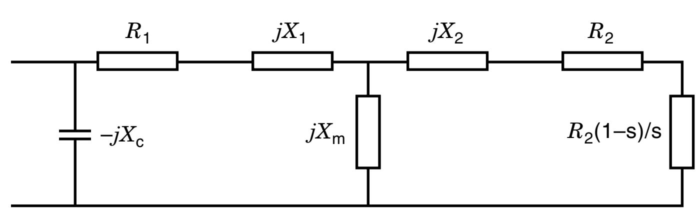

Figure 8. Equivalent circuit of an induction generator fitted with power factor correction capacitance. (1) X represents leakage reactance; (2) R represents resistance; (3) X_m represents magnetizing reactance; (4) X_c represents capacitive reactance; (5) 1 indicates stator circuit; (6) 2 indicates rotor circuit; and (7) s represents slip.

a parallel resonant condition exists when

$$X_c = X_m$$
$$\frac{1}{\omega C} = \omega L_m$$

where C is the capacitance of the power factor correction capacitors, L_m is the magnetizing inductance, and ω is the angular frequency of the islanded system, which, in this simple analysis, is assumed to be equal to the rotational speed of the generator. In this self-excited condition the induction machine is able to sustain a terminal voltage without a connection to the network and, in fact, as the rotational speed of the turbine rises, very large transient overvoltages may be experienced. Many utilities are extremely concerned about self-excited induction generators supplying parts of their network that have become disconnected or "islanded" from the main system under fault conditions. Thus, most wind farms will have sophisticated protection to detect this loss-of-mains or islanding condition. This protection is located at the point of connection of the wind farm to the public electricity supply network and often uses relays either based on detection of the rate of change of system frequency or on a rapid change in the position of the voltage vectors. Both conditions will occur when a wind farm is islanded.

Obtaining a low impedance connection to the mass of earth at all points in a large wind farm is difficult. This is particularly the case where the wind turbines are located on rocky, high-resistivity ground. A low impedance earth or ground connection is required for personnel and animal safety as well as to protect the wind farm plant from the effects of both electrical faults and of lightning (8). Usual practice is to install some local earth rods and conductors at each wind turbines site, but also to lay bare copper earthing conductor with the main power collection cables and to bond the earths of the entire wind farm together. This can result in extremely long horizontal earth electrodes of up to, say, 5 km in length. These conductors then have a significant self-inductance and series resistance which need to be considered in the design and testing of the earthing system. It is also important to be aware of the possibility of external earth connections being transferred into the site via telephone circuits or other services because these can lead to large potential differences in the earthing system under fault conditions.

IMPACT OF WIND POWER PLANTS ON THE POWER SYSTEM

Modern conventional power systems rely mainly on large central power stations generating very large quantities of power (up to 2000 MW) often at considerable distances from the load centers. The power is transported by a high-voltage interconnected transmission grid network before being passed to distribution networks for supply to the customers. In general, wind power plants are much smaller. Typically, sizes range from individual turbines located on the owner's land (50 to 600 kW) up to wind farms of 30 to 50 MW, although there are some examples of larger wind farms in the United States. These wind power plants are connected directly to the distribution system and most of the power generated is consumed locally. At times of high wind speed and low customer load, power may flow into the transmission network but this is not common with the capacities of wind generation now in service. Therefore, wind power has an impact on the power system both because of the nature of the wind resource but also because of its location within the power system.

Table 1. Savings in Gaseous Emissions from Wind Generation under Typical United Kingdom Conditions

Emission	Each Kilowatt-Hour of Electricity Saves (Grams of Oxide)	Annual Saving for a 5-MW Wind Farm (Tons of Oxide)
Carbon dioxide	800	10,500–16,100
Sulfur dioxide	10	150–240
Nitrogen oxides	3.4	50–80

Impact on the Generation System

The main impact of wind power plants on the generation system is the saving in fossil fuel. This translates directly into a reduction in gaseous emissions and hence in environmental damage due to acid rain and climate change or global warming. The extent of this reduction in environmental impact clearly depends on the plant mix of the generation system into which the wind farms are connected. However, typical savings for the United Kingdom generating system, which is still heavily reliant on coal-fired plants, are shown in Table 1. The proportion of generation due to wind power in all global major power systems remains low (generally much less than 5%) and is unlikely to rise above 10% for many years. At these levels of penetration, the effect of the intermittent nature on the wind is small as any changes in wind generation are masked by the much larger changes in conventional central generator loading due to variations in customer demand and plant breakdowns.

In addition to the saving in fuel it is also possible to allocate some capacity credit to wind power plants (9). The capacity credit indicates the capacity of other forms of generation, which is no longer required because of the connection of the wind power plants. It is usual to calculate this using a substitution technique based on loss-of-load-probability (LOLP). Although the results of such calculations depend on the type of generating system considered, a number of studies in different countries indicate that at low penetrations of wind power (less than 1%) the capacity credit of wind power plants is at least equal to the mean annual output while it drops to half this value at penetrations of 10%.

Studies in a number of countries have also indicated that at wind power penetration levels of up to 10% there will be no significant problems with the stability of conventional generating plants.

Impact on the Transmission System

Wind power plants have only a modest impact on the transmission system. There are no significant technical problems caused by wind power plants or of power flowing into the transmission system from one part of the distribution system during periods of light local customer load. The effect of such generation embedded in the distribution system is generally to reduce the mean value of load experienced by the transmission system but also to increase its variance. Therefore, under most circumstances the electrical losses in the transmission system will be reduced as less power has to be transported to customers. As the design of interconnected transmission systems is based not on normal operation but on outage conditions (i.e., when one or more circuits have failed), there is an argument to be made that a reduction in the mean load even with an intermittent energy source such as wind will lower the requirement for the transmission system plant. However, this remains the subject of debate.

Impact on the Distribution System

Wind power plants may have a significant impact on local distribution networks and some care is required to ensure that the quality of power delivered to other customers of the network is not degraded by the connection of wind farms (10). The issue of power quality can be considered under a number of headings, for example: (1) steady-state voltage variations; (2) dynamic voltage variations or flicker; and (3) harmonic distortion.

Most public utility distribution circuits were originally designed to accept power from the transmission system and to supply it to customers. The voltage control systems using transformer tap-changers and network capacitors were arranged for this unidirectional power flow. Thus they may not function as intended when the direction of the power flow is reversed and hence may need modification.

The general expression for the voltage change in a lightly loaded radial distribution circuit due to an induction generator is given by

$$\frac{\Delta V}{V} = \frac{(PR - XQ)}{V}$$

P is the real power exported by the generator and Q is the reactive power absorbed by it; R and X are the real and imaginary components of the network source impedance. Thus it may be seen that the real power export from the wind power plant acts on the circuit resistance to raise the voltage while the reactive power drawn by the induction generators acts on the circuit inductive reactance to lower the network voltage. Therefore, depending on the circuit source impedance and the circle diagram of the induction generator (Fig. 6), voltage changes may be quite modest. Variable speed wind turbines can be arranged to operate at unity power factor (i.e., with $Q = 0$); but although this results in minimum electrical losses a significant voltage rise may occur at the wind farm.

Dynamic changes in the voltage supplied to customers can cause annoyance and complaints, particularly if incandescent light bulbs are used. The human eye and brain are extremely sensitive to the changes in the light intensity emitted by an incandescent light bulb supplied with a varying voltage and hence this effect is normally referred to as light "flicker." The effect of light flicker on humans is highly frequency-dependent with a maximum sensitivity at around 9 Hz. All utilities will specify a maximum level of flicker which is permitted on their networks.

Voltage flicker on distribution systems may be caused by wind turbines in several ways: (1) by current transients on connection; (2) by the changes in the wind field at the rotor caused by turbulence; and (3) by the cyclic effect of the aerodynamic rotor cutting the varying wind field. In Germany, every wind turbine design is type-tested to establish its performance with respect to flicker. This type-test data are then used to predict its performance at the proposed site. In the United Kingdom, this testing is not a mandatory requirement as, in practice, flicker from wind turbines has not led to complaints. Some United Kingdom research has indicated that connection of wind farms on very weak rural circuits has actually led to a reduction in voltage flicker on the network as the wind turbines increase the fault level.

Harmonic distortion of the network voltage by wind power plants is only of significant concern if variable speed turbines are used. Early designs of frequency conversion equipment used thyristors and this gave rise to significant low-order harmonic currents. Modern converters use IGBTs with a PWM switching pattern and should not create low-order harmonics. However, there will be significant harmonic energy at around the switching frequency of the converter.

In addition to their effect on power quality, wind power plants alter the way the distribution system functions. Rather than all the power being supplied from the bulk supply points of the transmission network, some power is now provided by generators embedded within the distribution network. This will result in changes in the operating costs of the network particularly with respect to losses. If the wind power plant supplies a local load, then it is likely that the distribution network losses will be reduced; if it is necessary to transport the power from a wind farm a long distance, then losses may be increased. Each case needs to be examined and the calculation is not straightforward given the nonlinear nature of the losses. A simple approximate calculation technique is to examine a number of scenarios of network load and to evaluate the network losses with varying wind farm outputs. An estimate is then made as to how many hours in the year each scenario would occur, and hence the impact of the wind farm throughout the year is determined.

In a simple radial distribution circuit, wind power plants do not provide capacity credit as the circuit is required to provide reactive power to allow the wind farm to operate. In more complex, interconnected distribution systems, wind power plants may make some contribution to the capacity of the system.

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