WIND POWER

Energy comes from various sources. The major sources of energy for human use are fossil fuels such as oil, coal, and natural gas. Another important contributor is nuclear energy. All these sources produce environmental pollution. Alternatives to them are renewable sources such as solar, ocean waves, and wind energy. In some areas of the world, wind can be an important contributor to electricity production. It gives electrical power without any emission or pollution. The energy from the wind is normally extracted by a wind turbine, which converts the kinetic power in the wind to mechanical power, which in many applications again is converted into electrical power by use of an electrical generator. Figure 1 shows photographs of a wind turbine and a whole wind turbine park.

There are two basic wind power systems. In a standalone system where wind is a dominant source of generation, a backup source based on diesel engines is needed because the wind is not constant. In the other system, the wind-electric generator directly feeds power into a well-established electrical power grid. Here also, if wind-electric is a significant portion of the overall generation, fluctuations in wind speeds cause undesirable power system oscillations. To overcome this, energy storage has to be available on a large scale, which is usually not economical. Batteries, superconducting inductors, and fuel cells are obvious means, but in general, storage systems reduce the overall efficiency and cause the price to be too high. Another solution, to keep wind-electric generation fairly constant, requires reducing the power production of the wind turbine system by control at high wind speeds. However, this solution is not beneficial for the economy of the wind power system.

In many areas wind power will be a fractional supplement (<10%) to future energy production because of the necessity of a backbone power source. In some special areas where the energy transportation cost is high, the wind power can be a significant portion. Typical wind power systems are today in the power range of 400–600 kW, but new commercial 1.5 MW systems are on the market now. Wind turbines are also moving offshore in order to get the maximum power from the wind. Offshore the landscape is flat with high wind speeds.

POWER IN THE WIND

When the wind blows, kinetic energy is stored in it. This energy is transformed to mechanical energy by use of a wind turbine. The transfer function from the wind to the mechanical shaft power P_v in a wind turbine is

$$P_v = \frac{1}{2} A v^3 \rho C_p \quad (1)$$

$$A = \pi (d/2)^2 \quad (2)$$

where P_v is the mechanical shaft power (W), A is the total area swept by the wind turbine (m^2), d is the turbine diameter (m), v is the wind speed (m/s), ρ is the mass density of air (1.225 kg/m^3), and C_p is the power coefficient for the turbine.

Equation (1) shows that the power in the wind is proportional to the cube of the wind speed.

POWER IN A WIND TURBINE

The only unknown parameter in Eq. (1) is the power coefficient C_p for the turbine. This coefficient is a characteristic of a specific wind turbine construction, and it is normally shown as a function of the ratio λ of the tip speed to the wind speed:

$$\lambda = \frac{(d/2)\omega_r}{v} \quad (3)$$

where ω_r is the rotor speed and λ is the tip–wind-speed ratio.

The tip speed will typically be fixed if an induction generator is used and connected directly to the grid. Measured C_p characteristics for two windmills are shown in Fig. 2. The measured curves show that C_p has an experimental maximum of 0.48–0.5. It can be shown theoretically that the absolute maximum C_p is 0.59. The C_p curve is used for power control of a windmill and is an important consideration when a wind rotor is designed aerodynamically. The C_p curve also shows that the maximum C_p can be obtained at only one wind speed if the blade tip speed is fixed.

POWER CONTROL METHODS

Stall Regulation

The most commonly used power control method at higher wind speeds is stall regulation, where the rotor profile of the wind turbine controls the mechanical power and limits it. The position of the rotor profile is always fixed in relation to the windmill, and since the rotor speed is almost fixed (varies only 1% to 2% due to the slip of the induction generator), the wind speed across the rotor profile will increase, and if the speed exceeds a certain limit, turbulence (stall) will result. Then power is lost and the C_p value decreases. If the wind turbine is properly designed, stall regulation along the whole wind turbine profile can be used to control the maximum shaft power P_{max} according to the equation

$$P_{max} = C_p(\lambda) P_v = \text{constant} \quad (4)$$

(a) (b)

Figure 1. Photographs of (a) a single wind turbine, (b) a wind turbine farm.

where P_{max} is the maximum allowable shaft power to the electrical generator. The main benefits of such a control system are that it is simple, cheap, and reliable. Figure 3 shows a measured power curve for a stall-regulated 500 kW windmill obtained at different wind speeds. There is only a small overshoot above the 500 kW maximum level. The power is obtained as an average over ten minutes.

Pitch Control

An alternative method to control the power is pitch control, where the rotor turbine (pitch) changes position continuously. When the generator reaches its power limit at high wind speeds, the pitch position is changed so that a fixed mechanical power is obtained and thereby also a fixed electrical power. This also reduces the mechanical stress in the system compared to stall regulation. A second effect is that at lower wind velocities the highest possible C_p value can be obtained all the time.

This strategy gives a more flexible control system, but it also requires a more complex system to control the pitch. This is traditionally done by a hydraulic system in the windmill but some systems are also electrically based. A basic control system is shown in Fig. 4, where a control unit adjusts the pitch.

The control unit can work in different modes. One mode is based on the measured active power to the grid; a search algorithm is used in order to get the maximum output power. Another method is to measure the wind speed and use a lookup table to give the pitch angle. It is then possible to obtain more power from the wind over the whole range of speeds. Figure 5 shows a measured power curve for a pitch-controlled 500 kW windmill.

Figure 5 shows that a very constant power is measured at higher wind speeds, but at lower wind speeds it is not significantly different to the stall-controlled windmill of Fig. 3. The power is again measured as an average over ten minutes. In both stall and pitch control fluctuations occur due to wind variations.

SIMPLE WIND POWER SYSTEMS

For low power (<1 MW) the cheapest generator on the market is widely used: the three-phase squirrel-cage induction generator (IG), which can be connected directly to the grid without any special power and control electronics. For higher power other systems can be preferable because of the requirement to cool the rotor. The only power electronics needed are thyristor silicon-controlled rectifiers (SCRs) for limiting the inrush cur-

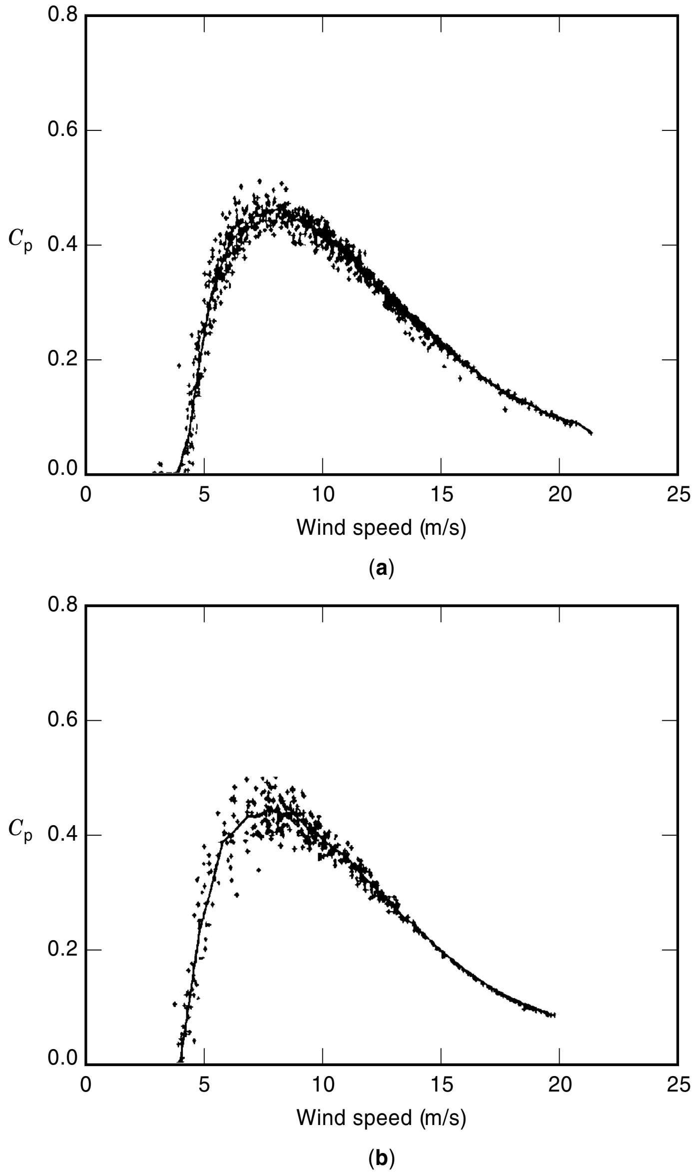

Figure 2. Power coefficient curves for two windmills (measured): (a) Nordtank NTK 500/37, (b) Vestas V39.

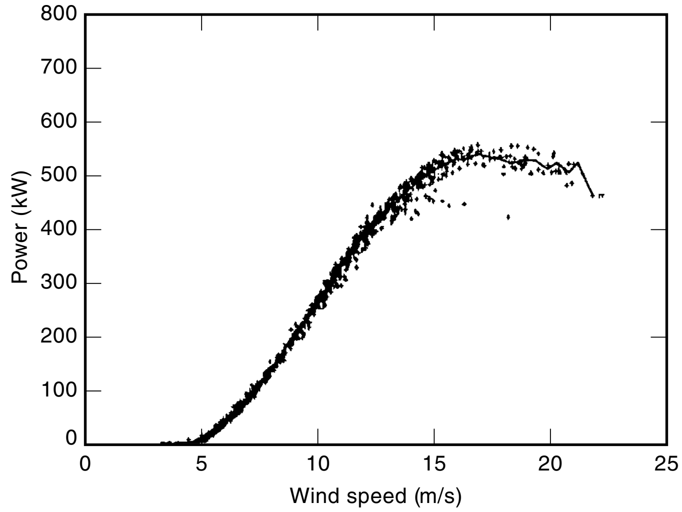

Figure 3. Measured power curve for a stall-regulated windmill: Nordtank NTK 500/37.

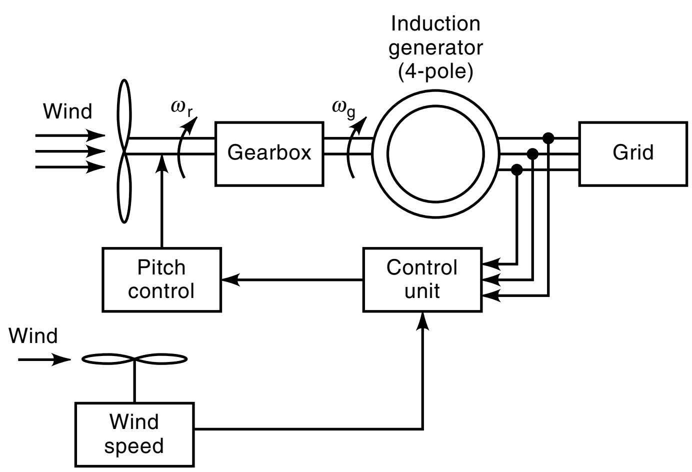

Figure 4. Pitch-controlled windmill.

rent during startup. One alternative is the three-phase synchronous generator (SG), but this generator is very stiff, and without any special damping of wind power fluctuations, which can give problems. The SG is also more expensive than the IG. The most cost-optimal solution at present is therefore a standard four-pole squirrel-cage induction generator with a gearbox. Multipole IGs and SGs can also be used. Figure 6 shows the systems for fixed-speed operation.

Some systems use also an induction generator with pole change, so the windmill can operate at two speeds. This gives a better utilization of the wind, but the generator is more expensive. Different techniques exist to get maximum energy from the wind at a given place in the landscape; in particular, it is not always best to have the highest C_p value of the turbine and windmill at maximum wind speed. It is better to maximize C_p at the wind speed that has the highest probability.

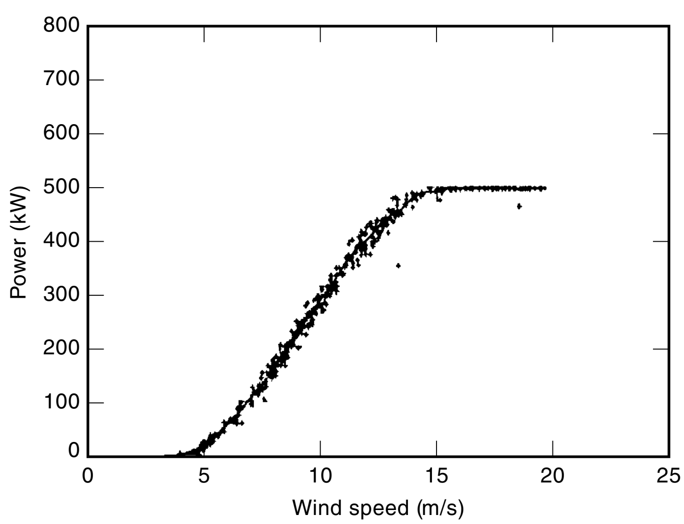

Figure 5. Measured power curve for a pitch-controlled windmill: VESTAS V39.

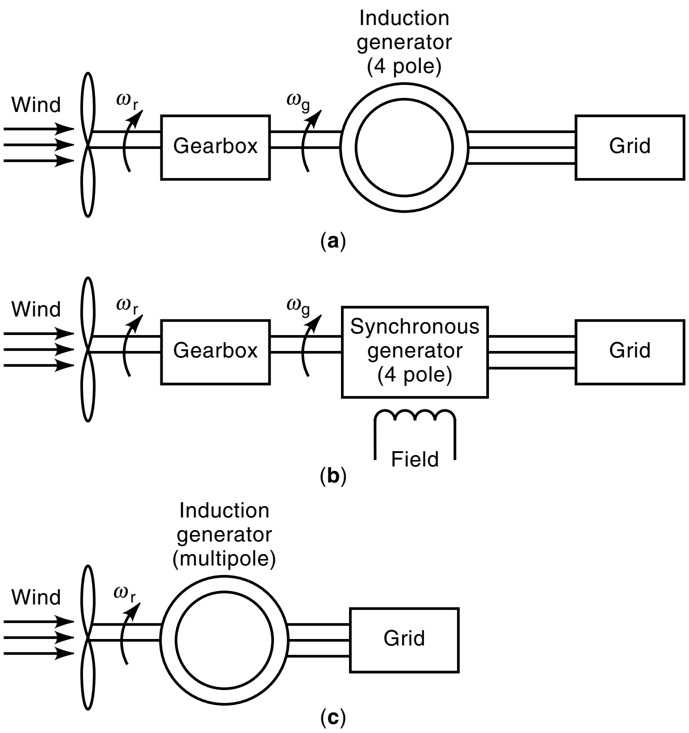

Figure 6. Fixed-speed windmill generator systems: (a) induction generator with gearbox, (b) synchronous generator with gearbox, (c) induction generator without gearbox.

Disturbances to the Grid

One of the main problems with windmills is that the induction generator requires reactive power for magnetization, which loads the grid unnecessarily. The problem is traditionally solved by inserting capacitor banks between the windmill and the grid as illustrated in Fig. 7.

The number of capacitor banks depends on the requirements of the grid utility company. In many cases there is only one capacitor bank, but for new 1.5 MW windmills in Denmark the requirement is that the power factor should be at least 0.99 over the whole operating region. Therefore a number of capacitor banks are used in high-power applications. The utility also requires the banks to be disconnected from the grid if the grid breaks down, to be sure that the windmill does not run as a standalone unit.

ADVANCED WIND POWER SYSTEMS

As mentioned, the maximum C_p of the wind turbine can only be reached at one point in fixed-speed operation. In order to obtain more energy from the wind, adjustable-speed systems can be used, but they require power electronics.

A number of different topologies are possible when adjustable speed is used. The most promising alternative is a forced-commutated, voltage-source ac–dc–ac converter with an induction generator, which is shown in Fig. 8. Another possibility is a current-source inverter, which has poorer dynamics, as shown in Fig. 9.

Up to 2 MW forced-commutated voltage-source systems are available using modern power electronic devices; current-source converters are used in very high-power applications. In Fig. 8, the inverter to the grid should not produce any significant harmonic currents. Another system for windmills that has been discussed for many years is based on a doubly fed induction generator (DIG), where the rotor is wound and connected by brushes to the outside world. Figure 10 shows a typical topology where the energy in the rotor is fed back to the grid.

Some of the advantages in this system are that ideally it is possible with a standard 1 MW generator to get 2 MW output without overloading the system, and the speed can be adjusted from synchronous speed upwards. Of course, the generator has a greater thermal load, which can reduce the output power, and it also operates at higher speed. The reactive power consumption in the stator can be compensated by the dc–ac converter. A transformer is necessary in order to optimize the size of the converter. The disadvantages are the brushes, the wound rotor, and a more complex control strategy.

An alternative to the system in Fig. 10 is a doubly wound induction generator where no brushes are used, as shown in Fig. 11. A variable resistance is put into the rotor and controlled by power electronics. The rotor resistance causes a speed variation (e.g., ±5%) and this can be used for power control. The losses in the resistor can be dissipated outside on the rotor shaft. The power electronics is built into the rotor.

Two obvious alternatives to the induction generator systems in Fig. 8 and Fig. 9 are a synchronous generator with the same converters. They are shown in Fig. 12 and Fig. 13. The synchronous generator offers higher efficiency, but is in general more expensive. However, a degree of freedom exists due to the possibility of controlling the field. For a long time

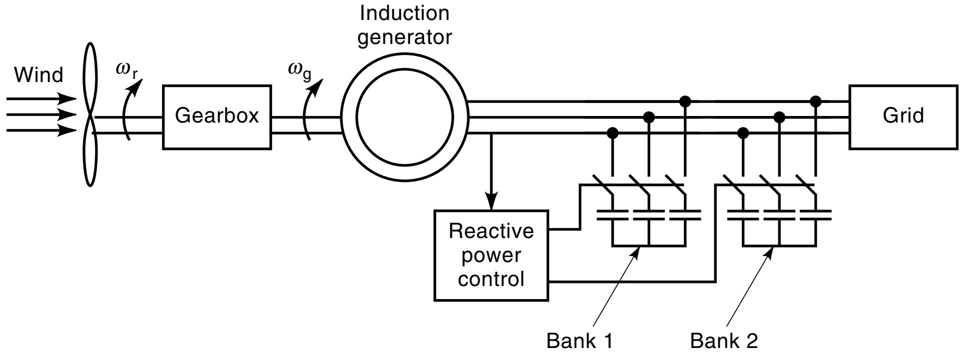

Figure 7. Capacitor banks in a typical windmill installation.

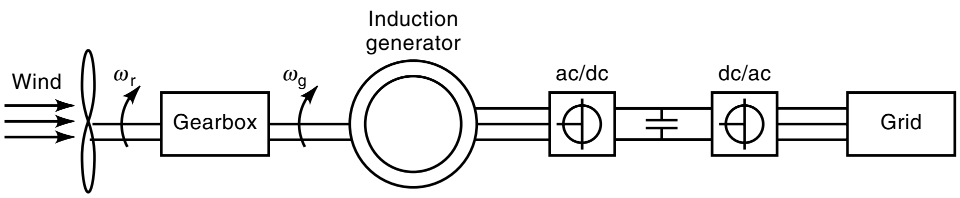

Figure 8. Forced-commutated voltage-source ac–dc–ac converter for induction generator.

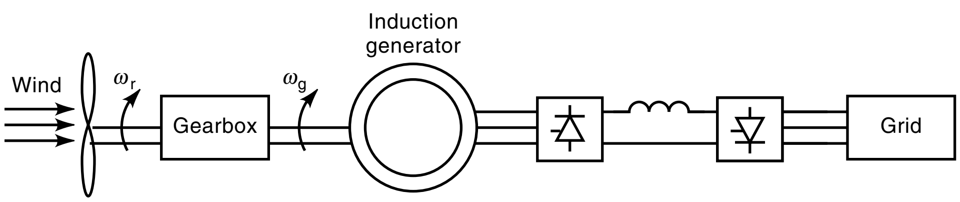

Figure 9. Current-source converter for induction generator.

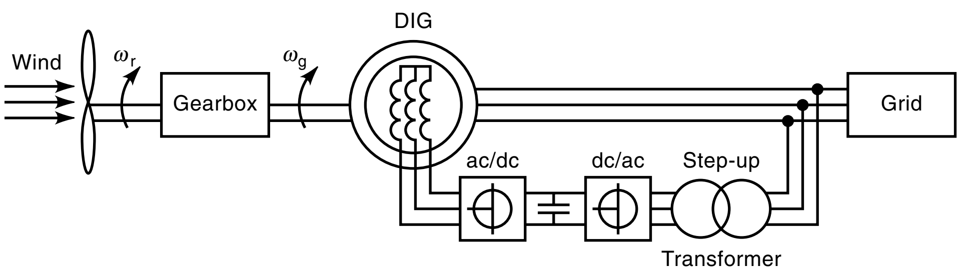

Figure 10. Doubly fed induction generator with ac–dc–ac converter and step-up transformer.

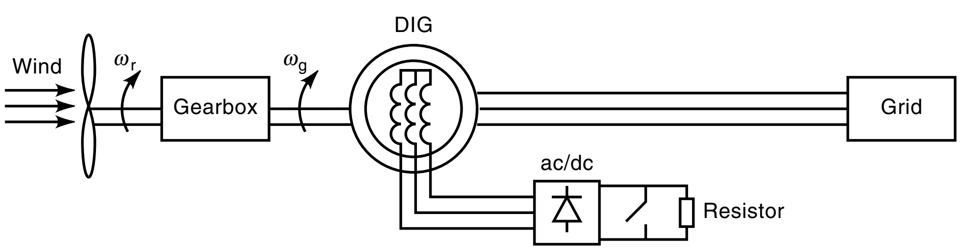

Figure 11. Doubly wound induction generator with variable rotor resistance.

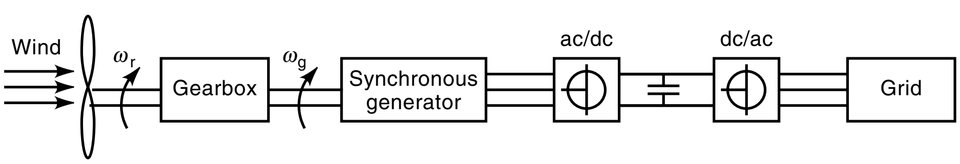

Figure 12. Forced-commutated voltage-sound ac–dc–ac converter for synchronous generator.

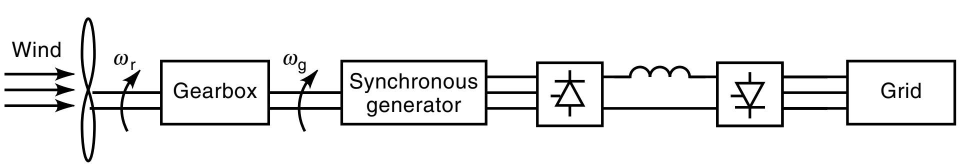

Figure 13. Current-source converter for synchronous generator.

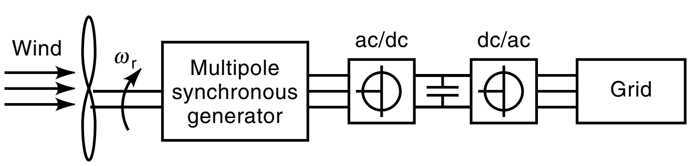

Figure 14. Multipole permanent-magnet synchronous generator with voltage-source forced-commutated converter.

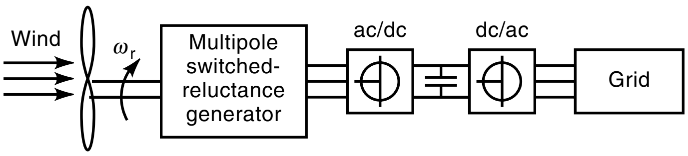

Figure 15. Multipole switched-reluctance generator with forced-commutated converter.

attempts have been made to avoid the gearbox because there are losses (4% or more) in it, and one less component in the system gives higher reliability. In order to avoid the gearbox, a multipole generator is one possibility. Two such machines are a multiple permanent-magnet synchronous generator (MPSG) and a multiple switched-reluctance generator (MSRG). The systems are shown in Fig. 14 and Fig. 15 respectively.

Major problems with multipole generators include the complexity of the windings and the size of the generator. A major drawback with the MSRG is the high reactive current, which leads to extra losses. Readers interested in these topics may refer to the Bibliography.

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