WIND TURBINES

Wind power is gradually gaining prominence as a suitable source of renewable energy. Implementations range from the propeller-type, horizontal axis wind turbine (HAWT) to vertical axis or VAWT systems. Power ratings vary from several kW for remote area, off-grid applications to several MW for systems connected to the ac power grid. As wind speeds, in practice, vary over a wide range, so does the amount of power generated by the turbine. Hence, if wind turbines are only operated at a constant rotor speed, they are not capable of optimizing power extraction over a wide range of wind speeds. This can be improved mechanically by providing for adjustments in the pitch of the turbine blades or by utilizing the electrical system for simple, step-wise speed control employing pole-changing techniques. However, implementing mechanical controls renders the system structure more complicated and less reliable. Also, due to the narrow control bandwidth of the mechanical controls, improvement in energy capture is only marginal. With the advent of modern power electronic converters, it is possible to refer the entire control function to the electrical side and, consequently, substantially improve energy capture and system reliability. Thus, many modern, commercial wind turbines are of the variable speed design, requiring a power electronic interface between the variable frequency wind turbine and the fixed frequency electric utility grid.

Horizontal axis turbines can have blade spans of up to approximately 90 m, with the majority of commercial systems being in the range of 15–45 m, with a power rating of 100 to 600 kW. Rotational speeds are in the range of 30–100 r/min, necessitating a gearbox to increase the speed to a value suitable for low pole number electric machines, typically around 1800 r/min. Fixed speed systems utilize either conventional synchronous machines or squirrel cage induction machines. Converter-fed variable speed systems can be based on conventional generators or can be implemented utilizing doubly-fed machines to reduce rating and cost of the power electronic converter (1). In HAWT systems, the gearbox and the generator are housed in the nacelle at the top of the tower structure, while in VAWT installations, all generating equipment can be positioned on the ground at the base of the turbine. In order to increase efficiency and decrease complexity, low speed generators can be utilized to eliminate the need for a step-up gearbox and couple the electric generator to the turbine rotor in a direct-drive configuration.

Wind power is a renewable resource and freely available worldwide. However, site preparation, system installation, and provision for maintenance require significant investment. Economic considerations require that the cost of wind energy has to be competitive with conventional fossil resources in order to be a viable alternative. This becomes important in variable speed systems which, while extracting more energy from the wind, suffer an initial cost disadvantage due to either the increased mechanical complexity or the power electronic converter requirement (2). This cost penalty may eventually negate the gains associated with additional energy capture. Thus, reducing the cost of the power generating hardware is essential for variable-speed generating systems to achieve viable and competitive $/kWh ratios.

The power electronic utility interface necessary for converter based variable speed systems provides many additional benefits beyond enhanced energy capture. While acoustic noise produced during low power operation can be minimized, it is also possible to improve the poor displacement power factor associated with induction generators. At the same time, harmonics from other generators or non-linear loads can be compensated using appropriate converter control algorithms and utilizing passive or active harmonic filters.

While offering significant benefits in operational performance, variable-speed generators have the drawbacks of higher initial cost as well as increased complexity and potentially lower reliability. In a well designed and engineered system, however, the additional costs should be offset by increased energy capture while providing for improved control flexibility.

This article gives a basic overview on fixed and variable speed wind generation systems followed by a discussion of conversion systems, including electric machinery and power electronic converters. Steady state and dynamic control issues for wind generators are discussed in detail. Operational characteristics and economic considerations for wind plant operation are presented, and the article concludes with a summary and an evaluation of possible future developments.

For further study and detailed information, the article provides for a representative selection of appropriate references in the technical literature. Other sections of the encyclopedia may also be consulted for a discussion of individual system components. The articles entitled WIND POWER and WIND POWER PLANTS give additional detail on wind turbines.

BASIC WIND TURBINE CHARACTERISTICS

Wind Energy Conversion

The conversion of wind energy into electricity on a large scale raises the problem of energy storage. Although work is in progress on a variety of energy storage systems, including batteries, pumped storage, compressed air, and flywheels, the electrical supply grid is a convenient absorber of electricity generated from wind on a large scale, provided the capacity of the wind generation equipment is still small in relation to the total generating capacity coupled to the supply grid. Thus, other than in relatively low power, remote area applications, most wind turbines are coupled to the ac utility grid.

The energy in the wind as a result of the kinetic energy of the moving air mass is described by

$$E_{ke} = \frac{1}{2}mv^2 \tag{1}$$

J. Webster (ed.), *Wiley Encyclopedia of Electrical and Electronics Engineering*.

where m is air mass and v is speed of moving air. Air density is a function of altitude and temperature, given by

$$\rho = 3443\frac{P_a}{T} \quad (2)$$

where ρ is air density, P_a is atmospheric pressure, and T is absolute temperature. The mass of the air moving through a wind turbine of sweep area A per unit time is

$$m = \rho Av \quad (3)$$

and the total available power from the air movement through area A is expressed as

$$P_w = \frac{1}{2}\rho Av^3 \quad (4)$$

Wind power is thus proportional to the cube of the wind speed, v, and the power extracted by the wind turbine in mechanical form can be described as

$$P_{wt} = C_p P_w \quad (5)$$

where C_p is the wind turbine power coefficient. It is not possible to extract all energy from the moving air, since in this case, the air movement would seize and the air would pile up behind the turbine. It was shown by Betz (3) that for maximum power extraction, the air velocity at the wind turbine is 2/3 of the upstream wind speed, further decreasing to 1/3 well downstream of the turbine. Thus, the theoretical maximum power coefficient is C_p = 16/27 or 59.3%. Practical wind turbines do not reach this Betz limit, and the wind velocity at the turbine is somewhat greater than 2/3 v. The value of C_p is a function of wind and rotational speeds as well as form and pitch of the wind turbine and has a maximum at a fixed operating point, that is, at a constant ratio of rotor speed to wind speed. Thus, the power coefficient is normally expressed in terms of the tip-speed-ratio λ, which is defined as

$$\lambda = \frac{v_p}{v} = \frac{\Omega_t R}{v} \quad (6)$$

where v_p is the tip-speed of the turbine blade, R is the turbine rotor radius, Ω_T is the rotational turbine angular velocity, and v is the wind speed. Figure 1 illustrates the variation of the power coefficient for a conceptual 100 kW horizontal axis wind turbine (1).

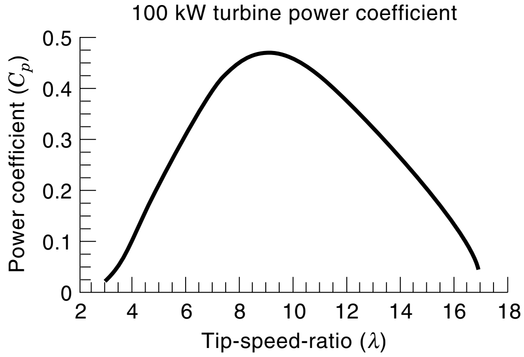

Figure 1. Power coefficient of a 100 kW wind turbine, illustrating what percentage of wind energy is extracted by the wind turbine as a function of the tip-speed ratio.

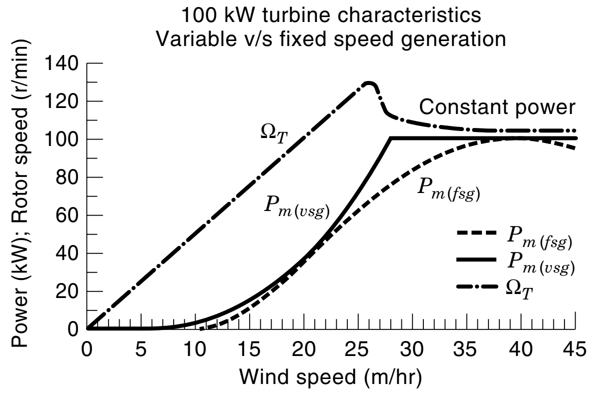

Figure 2. Variable and fixed speed power and speed characteristics of a 100 kW turbine, illustrating the enhanced energy capture possible with variable speed generation. The rotor speed shown maintains optimum tip-speed-ratio and thus, the maximum power coefficient as shown in Fig. 1 (wind speed in miles/hour).

The torque coefficient, C_T, of the wind turbine is related to C_p as

$$C_T = \frac{Torque}{\frac{1}{2}\rho v^2 AR} = \frac{1}{\lambda}C_p \quad (7)$$

Fixed and Variable Speed Generation

It is evident that for optimum energy extraction, the maximum power coefficient and, thus, the optimum tip-speed-ratio should be maintained at all wind speeds. With a constant speed constant frequency (CSCF) wind turbine system, it may be necessary to use pitch control of the blades to limit power input to the system (4), thus introducing additional mechanical control systems. Variable-speed generation can track the changes in wind speed by adapting shaft speed and, thus, maintaining optimal energy generation.

In Fig. 2, the rotor power for the wind turbine characteristic of Fig. 1 is plotted using variable speed generation (VSG) and fixed speed generation (FSG) strategies. The fixed speed system is optimized at only a single speed, generally representing maximum energy capture potential for a given site. Thus, power output at near cut-in and maximum power are significantly lower than in the case of the variable speed system. The fixed speed, fixed pitch system is inherently power limited, as increasing wind speeds lower the turbine power coefficient, a phenomenon referred to as stall regulation. On the other hand, the variable speed system will attempt to track maximum power at any wind speed. Once rated generator power or maximum rotational speed is reached, it becomes necessary to limit the turbine power by abandoning the optimum tip-speed-ratio. During variable speed operation, wind and rotor speeds are related linearly, whereas in the constant power regime, shaft speed drops off sharply and is kept essentially constant thereafter. The speed range for VSG operation is selected such that it only commences when the cut-in wind speed is reached, and torque is sufficient to operate. Due to the cubic power-speed relationship, the loss of energy is minimal. The upper cut-out or furling speed is determined by the limits of the turbine and its structural strength.

The improved energy capture for VSG systems is obtained at the expense of additional system components, most often in the form of a power electronic converter. The cost of this additional hardware needs to be low enough to achieve a reasonable rate of amortization given the additional energy generated. In addition to maximizing energy extraction from the wind, the generation system efficiency needs to be as high as economically feasible in order to maximize the energy delivered from generator to the electric power grid.

Other Wind Generation System Design Considerations

As illustrated in Fig. 2, wind turbines operate at a relatively low speed, in general below 100 r/min. Utilizing off-the-shelf electrical machinery with four (1800 r/min) to eight poles (900 r/min) requires a step-up gearbox with a gear ratio of at least 9 to 18, but often higher. This sometimes requires a multistage gearbox, with the resultant mechanical complexity and additional losses, which can be in the order of 4–8% of mechanical turbine power (5). Eliminating the gearbox leads to significant system benefits but requires generators of very high pole number, for example, 160 for a turbine speed of 45 r/min. Given a minimim pole pitch, machine diameter for a high number of poles becomes very large, sometimes unacceptably so, given manufacturability, cost constraints, and space restrictions in the nacelle at the top of the supporting tower in HAWT systems. System design needs to optimize the trade-off between using an off-the-shelf, relatively high speed generator in conjunction with a gearbox and utilizing a special purpose, directly coupled generator.

HAWTs produce a nonconstant torque due to tower shadow (6). As each blade passes the supporting tower, the output torque decreases. Thus, the torque produced by a two-blade wind turbine contains a harmonic at twice the rotational speed, the so-called 2P harmonic. Also contributing to torque pulsations is a wind shear effect due to the wind speed gradient along the height of the area swept by the wind. Typically, a fixed-speed system is unable to mitigate this effect in order to improve the quality of the output power. In large turbines, the power pulsations passed to the network can become unacceptable, especially when the penetration level is high. In VSG systems, though, appropriate control of the power electronic converter can minimize torque ripple, and, thus, output power pulsations (7,8). Here, the inertias of turbine and generator are used to store energy and mitigate torque pulsations. This not only improves the utility interface characteristics but also damps mechanical stresses on the system, thus allowing for relaxed safety factors, lighter construction, and hence, higher reliability and longer useful life.

Some large wind systems are not self-starting or self-stopping. Mechanical tower resonances at low frequencies require that the wind turbine be motored up to operating speed. Fixed-speed systems require the starting of a large induction machine with the resulting expense of soft start mechanisms; stopping a fixed-speed system usually requires a large mechanical braking system. A mechanical brake may also be required in converter fed systems, since the stopping capability needs to be available even in the absence of electrical excitation, such as during fault conditions.

While sharing many operational characteristics with HAWT systems, VAWTs, in general, are not self starting and require the generator to run as motor during start up. Certain VAWT systems, such as those of the Darrieus type (7), are not susceptible to tower shadow, but wind shear is still present, and torque pulsations are produced by the continuously changing angle of attack between wind and turbine blades.

Wind generation system design needs to account for the extreme environmental conditions encountered. Depending on the site, temperatures between −30 to +45 °C as well as internal condensation must be allowed for in the design of the generation system. Additionally, the differential temperature of system parts will vary with time and load. The nacelle cover can only provide for some protection against environmental effects, such as rain, snow, ice, particulates, and chemical pollution. Appropriate design of not only the mechanical system but especially the electronics for control and power processing is essential.

The design criteria for wind generation system design are summarized as follows:

- Reliable and low maintenance design optimized for the environmental constraints of a given site
- Minimum number of components and cost
- Maximum energy capture and efficiency
- Integration of mechanical and electrical systems (start-up, shut-down, mechanical stresses)
- Utility supply interaction and contamination

CONVERSION SYSTEMS FOR WIND POWER GENERATION

Constant Speed Generators

CSCF systems use a grid-connected synchronous or induction generator, so that variations in wind speed have to be accommodated by pitch control of the wind turbine itself to limit input power at or below rating. This refers the primary power flow control function to the mechanical side of the system.

Synchronous machines which can be utilized include conventional, wound-field machines as well as synchronous reluctance and permanent magnet machines. Conventional synchronous machines have the advantage of providing for reactive power control as well as voltage regulation via the rotor field winding. Many different power ratings are available off-the-shelf from established manufacturers, and machine development costs are minimized.

Permanent magnet (pm) synchronous machines have the advantage of a higher efficiency due to the absence of excitation losses. However, unlike in conventional synchronous generators, output control via the excitation is lost. Consequently, magnet flux and the number of stator turns have to chosen such that satisfactory operation over the entire load and voltage range is possible while minimizing transient currents during synchronization. Many different permanent magnet designs are feasible (5), including conventional radial field machines, axial flux machines, transverse flux geometries, and hybrid claw pole designs. Present day implementations are mainly based on the radial flux concept, utilizing either a buried magnet structure or surface magnets. Interior pm machines can be implemented using high energy, rare earth (SmCo or NeFeBo) magnets, or less expensive ferrites. Surface magnet machines, in general, require rare earth magnets to achieve the desired airgap flux density.

Synchronous reluctance machines also do not provide for excitation control but avoid the use of magnets and the associated costs. However, rotor designs to achieve the desired reluctance ratios are difficult to manufacture, which partially negates the cost advantage. In the absence of rotor excitation, synchronous reluctance machines require excitation from the connected power grid and have relatively poor displacement power factors. Thus, power factor correction capacitors are often employed.

All synchronous machines provide for a stiff coupling between the turbine and the grid. Neither pitch nor stall control can respond fast enough to the torque fluctuations due to tower shadow and wind gust effects. This transmits the torque pulsations directly to the generator and requires an increased torque capability of approximately 50% above nominal. This stiff coupling also subjects the mechanical system to considerable stresses. Subsequently, increase in compliance and damping are required in the power train to alleviate structural resonances. This discussion also applies to low-slip induction generators.

Many wind turbines utilize low cost, mass produced cage rotor induction machines. In the absence of rotor connections, these systems are also very robust. However, as with synchronous reluctance machines, excitation is required via the stator, which leads to poor power factors and requires power factor correction capacitors at the point of common coupling to the grid. The slip characteristic of induction machines is beneficial for wind turbine control as it reduces stiffness and provides for additional compliance and damping in the electrical system as compared to synchronous generators.

Variable Speed Generators

In variable speed constant frequency (VSCF) systems, the wind turbine operates at variable speed. If this speed range is made large enough, it is possible to operate a fixed pitch wind turbine and refer the entire power control function to the electrical side. Figure 3 reviews variable speed systems based on ac machines and voltage source inverter technology (1). These represent the desired implementation for medium power (approximately 100–500 kW) wind systems; higher power turbines may still utilize current-fed, supply commutated topologies. In most cases, a gearbox is used to interface the low speed wind turbine with the high speed generator (not shown in Fig. 3).

The system shown in Fig. 3(a) can be implemented using conventional, wound-field synchronous machines, or the permanent magnet, or synchronous reluctance options discussed previously. The system shown in Fig. 3(c) utilizes conventional, off-the-shelf, cage rotor induction machines. In both cases, all generated power is processed by a power electronic converter. In the case of reluctance and induction machines, the required reactive power is also provided by the converter, leading to large and expensive converters, typically with a continuous rating in excess of 125% of machine rating. The size of the converter also negatively influences the supply interaction, that is, the harmonics injected into the power grid due to converter switching. Despite these disadvantages, many commercial variable speed systems still utilize the cage rotor induction machine due to its simplicity, ruggedness, and low cost.

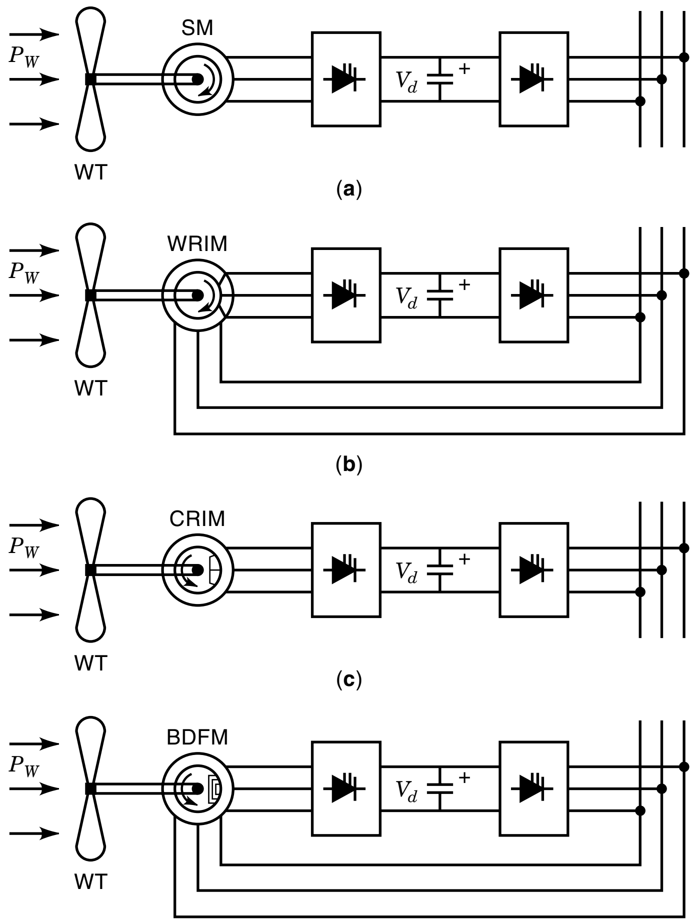

Figure 3. Energy conversion systems for variable speed generation: (a) synchronous, (b) wound rotor induction, (c) cage rotor induction, and (d) brushless doubly-fed systems. Shown are commonly used and promising ac implementations utilizing voltage source power conversion topologies with controllable (turn-on/turn-off) power semiconductors.

Only limited variable speed operation is possible with a conventional induction generator since otherwise, the efficiency becomes proportional to speed. This has led to the investigation of over-synchronous operation of slip ring or doubly-fed induction generators with rotor and stator power fed back to the supply (2,7). In this case, variable speed operation is possible while only controlling the electrical side. The system shown in Fig. 3(b) utilizes a wound-rotor induction machine, the stator of which is directly connected to the utility grid. Only slip power is processed by the rotor power electronic converter, reducing its required rating, size, and cost. If this so-called electronic Scherbius system is rated such that maximum power operation corresponds to rated torque at twice synchronous speed, the required rating of the power electronic converter is only 50% of that necessary for the synchronous machine system (2). This leads to an appreciable saving in capital investment and also reduces the negative impact of converter harmonics on the utility system. From a maintenance and reliability point of view, the use of slip rings is a disadvantage, especially considering that the wind turbine should be capable of working unattended, in adverse conditions, for extended periods.

Recently, doubly-fed machines without slip rings or brushes have been proposed as viable variable speed generators for wind turbines (1,9). Fig. 3(d) shows the Brushless Doubly-Fed Machine (BDFM) which is based on the induction principle and combines the advantages of the cage rotor systems (low machine cost, robust brushless machine construction) with the benefits of the electronic Scherbius configuration (reduced power converter rating and cost). The BDFM has two stator windings of different pole number to avoid direct transformer coupling (10). The power and control stator windings interact through the rotor, which has a specialized cage structure with a number of identical sections corresponding to the sum of the pole pairs of the stator windings. The machine exhibits synchronous behavior where stator frequencies and shaft speed are related by (10).

$$f_c = f_r(p_p + p_c) - f_p \tag{8}$$

where f_p is the utility grid frequency (60 Hz), f_r is the shaft speed dictated by the variable-speed generation algorithm, f_c is the required converter output frequency, p_p is the pole pair number of the grid-connected winding, and p_c is the pole pair number of the converter-controlled winding. Only a fraction of the generator power is processed electronically, resulting in reduced size and cost as well as improved power quality. The die-castable rotor cage ensures robust and inexpensive machine construction. An alternative design with very similar characteristics is the doubly-fed reluctance machine (9), which uses an equivalent stator configuration but replaces the rotor with a reluctance geometry similar to the one found in the synchronous reluctance machine. The dual power flow paths found in double-fed machines enables efficiency-optimized controls not possible with singly-fed machines.

The generator systems discussed so far are all based on three-phase technology with distributed stator windings. Another system which has been suggested for wind power applications is the variable reluctance machine, which differs considerably from the synchronous reluctance generator discussed previously (11). The variable reluctance machine has a double salient structure, with distinct stator and rotor poles, much like a stepper motor. Unlike in conventional ac machines, the stator windings are not distributed, but rather are concentrated on the stator poles. Combined with the simple rotor structure, this leads to ease of manufacturing and potential economic advantages. The converter topology for variable reluctance machines differs significantly from its counterpart for conventional machines. Development work is also under way to introduce magnets into variable reluctance machines in an effort to enhance generator performance (12).

Rather than follow the optimum VSG power curve (see Fig. 2) in a continuous fashion using the VSG systems described above, often a two-speed system is implemented to improve upon fixed speed generator performance. This can be realized with pole changing induction machines, and the resulting system avoids the use of a power converter completely.

Power Converter Considerations

Technological advances in gate turn-off, high power semiconductor devices have revolutionized the power electronics applications industry, especially in the medium power range. Extremely fast turn-on and turn-off characteristics are obtained for insulated gate bipolar transistor (IGBT) modules rated in excess of 2000 A. These devices allow for high switching frequency and control bandwidth with relatively simple drive requirements. Hence, for medium power (<500 kW) wind generation applications, hard switched, pulse-width-modulation (PWM) based power interfaces are typically employed. To ameliorate the performance of the switches by reducing the switching stresses and losses and to reduce the unwanted dv/dt and di/dt effects of hard switching, topologies utilizing soft switching techniques can be incorporated in wind generation systems (13).

For power converters rated at above 1 MVA, present day technology still favors silicon controlled rectifiers (SCR) and gate turn-off thyristors (GTO), which are available in ratings of over 4000 A. However, only slow switching frequencies, typically less than 500 Hz, can be attained employing SCRs and GTOs at the high power levels. Generally, SCR-based current link converters utilizing either load or forced commutation are used for high power synchronous or induction generator based systems. Cycloconverters provide the electronic grid interface for high power, direct drive synchronous generators and limited speed range, high power doubly-fed induction machines.

Direct Drive Wind Turbines

The gearbox used to interface slow speed wind turbines with conventional, relatively high speed electric machines is a source of additional cost and losses. Direct-drive wind turbines require generators with very high pole numbers and, given a minimum pole pitch requirement, this leads to very large generators with approximately double the outer diameter and weight of high speed machines. Low speed generator efficiency is also lower by a few percentage points, and machine cost is higher, due to both the increase in size and the higher cost for these special purpose machines, which do not enjoy the economies of scale of mass manufacturing. Nevetheless, it has been shown (5,14) that the overall direct-drive system can have significant advantages in terms of initial cost, efficiency, reliability, and return on investment, when compared to the high speed, geared generators.

Due to the benefits associated with direct drive systems, numerous development programs are under way investigating suitable machine geometries. Proposed machine geometries include variable-reluctance generators (11), surface-mount (14), and buried magnet permanent magnet machines. It is expected that significant progress will be made in this area over the coming decade and that market penetration of direct-drive wind turbines will increase significantly.

WIND TURBINE CONTROL SYSTEMS

Fixed Speed Generator Control

The simplest wind-turbine configuration is without pitch control and a synchronous link to the grid, where the turbine speed is constant due to the generator being directly connected to the fixed-frequency grid. While it is possible to limit the power input by stall regulation with this arrangement, it is not possible to control the amount of power delivered by the turbine to the electrical generator within its operating range. It is solely dependent on the wind variations.

However, since the available aerodynamic power is a function of both the wind speed, v, and the angular speed of the turbine, Ω_T, the power delivered by the turbine could possibly be only a fraction of the maximum available power. As shown in Fig. 1, a fixed speed system is typically optimized at only a single speed of operation. This inherently limits the deliverable power as increasing wind speeds lower the power coefficient. Although fixed speed wind turbine systems do not employ sophisticated speed control systems, they may still need to be equipped with electrical or mechanical control for power limiting, torque-ripple mitigation, and resonance avoidance.

The tower passing effect of the turbine blades causes dynamic speed variations even for fixed speed generation systems, which could affect their performance. The use of tip vanes for dynamic rotational speed control of HAWT has been reported (15). The tip vane is located at the tip of a turbine blade and functions as a device for power augmentation by varying the power coefficient, C_p. It can also be operated as a rotor speed braking device by varying the sweep angle between the vane orientation and the axis of rotation of the turbine blades. At zero sweep angle, the turbine power coefficient, C_p, is at its maximum. Any change in the sweep angle provides a means for turbine deceleration or acceleration. The tip vane sweep angle controller utilizes turbine speed error and its derivative to determine the absolute value of the sweep angle. In situations where large wind fluctuations occur, tip vane control in conjunction with blade pitch control can provide for effective fixed speed operation.

The wind turbine and the energy conversion system can be represented by a rigid rotor of inertia J_R with an applied aerodynamic torque of T_A. This torque is transmitted as T_L to the shaft of rigidity K_L and damping C_L as shown in Fig. 4. Upon simple analysis, the transfer function $H(s)$ between the transmitted torque, T_L and the aerodynamic torque, T_A can be formulated as

$$H(s) = \frac{T_L}{T_A} = \frac{C_L s + K_L}{J_R s^2 + C_L s + K_L} \tag{9}$$

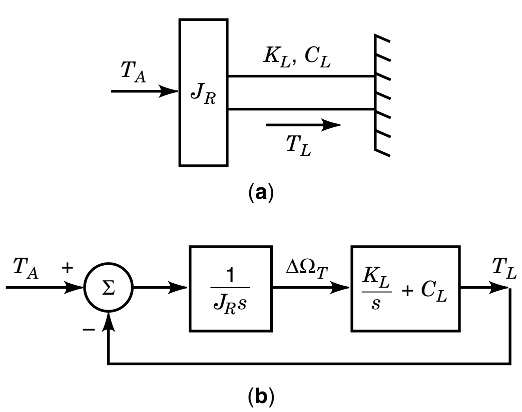

Figure 4. Wind turbine (a) simplified model and (b) block diagram, illustrating a model of the wind turbine mechanical system utilized for determination of mechanical system resonances and responses.

The natural frequency, ω_N, of the denominator of $H(s)$ (i.e., the characteristic equation) can be determined to be

$$\omega_N = \sqrt{\frac{K_L}{J_R}} \tag{10}$$

which corresponds to the first torsional mode or the system mode (6). Developing a more elaborate model of the wind turbine system by representing the wind turbine by two discs of equal inertia, it is observed that there exists a second resonant peak of the transfer function when plotted in the frequency domain (16). Due to the existence of these two resonant peaks in the transfer function of the wind turbine system, usually both the 2P and the 4P (for a vertical axis turbine) harmonics are minimally attenuated, enabling them to propagate through the drive train and appear as electrical torque ripple. The ripple, if not compensated, affects the quality of electrical power generated and causes torsional fatigue of the components of the drive train. In an effort to increase the difference between the 2P harmonic of a turbine and the natural frequency, ω_N, various mechanical methods have been devised to reduce the rigidity of the low speed shaft. From Eq. (10) above, it is readily seen that ω_N decreases as K_L, the rigidity of the low speed shaft, decreases. This has led to the use of a low rigidity shaft, also known as the quill shaft, on the low speed, turbine side of the gear-box. Further separation in the 2P harmonic and the natural frequency ω_N is possible by electrical means as discussed in the section "Variable speed generation systems."

Torque pulsations and the associated power angle oscillations in slow speed direct coupled generators (small pole pitch permanent magnet synchronous generators) cannot be damped using damper windings on the rotor, as they would incur unacceptable losses as well as increase the physical size of the generator. Once the torque oscillations are passed on to the stator, they can be damped using a passive viscous damper, consisting of a spring and a mechanical damper, which connects the stator of the generator to the wind turbine housing. An adaptive mechanical damping method for wind turbine torque stabilization (16) uses a bearing-mounted stator, which oscillates about the machine axis against a torsional spring. By selecting an appropriate stiffness, K_S, and inertia, J_S, of the stator damper, the "blank" frequency

$$f_{\text{blank}} = \frac{1}{2\pi}\sqrt{\frac{K_S}{J_S}} \tag{11}$$

can be set equal to the 2P frequency. The blank frequency is the frequency at which stator and rotor oscillate as a single mass, thus rendering the system nonresponsive to any input. Hence, when the blank frequency equals the 2P frequency, all torque pulsations can be eliminated.

However, this results in excessively large stator oscillations and requires slight stator damping, thus sacrificing transient response to improved passing response. An adaptive damping system can be based upon the fact that an optimum system allows the stator to oscillate freely at the tower passing frequency but damps oscillations at any other frequency (16).

Variable Speed Generator Control

In addition to dynamically maximizing the wind turbine efficiency, variable speed can also serve to reduce system stresses such as torque pulsations. The following advantages are beneficial with respect to system reliability and generated power quality:

- Variable speed control can lead to a substantial reduction of the torque ripple in the drive train and, hence, improved power quality. This is achieved by an increase in compliance, whereby a variation in the aerodynamic power results in system acceleration or deceleration rather than in output power fluctuations.
- The attenuation of torsional mode resonances in variable speed operation allows for a relaxation of design requirements.
- Dynamic loads are reduced, and safety margins can be relaxed.

Some electrical systems available for variable speed generation (VSG) operation are shown in Fig. 3. As illustrated, both singly and doubly-fed electrical generators have been employed in variable speed wind generation configurations (1).

Singly-Fed Generator Control. Speed control of a wind turbine system can be accomplished by controlling either the turbine blade angle (pitch control) or the electrical generator speed if an electronic power converter is available. The compliance of the electrical coupling between the grid and the generator varies based on the type of generator. Typically, the mechanical compliance in the drive train is higher than the electrical compliance. This leads to a lightly damped, low frequency torsional mode (17). Speed control allows for efficient system operation and also provides for an effective way of damping the low frequency torsional mode.

From Figs. 1 and Fig. 2, it is clear that in order to obtain maximum power from the wind turbine, it is necessary to keep the tip speed ratio, λ, constant over a wide range of wind speeds. This is achieved by a maximum power point tracking (MPPT) system, an essential component of any VSG controller, which tracks the optimum tip speed ratio for large variations of wind speeds. Here, it should be noted that the MPPT speed range needs to avoid areas of mechanical resonance. Wind speed is a difficult quantity to measure and should not be incorporated as a control input for MPPT design. A basic search algorithm involves sweeping the generator speed command over a certain range until a maximum output power is measured (18). Other algorithms involve the determination of the wind generator model (19,20), employ techniques of system identification (1), or utilize a model independent control method (21).

Unlike in a dc machine, in a cage rotor induction machine, the magnetic flux and the electromechanical torque are coupled; that is, the torque controller affects the flux and vice versa when scalar control methods are employed. Field oriented or vector control of induction machines utilizes real-time mathematical transformations to effectively decouple the control of flux and torque production, thus duplicating the features inherently available in a dc machine. The availability of sophisticated low-cost microcontrollers and digital signal processors has led to wide spread implementation of field oriented control techniques for variable speed induction generators. Employing field oriented control techniques for effective torque control and fast speed response allows for both maximum power point tracking and the compensation of torque pulsations (8). Reactive power control is also possible by appropriately controlling the power electronic grid interface.

Double-Fed Generator Control. Utilizing a PWM converter for slip power recovery, a double-fed wound rotor induction machine can be operated as a variable speed generator (20). The power converter rating and, hence, the initial cost is reduced as the converter handles only the slip power. Control of torque and, thus, active power can be achieved by controlling the rotor current component orthogonal to the stator flux; stator reactive power is controlled by the in-phase rotor current. The decoupling of stator active and reactive power flows allows for an additional control function which can be used to maintain optimal stator flux and minimize copper losses (20).

The modeling of wind turbine systems is an extremely difficult task due to the uncertainties in the modeling of the aerodynamics, such as the effects of tower shadow, wind shear, blade surface smoothness, wind turbulence, and others. This suggests the use of approaches which do not rely on the physical model, as outlined in (1) for an efficiency maximization algorithm for doubly-fed generators. The doubly-fed machine provides an additional degree of control freedom, not present in a singly-fed system, whereby stable operation is possible for a variety of control winding current levels at a particular operating speed. Figure 5 illustrates the optimization control algorithm in block diagram form. The overall optimization problem for the mechanical (turbine) and electrical (generator) systems involves finding the maximum of power output as a function of both speed and control current, a three-dimensional optimization problem (1).

In order to keep the controller simple, mechanically robust, and inexpensive, no mechanical inputs such as shaft torque should be required for the control algorithm. In addition to the power and efficiency maximizing function, the controller can also perform reactive power as well as harmonic compensation. Based on output power measurement, the controller sets converter frequency and current magnitude. Hence, as implemented in Fig. 5, no mechanical feedback signals are required. However, the compensation of torque pulsations requires an inner speed loop, which is based on field oriented control and requires rotor position feedback (22).

Compensation of Torque Pulsations. Torque pulsations are a nuisance problem even in VSG systems. They corrupt power quality as explained in the section on fixed speed generator control. The use of a power converter in variable speed generation enhances the control options for mitigation of torque oscillations. The increase in the available power due to a tower passing spike can be stored either

- In the inertia of the system by speeding up the generator utilizing field oriented control (8) or
- In the energy storage link, capacitors in voltage source inverters (VSI) or inductors in current source inverters (CSI).

The second option is impractical due to the significant increase in the required capacitance or inductance of the converter. Hence, the first option is the only practical solution

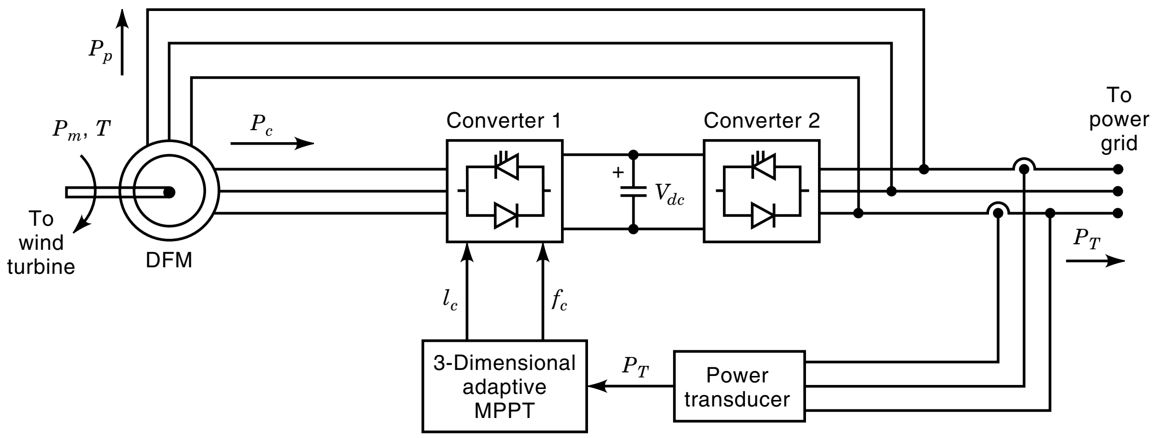

Figure 5. Adaptive power maximization algorithm for doubly-fed machines, illustrating the input and output variables utilized to maximize electrical output power for any given input power.

and is commonly implemented in wind generation systems. The torque pulsation compensation is usually a fast inner control loop, with the MPPT algorithm implemented in a much slower and overall system control loop.

An older electrical approach for torque pulsation mitigation is to reduce the stiffness of the electric coupling with the help of a current power electronic converter between the synchronous generator and the grid (6). Employing a proportional-integral dc-link current regulator and operating the synchronous generator with constant air gap flux yields the following relationship between electromagnetic torque and generator speed:

$$\frac{\Delta T_E}{\Delta \omega_E} = K_P + \frac{K_I}{s} \tag{12}$$

Equation (12) above corresponds to the model of an electric generator with electrical stiffness, K_I, and electric damping, K_p. Hence, the PI dc-link current regulator can be adjusted for the parameters of the electromagnetic coupling to the electric grid. Also, the integral constant K_I can be tuned to fix the first torsional mode at any desired low value of frequency.

WIND TURBINE OPERATION

The amount of power generated by a wind turbine depends on the design characteristics of turbine and generator as well as on the properties of the wind resource. As an example, Fig. 6 shows the annual wind speed distribution for a wind site on the Oregon coast (1). This variation of wind speed, v can be represented by a Weibull or Rayleigh probability distribution (23):

$$f(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} \exp\left[-\left(\frac{v}{c}\right)^{k}\right] \tag{13}$$

where c is the scale factor and k is the shape factor. The turbine power output characteristic as shown in Fig. 2 can also be expressed as a function of wind speed, v:

$$P_m = P_{\max}\, g(v) \tag{14}$$

where $g(v)$ will be different for fixed and variable speed generators. The average power output of the turbine can now be

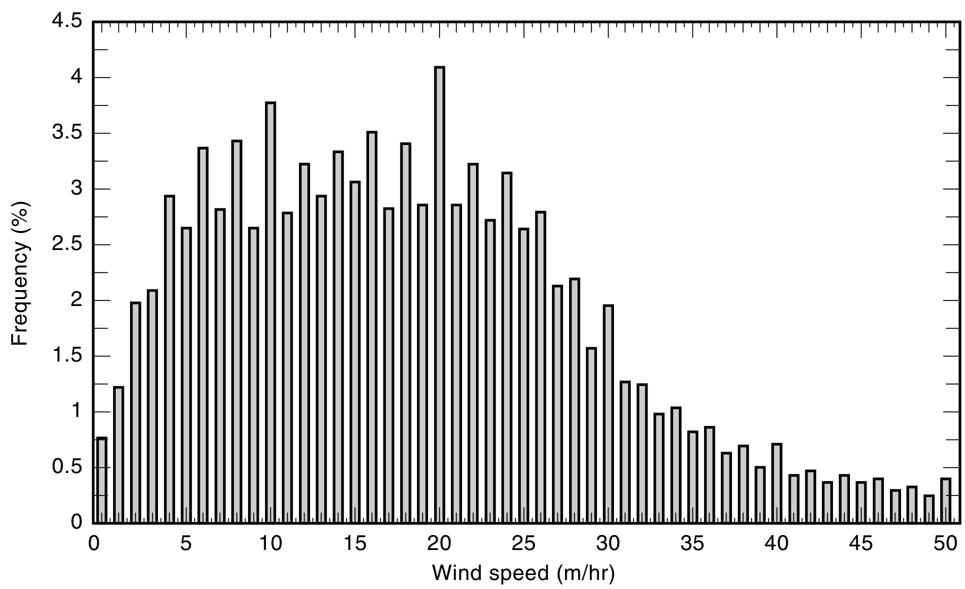

Figure 6. Sample annual wind speed distribution, illustrating the Rayleigh distribution of wind speeds. Wind energy is distributed over a wide range of wind speeds, indicating the advantages of available speed generation (wind speed in miles/ hours).

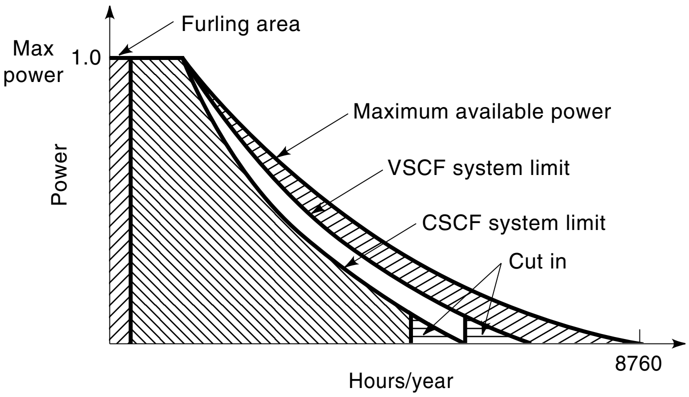

Figure 7. Power extraction from wind using VSCF and CSCF systems, illustrating the annual energy extraction from wind for a site by integration of the wind distribution such as shown in Fig. 6. The white area represents, typically, the additional energy capture due to VSCF control.

determined by

$$P_{\text{avg}} = P_{\max} \int f(v)\, g(v)\, dv \tag{15}$$

The quantity inside the integral is defined as the wind turbine capacity factor and represents the ratio of average to maximum turbine outputs. Typical values are significantly below unity, in the range of 0.3 to 0.4, reflecting the variable nature of the wind resource.

Figure 7 (1) shows the result of the integration in Eq. (15) and illustrates the annual wind power availability and power extraction possible with CSCF and VSCF systems. The area shown in white represents the additional energy captured using VSCF generation systems and has to be weighed against the added complexity and cost of variable speed generators.

Wind power is a very competitive industry, and plants are required to be competitive with fossil resources and yield a satisfactory return on investment. Issues of initial cost, generator sizing and efficiency, as well as maintenance and reliability have to be carefully weighed in order to achieve satisfactory $/kWh results from a wind power plant.

OUTLOOK AND FURTHER INFORMATION

Utility-scale wind power generation has been an active research and development area for several decades. Activities are somewhat cyclical, as overall interest and funding are related to government incentives as well as cost and availability of other energy resources. Nevertheless, many companies and agencies are continuously pursuing developmental work in the wind power area. In the last decade, the research emphasis has shifted from mainly addressing mechanical system aspects to improving electrical generator performance. This trend is expected to continue, with an emphasis on cost reduction, increased efficiency, and energy capture, as well as enhanced reliability and power quality. Most new and updated wind installations will likely be of the variable speed type. In this area, research activities are expected to concentrate on the development of generators for direct drive systems, appropriate power electronic converters, and advanced control systems.

The reader may find further information in the references cited at the end of the article. The journal *Renewable Energy* (Pergamon Press) is devoted to renewable energy issues and provides for continuing updates on wind power issues. Information on subsystems, such as generators and power electronic converters, can be found in publications of the Institute of Electrical and Electronics Engineers (IEEE) in the U.S. as well as in the Proceedings of the Institution of Electrical Engineers (IEE) in the U.K. Recommended IEEE Journals include the transactions on power systems, energy conversion, power electronics, and industry applications. Several international conferences also provide a forum for wind power research and development activities.

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WIRELESS COMMUNICATION, HISTORY. See History of wireless communication.

WIRELESS NETWORKS, ACCESS METHODS. See Multiple access mobile communications.

WIRELESS STANDARDS. See Mobile telecommunications standards.

WIRES. See Conductors, electric.

WORD RECOGNITION. See Optical character recognition; Speech perception.

WORKFLOW. See Office automation.

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WORLD WIDE WEB. See Hypermedia; Internet technology; Java, javascript, hot java; Telecommunication of engineering.

WORLD WIDE WEB HYPERTEXT LINKS. See Universal resource locator.

WORLD WIDE WEB RESOURCE LOCATION NAMES. See Universal resource locator.

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