- Allows the grid-connected wind farm to commit to power purchase contracts in advance for a better price

- Allows investors to proceed with new wind farms and avoid the penalties they must pay if they do not meet their hourly generation targets

Therefore, development of short-term wind-speed-forecasting tools helps wind energy producers. NWTC researchers work in cooperation with the National Oceanic and Atmospheric Administration (NOAA) to validate the nation’s wind resource maps and develop methods of short-term (1 to 4 h) wind forecasting. Previously have also proposed a new technique for forecasting wind speed and power output up to several hours in advance. Their technique is based on cross-correlation at neighboring sites and artificial neural networks and is claimed to significantly improve forecasting accuracy compared to the persistence-forecasting model.

2.5 Wind Power System

SYSTEM COMPONENTS

The wind power system comprises one or more wind turbine units operating electrically in parallel. Each turbine is made of the following basic components:

- Tower structure

- Rotor with two or three blades attached to the hub

- Shaft with mechanical gear

- Electrical generator

- Yaw mechanism, such as the tail vane

- Sensors and control

Because of the large moment of inertia of the rotor, design challenges include starting, speed control during the power-producing operation, and stopping the turbine when required. The eddy current or another type of brake is used to halt the turbine when needed for emergency or for routine maintenance.

In a modern wind farm, each turbine must have its own control system to provide operational and safety functions from a remote location. It also must have one or more of the following additional components:

- Anemometers, which measure the wind speed and transmit the data to the controller.

- Numerous sensors to monitor and regulate various mechanical and electrical parameters. A 1-MW turbine may have several hundred sensors.
- Stall controller, which starts the machine at set wind speeds of 8 to 15 mph and shuts off at 50 to 70 mph to protect the blades from overstressing and the generator from overheating.
- Power electronics to convert and condition power to the required standards.
- Control electronics, usually incorporating a computer.
- Battery for improving load availability in a stand-alone plant.
- Transmission link for connecting the plant to the area grid.

The following are commonly used terms and terminology in the wind power industry:

Low-speed shaft: The rotor turns the low-speed shaft at 30 to 60 rotations per minute (rpm).

High-speed shaft: It drives the generator via a speed step-up gear.

Brake: A disc brake, which stops the rotor in emergencies. It can be applied mechanically, electrically, or hydraulically.

Gearbox: Gears connect the low-speed shaft to the high-speed shaft and increase the turbine speed from 30 to 60 rpm to the 1200 to 1800 rpm required by most generators to produce electricity in an efficient manner.

Because the gearbox is a costly and heavy part, design engineers are exploring slow-speed, direct-drive generators that need no gearbox.

Generator: It is usually an off-the-shelf induction generator that produces 50- or 60-Hz AC power.

Nacelle: The rotor attaches to the nacelle, which sits atop the tower and includes a gearbox, low- and high-speed shafts, generator, controller, and a brake. A cover protects the components inside the nacelle. Some nacelles are large enough for technicians to stand inside while working.

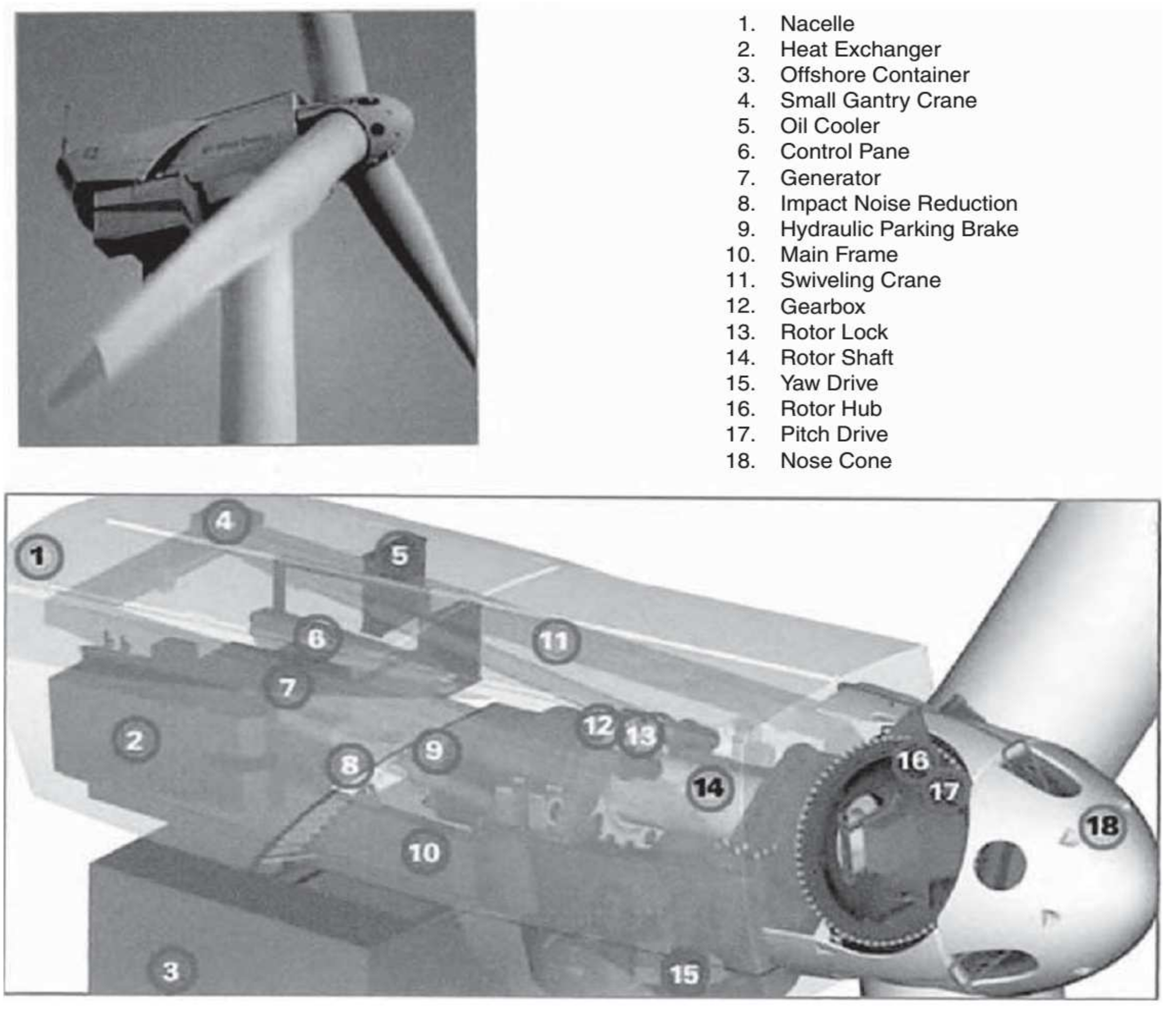
Pitch: Blades are turned, or pitched, out of the wind to keep the rotor from turning in winds that have speeds too high or too low to produce electricity.

Upwind and downwind: The upwind turbine operates facing into the wind in front of the tower, whereas the downwind runs facing away from the wind after the tower.

Vane: It measures the wind direction and communicates with the yaw drive to orient the turbine properly with respect to the wind.

Yaw drive: It keeps the upwind turbine facing into the wind as the wind direction changes. A yaw motor powers the yaw drive. Downwind turbines do not require a yaw drive, as the wind blows the rotor downwind.

The design and operating features of various system components are described in the following subsections.



Nacelle details of a 3.6-MW/104-m-diameter wind turbine. (From GE Wind Energy. With permission.)

A. TOWER

The wind tower supports the rotor and the nacelle containing the mechanical gear, the electrical generator, the yaw mechanism, and the stall control. Figure depicts the component details and layout in a large nacelle, and Figure shows the installation on the tower. The height of the tower in the past has been in the 20 to 50 m range. For medium- and large-sized turbines, the tower height is approximately equal to the rotor diameter, as seen in the dimension drawing of a 600-kW wind turbine (Figure 4.4). Small turbines are generally mounted on the tower a few rotor diameters high. Otherwise, they would suffer fatigue due to the poor wind speed found near the ground surface. Figure 4.5 shows tower heights of various-sized wind turbines relative to some known structures.

Both steel and concrete towers are available and are being used. The construction can be tubular or lattice. Towers must be at least 25 to 30 m high to avoid turbulence caused by trees and buildings. Utility-scale towers are typically twice as high to take advantage of the swifter winds at those heights.

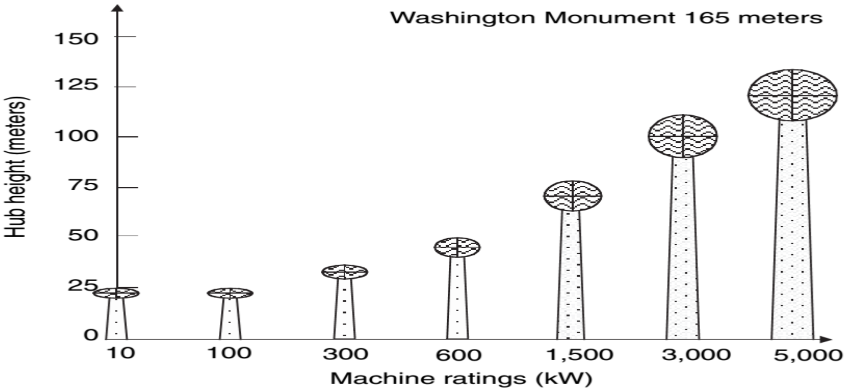
The main issue in the tower design is the structural dynamics. The tower vibration and the resulting fatigue cycles under wind speed fluctuation are avoided by the design. This requires careful avoidance of all resonance frequencies of the tower, the rotor, and the nacelle from the wind fluctuation frequencies. Sufficient margin must be maintained between the two sets of frequencies in all vibrating modes.

The resonance frequencies of the structure are determined by complete modal analyses, leading to the eigenvectors and Eigen values of complex matrix equations representing the motion of the structural elements. The wind fluctuation frequencies are found from the measurements at the site under consideration. Experience on a similar nearby site can bridge the gap in the required information.

Big cranes are generally required to install wind towers. Gradually increasing tower height, however, is bringing a new dimension in the installation. Large rotors add to the transportation problem as well. Tillable towers to nacelle and rotors moving upwards along with the tower are among some of the newer developments in wind tower installation. The offshore installation comes with its own challenge that must be met.

B. TURBINE

Wind turbines are manufactured in sizes ranging from a few kW for stand-alone remote applications to a few MW each for utility-scale power generation. The turbine size has been steadily increasing. The average size of the turbine installed worldwide in 2002 was over 1 MW. By the end of 2003, about 1200 1.5-MW turbines made by GE Wind Energy alone were installed and in operation. Today, even larger machines are being routinely installed on a large commercial scale, such as GE's new 3.6-MW turbines for offshore wind farms both in Europe and in the U.S. It offers lighter variable-speed, pitch-controlled blades on a softer support structure, resulting in a cost-effective foundation. Its rated wind speed is 14 m/sec with cut in speed at 3.5 m/sec and the cutout at 25 m/sec. The blade diameter is 104 m with hub height 100 m on land and 75 m offshore. In August 2002, Enercon's 4.5-MW wind turbine prototype was installed near Magdeburgh in eastern Germany. It has a 113-m rotor diameter, 124-m hub height, and an egg-shaped nacelle. Its reinforced concrete tower diameter is 12 m at the base, tapering to 4 m at the top. Today, even 5-MW machines are being installed in large offshore wind farms. The mass of a 5-MW turbine can vary from 150 to 300 t in nacelle and 70 to 100 t in the rotor blades, depending on the manufacturing technologies adopted at the time of design. The most modern designs would naturally be on the lighter side of the range.



Tower heights of various capacity wind turbines.

Turbine procurement requires detailed specifications, which are often tailored from the manufacturers' specifications. The leading manufacturers of wind turbines in the world are listed in Table 4.1, with Denmark's Vestas leading with 22% of the world's market share. The major suppliers in the U.S. are GE Wind (52%), Vestas (21%), Mitsubishi (12%), NEG Micon (10%), and Gamesha (3%).

C. BLADES

Modern wind turbines have two or three blades, which are carefully constructed airfoils that utilize aerodynamic principles to capture as much power as possible. The airfoil design uses a longer upper-side surface whereas the bottom surface remains somewhat uniform. By the Bernoulli principle, a "lift" is created on the airfoil by the pressure difference in the wind flowing over the top and bottom surfaces of the foil. This aerodynamic lift force flies the plane high, but rotates the wind turbine blades about the hub. In addition to the lift force on the blades, a drag force is created, which acts perpendicular to the blades, impeding the lift effect and slowing the rotor down. The design objective is to get the highest lift-to-drag ratio that can be varied along the length of the blade to optimize the turbine's power output at various speeds.

The rotor blades are the foremost visible part of the wind turbine, and represent the forefront of aerodynamic engineering. The steady mechanical stress due to centrifugal forces and fatigue under continuous vibrations make the blade design the weakest mechanical link in the system. Extensive design effort is needed to avoid premature fatigue failure of the blades. A swift increase in turbine size has been recently made possible by the rapid progress in rotor blade technology, including emergence of the carbon- and glass-fiber-based epoxy composites. The turbine blades are made of high-density wood or glass fiber and epoxy composites.

The high pitch angle used for stall control also produces a high force. The resulting load on the blade can cause a high level of vibration and fatigue, possibly leading to a mechanical failure. Regardless of the fixed- or variable-speed design, the engineer must deal with the stall forces. Researchers are moving from the 2-D to 3-D stress analyses to better understand and design for such forces. As a result, the blade design is continually changing, particularly at the blade root where the loading is maximum due to the cantilever effect.

The aerodynamic design of the blade is important, as it determines the energy capture potential. The large and small machine blades have significantly different design philosophies. The small machine sitting on a tower relatively taller than the blade diameter, and generally unattended, requires a low-maintenance design. On the other hand, a large machine tends to optimize aerodynamic performance for the maximum possible energy capture. In either case, the blade cost is generally kept below 10% of the total installed cost.

D. SPEED CONTROL

The wind turbine technology has changed significantly in the last 25 yr.1 Large wind turbines being installed today tend to be of variable-speed design, incorporating pitch control and power electronics. Small machines, on the other hand, must have simple, low-cost power and speed control. The speed control methods fall into the following categories:

No speed control whatsoever: In this method, the turbine, the electrical generator, and the entire system are designed to withstand the extreme speed under gusty winds.

Yaw and tilt control: The yaw control continuously orients the rotor in the direction of the wind. It can be as simple as the tail vane or more complex on modern towers. Theoretical considerations dictate free yaw as much as possible. However, rotating blades with large moments of inertia produce high gyroscopic torque during yaw, often resulting in loud noise. A rapid yaw may generate noise exceeding the local ordinance limit. Hence, a controlled yaw is often required and used, in which the rotor axis is shifted out of the wind direction when the wind speed exceeds the design limit.

Pitch control: This changes the pitch of the blade with changing wind speed to regulate the rotor speed. Large-scale power generation is moving towards variable-speed rotors with power electronics incorporating a pitch control.

Stall control: Yaw and tilt control gradually shifts the rotor axis in and out of the wind direction. But, in gusty winds above a certain speed, blades are shifted (profiled) into a position such that they stall and do not produce a lift force. At stall, the wind flow ceases to be smooth around the blade contour, but separates before reaching the trailing edge. This always happens at a high pitch angle. The blades experience a high drag, thus lowering the rotor power output. This way, the blades are kept under the allowable speed limit in gusty winds. This not only protects the blades from mechanical overstress, but also protects the electrical generator from overloading and overheating. Once stalled, the turbine has to be restarted after the gust has subsided.

2.6 TURBINE RATING

The method of assessing the nominal rating of a wind turbine has no globally accepted standard. The difficulty arises because the power output of the turbine depends on the square of the rotor diameter and the cube of the wind speed. The rotor of a given diameter, therefore, would generate different power at different wind speeds. A turbine that can generate 300 kW at 7 m/sec would produce 450 kW at 8 m/sec wind speed. What rating should then be assigned to this turbine? Should we also specify the rated speed? Early wind turbine designers created a rating system that specified the power output at some arbitrary wind speed. This method did not work well because everyone could not agree on one speed for specifying the power rating. The “rated” wind speeds varied from 10 to 15 m/sec under this practice. Manufacturers quoted on the higher side to claim a greater output from the same design.

Such confusion in quoting the rating was avoided by some European manufacturers who quoted only the rotor diameter. But the confusion continued as to the maximum power the machine can generate under the highest wind speed in which the turbine can continuously and safely operate. Many manufacturers have, therefore, adopted the combined rating designations x/y, the generator’s peak electrical capacity followed by the wind turbine diameter. For example, a 300/30-kW/m wind system means a 300-kW electrical generator and a 30-m diameter turbine. The specific rated capacity (SRC) is often used as a comparative index of the wind turbine designs. It measures the power generation capacity per square meter of the blade-swept area, and is defined as follows in units of kW/m^2:

$$SRC = \frac{\text{Generator electrical capacity}}{\text{Rotor-swept area}}$$

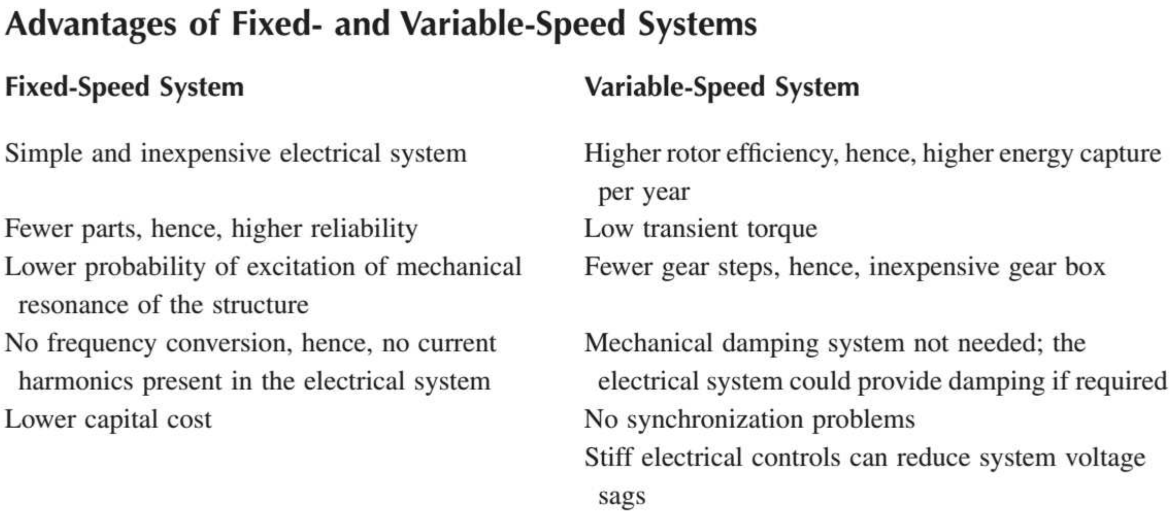
The SRC for a 300/30 wind turbine is $300/\pi \times 15^2 = 0.42$ kW/m^2. It increases with diameter, giving favorable economies of scale for large machines, and ranges from approximately 0.2 kW/m^2 for a 10-m diameter rotor to 0.5 kW/m^2 for a 40-m diameter rotor. Some aggressively rated turbines have an SRC of 0.7 kW/m^2, and some reach as high as 1 kW/m^2. The higher-SRC rotor blades have higher operating stresses, which result in a shorter fatigue life. All stress concentration regions are carefully identified and eliminated in high-SRC designs. Modern design tools, such as the finite element stress analysis and the modal vibration analysis, can be of great value in rotor design.

Turbine rating is important as it indicates to the system designer how to size the electrical generator, the plant transformer, and the connecting cables to the substation and the transmission link interfacing the grid. The power system must be sized on the peak capacity of the generator. Because turbine power depends on the cube of the wind speed, the system-design engineer matches the turbine and the generator performance characteristics. This means selecting the rated speed of the turbine to match with the generator. As the gearbox and generator are manufactured only in discrete sizes, selecting the turbine’s rated speed can be complex. The selection process goes through several iterations, trading the cost with benefit of the available speeds. Selecting a low rated speed would result in wasting much energy at high winds. On the other hand, if the rated speed is high, the rotor efficiency will suffer most of the time.

2.7 MAXIMUM ENERGY CAPTURE

The wind power system design must optimize the annual energy capture at a given site. The only operating mode for extracting the maximum energy is to vary the turbine speed with varying wind speed such that at all times the TSR is continuously equal to that required for the maximum power coefficient Cp. The theory and field experience indicate that the variable-speed operation yields 20 to 30% more power than with the fixed-speed operation. Nevertheless, the cost of variable-speed control is added. In the system design, this trade-off between energy increase and cost increase has to be optimized. In the past, the added costs of designing the variable pitch rotor, or the speed control with power electronics, outweighed the benefit of the increased energy capture. However, the falling prices of power electronics for speed control and the availability of high-strength fiber composites for constructing high-speed rotors have made it economical to capture more energy when the speed is high. The variable-speed operation has an indirect advantage. It allows controlling the active and reactive powers separately in the process of automatic generation control. In fixed-speed operation, on the other hand, the rotor is shut off during high wind speeds, losing significant energy. The pros and cons of fixed- and variable speed operations are listed in Table.

Almost all major suppliers now offer variable-speed systems in combination with pitch regulation. Potential advantages of the variable-speed system include active grid support, peak-power-tracking operation, and cheaper offshore foundation structure. The doubly fed induction generator is being used in some large wind turbines such as NEG Micon's 4.2-MW, 110-m diameter machines and multi-megawatt GE machines. It is an emerging trendsetting technology in the variable-speed gear-driven systems, primarily because only the slip frequency power (20 to 30% of the total) has to be fed through the frequency converter. This significantly saves power electronics cost.



Advantages of Fixed- and Variable-Speed Systems

Fixed-Speed System	Variable-Speed System
Simple and inexpensive electrical system	Higher rotor efficiency, hence, higher energy capture per year
Fewer parts, hence, higher reliability	Low transient torque
Lower probability of excitation of mechanical resonance of the structure	Fewer gear steps, hence, inexpensive gear box
No frequency conversion, hence, no current harmonics present in the electrical system	Mechanical damping system not needed; the electrical system could provide damping if required
Lower capital cost	No synchronization problems
	Stiff electrical controls can reduce system voltage sags

MAXIMUM POWER OPERATION

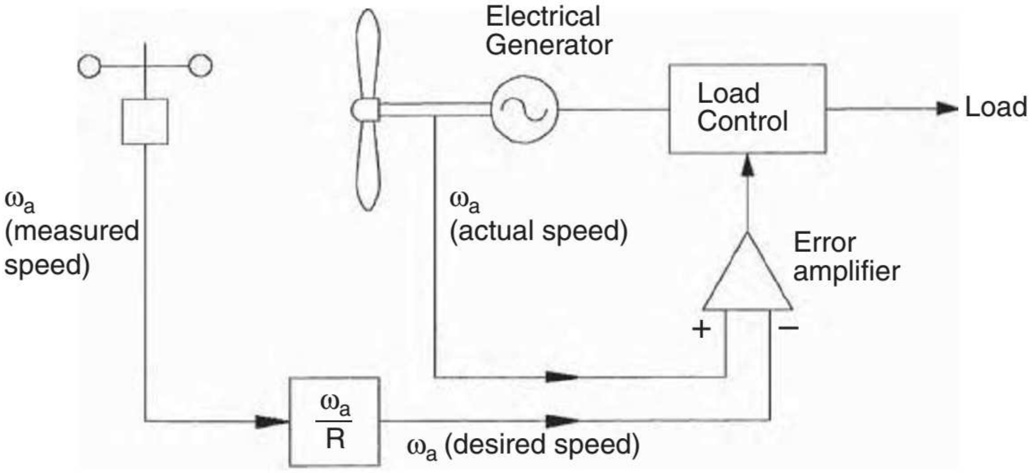
As seen earlier, operating the wind turbine at a constant TSR corresponding to the maximum power point at all times can generate 20 to 30% more electricity per year. However, this requires a control scheme to operate with a variable speed to continuously generate the maximum power. Two possible schemes for such an operation are as follows:

2.7.1 CONSTANT-TSR SCHEME

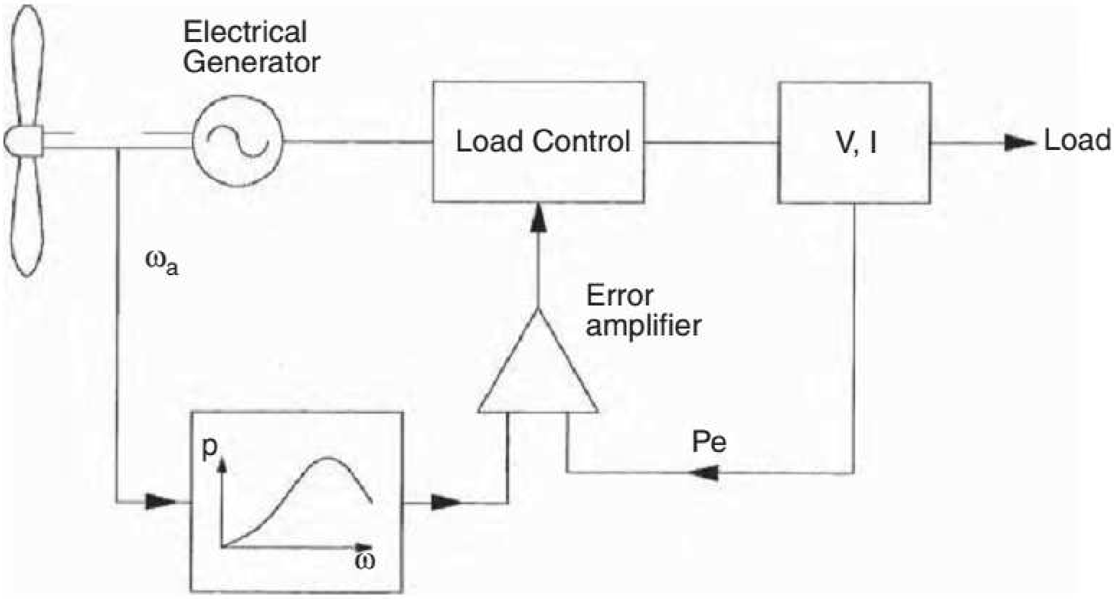
In this scheme the machine is continuously operated at its optimum TSR, which is a characteristic of the given wind turbine. This optimum value is stored as the reference TSR in the control computer. The wind speed is continuously measured and compared with the blade tip speed. The error signal is then fed to the control system, which changes the turbine speed to minimize the error. At this time the rotor must be operating at the reference TSR, generating the maximum power. This scheme has the disadvantage of requiring the local wind speed measurements, which could have a significant error, particularly in a large wind farm with shadow effects. Being sensitive to the changes in the blade surface, the optimum TSR gradually changes with age and environment. The computer reference TSR must be changed accordingly many times, which is expensive. Besides, it is difficult to determine the new optimum TSR with changes that are not fully understood or easily measured.

2.7.2 PEAK-POWER-TRACKINGSCHEME

The power vs. speed curve has a single well-defined peak. If we operate at the peak point, a small increase or decrease in the turbine speed would result in no change in the power output, as the peak point locally lies in a flat neighborhood. In other words, a necessary condition for the speed to be at the maximum power point is as follows:



Maximum power operation using rotor tip speed control scheme.



Maximum power operation using power control scheme.

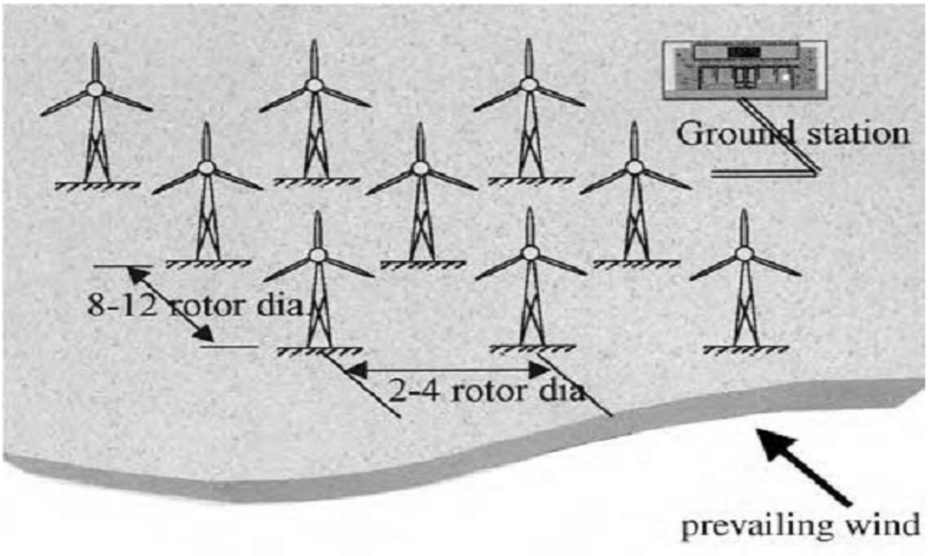
This principle is used in the control scheme. The speed is increased or decreased in small increments, the power is continuously measured, and ΔP/Δω is continuously evaluated. If this ratio is positive — meaning we get more power by increasing the speed — the speed is further increased. On the other hand, if the ratio is negative, the power generation will reduce if we change the speed any further. The speed is maintained at the level where ΔP/Δω is close to zero. This method is insensitive to errors in local wind speed measurement, and also to wind turbine design. It is, therefore, the preferred method. In a multiple-machine wind farm, each turbine must be controlled by its own control loop with operational and safety functions incorporated.

2.8 SYSTEM-DESIGN FEATURES

When the land area is limited or is at a premium price, one optimization study that must be conducted in an early stage of the wind farm design is to determine the number of turbines, their size, and the spacing for extracting the maximum energy from the farm annually. The system trade-offs in such a study are as follows:

2.8.1. TURBINETOWERS ANDSPACING

Large turbines cost less per megawatt of capacity and occupy less land area. On the other hand, fewer large machines can reduce the megawatt-hour energy crop per year, as downtime of one machine would have larger impact on the energy output. A certain turbine size may stand out to be the optimum for a given wind farm from the investment and energy production cost points of view.



Optimum tower spacing in wind farms in flat terrain.

Tall towers are beneficial, but the height must be optimized with the local regulations and constrains of the terrain and neighborhood. Nacelle weight and structural dynamics are also important considerations.

When installing a cluster of machines in a wind farm, certain spacing between the wind towers must be maintained to optimize the energy crop over the year. The spacing depends on the terrain, wind direction, wind speed, and turbine size.

The optimum spacing is found in rows 8 to 12 rotor diameters apart in the wind direction, and 2 to 4 rotor diameters apart in the crosswind direction. A wind farm consisting of 20 towers, rated at 500 kW each, needs 1 to 2 km^2 of land area. Of this, less than 5% of the land is actually required for turbine towers and access roads. The remaining land could continue its original use. Thus, wind turbines can co-exist with grazing, farming, fishing, and recreational use. The average number of machines in wind farms varies greatly, ranging from several to hundreds depending on the required power capacity of the farm. The preceding spacing rules would ensure that the turbines do not shield those further downwind. Some wind farms have used narrow spacing of five to six rotor diameters in the wind direction. One such farm in Mackinaw City, MI, has reported the rotors in downwind direction running slower due to the wake effect of the upwind rotors. The wind power fluctuations and electrical transients on fewer large machines would cost more in the filtering of power and voltage fluctuations, or would degrade the quality of power, inviting penalty from the grid.

The optimization method presented, takes into account the preceding trades. Additionally, it includes the effect of tower height that goes with the turbine diameter, available standard ratings, cost at the time of procurement, and wind speed.

The wake interaction and tower shadow are ignored for simplicity. Such optimization leads to a site-specific number and size of the wind turbines that will minimize the energy cost.

2.8.2 NUMBER OF BLADES

One can extract the power available in the wind with a small number of blades rotating quickly, or a large number of blades rotating slowly. More blades do not give more power, but they give more torque and require heavier construction. A few fast-spinning blades result in an economical system. Wind machines have been built with the number of blades ranging from 1 to 40 or more. A one-blade machine, although technically feasible, gives a supersonic tip speed and a highly pulsating torque, causing excessive vibrations. It is, therefore, hardly used in large systems. A very high number of blades were used in old low-TSR rotors for water pumping and grain milling, the applications requiring high starting torque. Modern high-TSR rotors for generating electric power have two or three blades, many of them with just two, although the Danish standard is three blades. The major factors involved in deciding the number of blades are as follows:

- The effect on power coefficient
- The design TSR
- The means of limiting yaw rate to reduce the gyroscopic fatigue

Compared to the two-blade design, the three-blade machine has smoother power output and a balanced gyroscopic force. There is no need to teeter the rotor, allowing the use of a simple rigid hub. Three blades are more common in Europe, where large machines up to a few MW are being built using the three-blade configuration.

2.8.3. ROTOR UPWIND OR DOWNWIND:

Operating the rotor upwind of the tower produces higher power as it eliminates the tower shadow on the blades. This results in lower noise, lower blade fatigue, and smoother power output. A drawback is that the rotor must constantly be turned into the wind via the yaw mechanism. The heavier yaw mechanism of an upwind turbine requires a heavy-duty and stiffer rotor compared to a downwind rotor.

The downwind rotor has the wake (wind shade) of the tower in the front and loses some power from the slight wind drop. On the other hand, it allows the use of a free yaw system. It also allows the blades to deflect away from the tower when loaded. Its drawback is that the machine may yaw in the same direction for a long period of time, which can twist the cables that carry current from the turbines.

Both types have been used in the past with no clear trend. However, the upwind rotor configuration has recently become more common.

2.8.4. HORIZONTAL VS. VERTICAL AXIS

In the horizontal-axis Danish machine, considered to be classical, the axis of blade rotation is horizontal with respect to the ground and parallel to the wind stream. Most wind turbines are built today with the horizontal-axis design, which offers a cost-effective turbine construction, installation, and control by varying the blade pitch. The vertical-axis Darrieus machine has different advantages. First of all, it is Omni directional and requires no yaw mechanism to continuously orient itself toward the wind direction. Secondly, its vertical drive shaft simplifies the installation of the gearbox and the electrical generator on the ground, making the structure much simpler. On the negative side, it normally requires guy wires attached to the top for support. This could limit its applications, particularly at offshore sites. Overall, the vertical-axis machine has not been widely used, primarily because its output power cannot be easily controlled in high winds simply by changing the blade pitch. With modern low-cost variable-speed power electronics emerging in the wind power industry, the Darrieus configuration may revive, particularly for large-capacity applications.

The Darrieus has structural advantages compared to a horizontal-axis turbine because it is balanced. The blades only “see” the maximum lift torque twice per revolution. Seeing maximum torque on one blade once per revolution excites many natural frequencies, causing excessive vibrations. Also a vertical-axis wind turbine configuration is set on the ground. Therefore, it is unable to effectively use higher wind speeds using a higher tower, as there is no tower here.

2.10. SYSTEM CONTROL REQUIREMENTS

Both the speed and the rate of change must be controlled in a good system design.

2.10.1. SPEEDCONTROL

The rotor speed must be controlled for three reasons:

- To capture more energy, as seen before.

- To protect the rotor, generator, and power electronic equipment from overloading during high-gust winds.

- When the generator is disconnected from the electrical load, accidentally or for a scheduled event. Under this condition, the rotor speed may run away, destroying it mechanically, if it is not controlled.

The speed control requirement of the rotor has five separate regions as shown in figure:

1. The cut-in speed at which the turbine starts producing power. Below this speed, it is not worthwhile, nor efficient, to turn the turbine on.

2. The constant maximum C_p region where the rotor speed varies with the wind speed variation to operate at the constant TSR corresponding to the maximum C_p value.

3. During high winds, the rotor speed is limited to an upper constant limit based on the design limit of the system components. In the constant-speed region, the C_p is lower than the maximum C_p, and the power increases at a lower rate than that in the first region.

4. At still higher wind speeds, such as during a gust, the machine is operated at a controlled constant power to protect the generator and power electronics from overloading. This can be achieved by lowering the rotor speed. If the speed is decreased by increasing the electrical load, then the generator will be overloaded, defeating the purpose. To avoid generator overloading, some sort of a brake (eddy current or another type) must be installed on the rotor.

5. The cutout speed, at which the rotor is shut off to protect the blades, the electrical generator, and other components of the system beyond a certain wind speed.

2.10.2. RATE CONTROL

The inertia of large rotors must be taken into account in controlling the speed. The acceleration and deceleration must be controlled to limit the dynamic mechanical stresses on the blades and hub, and the electrical load on the generator and power electronics. The instantaneous difference between the mechanical power produced by the blades and the electric power delivered by the generator will change the rotor speed as follows:

$$J\frac{d\omega}{dt}=\frac{P_m-P_e}{\omega} \tag{25}$$

where

J = polar moment of inertia of the rotor

ω = angular speed of the rotor

P_m = mechanical power produced by the blades

P_e = electric power delivered by the generator

2.11 Stand alone and grid connected operation

A. STAND ALONE OPERATION:

A simple stand-alone wind system using a constant-speed generator is shown in fig. It has many features that are similar to the PV stand-alone system. For a small wind system supplying local loads, a PM DC generator makes the system simple and easier to operate. The induction generator, on the other hand, gives AC power, which is used by most consumers these days. The generator is self-excited by shunt capacitors connected to the output terminals. The frequency is controlled by controlling the turbine speed. The battery is charged by an AC–DC rectifier and discharged through a DC–AC inverter.

The wind stand-alone power system is often used for powering farms. In Germany, nearly half the wind systems installed on farms are owned either by individual farmers or by an association. The performance of turbines under the “250 MW Wind” program is monitored and published by ISET, the Institute of Solar Energy and Technology at the University of Kassel.

The performance reports are also available from the German Wind Energy Institute. The reports list all installations, their performance, and any technical problems.

This includes determining the capacitor rating needed to self-excite the generator for the desired voltage and frequency. The power factor of load has a great effect on both the steady-state and the transient performance of the induction generator. The load power factor can be unity, lagging or leading, depending on the load’s being resistive, inductive, or capacitive, respectively. Most loads in the aggregate are inductive with a power factor of about 0.9 lagging. Unlike in the synchronous generator, the induction generator output current and power factor for a given load are determined by the generator parameters.

Therefore, when the induction generator delivers a certain load, it also supplies a certain in-phase current and a certain quadrature current. The quadrature current is supplied by the capacitor bank connected to the terminals. Therefore, the induction generator is not suitable for supplying a low-power-factor load.

The transient performance of the stand-alone, self-excited induction generator, on the other hand, is more involved. The generalized d-q axis model of the generator is required. Computer simulation using a d-q axis model shows the following general transient characteristics:

- Under sudden loss of self-excitation due to tripping-off of the capacitor bank, the resistive and inductive loads cause the terminal voltage to quickly reach the steady-state zero. A capacitive load takes a longer time before the terminal voltage decays to zero.

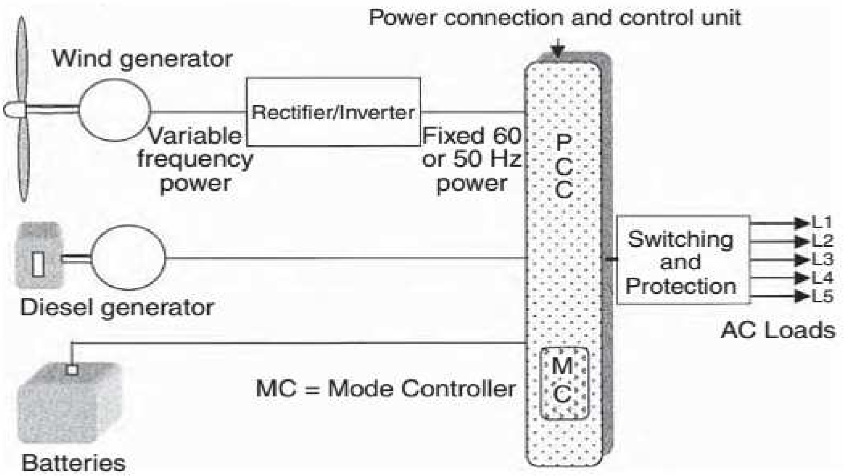
- Under sudden loading of the generator, resistive and inductive loads result in a sudden voltage drop, whereas a capacitive load has little effect on the terminal voltage.

- Under sudden loss of resistive and inductive loads, the terminal voltage quickly rises to its steady-state value.

- At light load, the magnetizing reactance changes to its unsaturated value, which is large. This makes the machine performance unstable, resulting in terminal-voltage collapse. To remedy this instability problem, the standalone induction generator must always have a minimum load, a dummy if necessary, permanently connected to its terminals.

HYBRID WITH DIESEL

The certainty of meeting load demands at all times is greatly enhanced by hybrid systems, which use more than one power source. Most hybrids use a diesel generator



Wind–diesel–battery hybrid system.

B. WIND FARM–GRID INTEGRATION

With restructuring and technological changes in the utility sector, electric utilities have begun to include wind farms and PV parks in their resource mix. The issues the power industry must deal with in integration of these new power sources are the following:

- Branch power flows and node voltages
- Protection scheme and its ratings
- Harmonic distortion and flicker
- Power system dynamics and dynamic stability
- Reactive power control and voltage control
- Frequency control and load dispatch from conventional generators

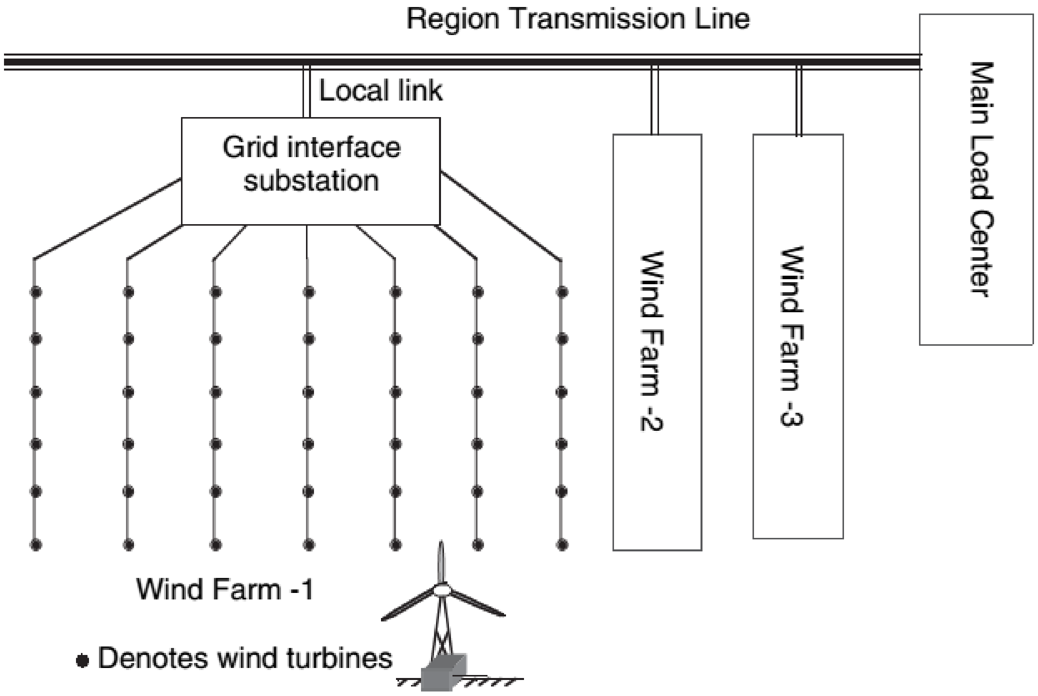
The first three have primarily local impacts, whereas the last three have broad grid-level impacts. In addressing these issues, however, there is an increased need for independent analysis of the technical and economic aspects. Projects funded by the National Renewable Laboratory’s (NREL) National Wind Technology Center (NWTC) and its partners in the utility and wind industries developed new information on integration and valuation issues and the reliability of new wind turbine products.

The program output has become a catalyst in a national outreach effort (with invest or owned utilities, electric cooperatives, public power organizations, energy regulators, and consumers) encouraging the use of wind power in generation portfolios and the purchase of wind-generated power using market-based activities. Numerous reports are available on these issues that can be downloaded from the Internet.

As for modeling the system performance, different wind farms are connected to different kinds of utility grids. The NWTC studies the behavior of power systems under different conditions to identify grid stability and power quality factors that enter into the development of wind farms throughout the U.S. Again, numerous reports are available on these issues that can be downloaded from the Internet.

As for the planning models and operations, researchers are studying how multiple wind farms or multiple wind generators in one large farm can smooth out each other’s output in a variable wind environment. Power output fluctuations are also being studied in the context of wind farm integration into utility grids. Hand and Madsen reports are just two examples of such studies.

Certification and standards are of equal importance when the country as a whole must deal with a new technology. The NREL/NWTC conducts a certification process and provides guidelines to help users prepare for certification. Underwriters Laboratory (UL) is NREL's partner in this process. NREL has developed checklists to help designers understand what the certification body is likely to be looking for in their documentation. These are the same checklists that NREL and UL would use when evaluating their design documentation. Sign-offs on these checklists are used as a report of compliance or resolution on each design issue. Also offered is a checklist to help users comply with the International Electro-technical Commission (IEC)'s requirements. NWTC has documented the general quality management, design evaluation, and testing procedures related to the certifications.



Distributed power generation with wind farms.