Is the Answer Blo

WIND POWER IS THE MOST RAPIDLY GROWING TECHNOLOGY FOR RENEWABLE power generation. However, fundamental differences exist between conventional thermal, hydro, and nuclear generation and wind power. These differences are reflected in the specific interaction of wind turbines with the power system. Further, there are differences between the various wind turbine types, which also affect their system interaction. In this article, first the current status and the technology of wind power are briefly discussed. The general working principles are explained and the different wind turbine types are described. Then, the differences between wind power and conventional power generation are highlighted as well as their consequences for interaction with the power system, both locally and on a system level.

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wing in the Wind?

The Current Status of Wind as a Renewable Energy Source and Its Power System Integration Issues

Status of Wind Power

As a result of increasing environmental concern, the impact of conventional electricity generation on the environment is being minimized and efforts are being made to generate electricity from renewable sources. One possibility is to use wind turbines that convert the energy contained in flowing air into electricity. During the last decade, the installed wind power capacity has grown rapidly. In Figure 1, the installed capacity in the United States, Europe, and the world is depicted. As can be seen, growth is not evenly distributed throughout the world, with Europe accounting for the largest part of it. A further detailing of the figures would show that, within Europe, growth is concentrated in a number of countries with both a good wind resource and favorable legislative arrangements. In countries where these two preconditions are not met, hardly any wind power is installed and growth of the installed capacity is rather low.

During recent years, a substantial scaling up has taken place in the wind power area. This applies both to the size of the individual turbine and to the scale of the typical project. For modern wind turbines of the multi-MW class, both the nacelle height and the rotor diameter are in the order of 100 m. Thus, at the vertical position, the blade tip can reach up to heights of 150 m. The development of the size and power of new wind turbines introduced on the market is depicted in Figure 2. Figure 3 shows the German Enercon E-112 wind turbine, which, with a rotor diameter of 112 m and a nominal power of 4.5 MW, is currently the largest wind turbine.

Further, in order to use good wind locations effectively and to geographically concentrate the visual impact of wind turbines at certain locations, a tendency to group wind turbines in *wind parks,* or *wind farms*, can be observed. Rather than individual turbines or small groups, wind farms with tens or even hundreds of turbines are erected, leading to a substantial increase in the scale of the typical wind power project. Figure 4 shows the 278.2-MW King Mountain Wind Ranch.

In densely populated countries adjacent to shallow waters, such as many countries in Northwest Europe, construction of offshore wind farms is considered a promising option. The advantages of offshore wind power are reduced visibility and noise problems and steadier winds with higher average speeds, resulting in a higher energy yield. The disadvantage is the cost increase when compared to onshore turbines, caused by the additional cost of constructing offshore and the longer distance that must be covered for connecting to the grid. Figure 5 depicts the Utgrunden offshore wind farm for the Swedish coast, which consists of seven 1.5-MW wind turbines.

Generating Systems

The working principle of a wind turbine encompasses two conversion processes, which are carried out by its main components: the rotor that extracts kinetic energy from the wind and converts it into generator torque and the generator that converts this torque into electricity and feeds it into the grid. This general working principle is depicted in Figure 6. Although this sounds rather straightforward, a wind turbine is a complex system in which knowledge from the areas of aerodynamics and mechanical, electrical, and control engineering is applied.

Currently, there are three main wind turbine types available. The main differences between these concepts concern

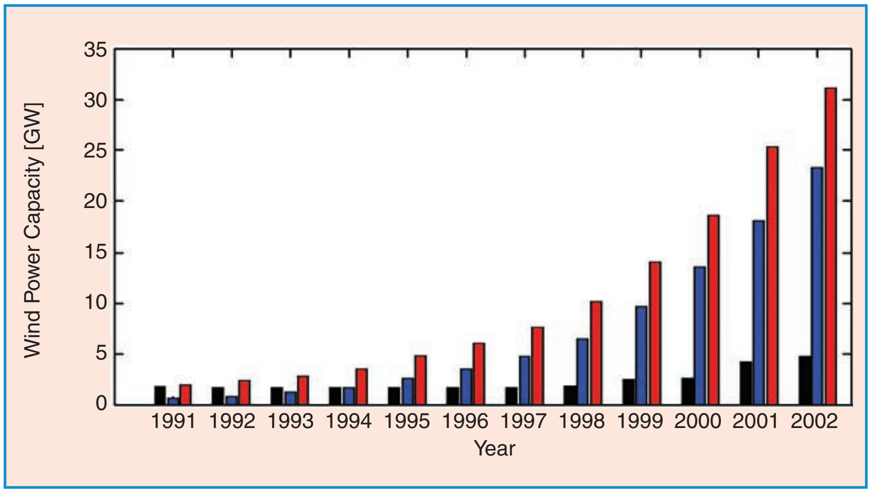

figure 1. Development of installed wind power capacity in the United States (black), Europe (blue), and the world (red). (Data: AWEA, EWEA, *Wind Power Monthly.)*

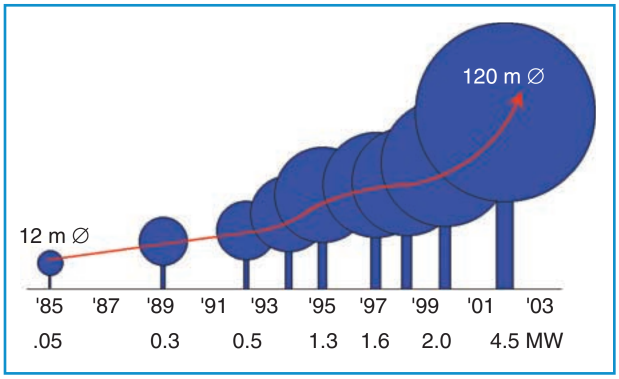

figure 2. Development of wind turbine sizes at market introduction. (Courtesy: Prof. G.A.M. van Kuik, Delft University of Technology.)

the generating system and the way in which the aerodynamic efficiency of the rotor is limited during wind speeds above the nominal value in order to prevent overloading.

As for the generating system, nearly all wind turbines currently installed use either one of the following systems (see Figure 7):

✔ squirrel-cage induction generator
✔ doubly fed (wound rotor) induction generator
✔ direct-drive synchronous generator.

The first generating system is the oldest one. It consists of a conventional, directly grid-coupled squirrel-cage induction generator. The slip, and hence the rotor speed, of a squirrel-cage induction generator varies with the amount of power generated. The rotor speed variations are, however, small: approximately 1 to 2%. Therefore, this type is normally referred to as a *constant speed* or *fixed speed* turbine. It should be mentioned that squirrel-cage induction generators used in wind turbines can often run at two different (but constant) speeds by changing the number of poles of the stator winding.

A squirrel-cage induction generator always consumes reactive power. In most cases, this is undesirable, particularly in the case of large turbines and weak grids. Therefore, the reactive power consumption of the squirrel-cage induction generator is nearly always partly or fully compensated by capacitors in order to achieve a power factor close to one.

The other two generating systems depicted in Figure 7 are variable-speed systems. These are used in *variable-speed turbines*. To enable variable-speed operation, the mechanical rotor speed and the electrical grid frequency must be decoupled. To this end, power electronics are used. In the doubly fed induction generator, a back-to-back voltage source converter feeds the three-phase rotor winding. In this way, the mechanical and electrical rotor frequency are decoupled and the electrical stator and rotor frequency can match, independently of the mechanical rotor speed. In the direct-drive synchronous generator, the generator is completely decoupled from the grid by a power electronics converter connected to the stator winding. The grid side of this converter is a voltage-source converter. The gen-

figure 3. Largest wind turbine (currently): Enercon E-112 with a rotor diameter of 112 m and a nominal power of 4.5 MW. (Courtesy: Enercon GmbH.)

erator side can be a voltage-source converter or a diode rectifier. The direct-drive generator is excited using an excitation winding or permanent magnets. In Figure 8, a technical drawing of the nacelle of a wind turbine with a gearbox and an induction generator (either squirrel cage or doubly fed) is depicted. A technical drawing of the nacelle of a direct-drive generator is shown in Figure 9.

Apart from these three main stream generating systems, there are some other varieties. One is the semi-variable speed system. In a semi-variable speed turbine, a squirrel-cage induction generator is used, of which the rotor resistance can be changed by means of power electronics. By changing the rotor resistance, the torque/speed characteristic of the generator is shifted and transient rotor speed increases of up to 10% of the nominal rotor speed are possible. In this generating system, a limited variable-speed capability is thus achieved at relatively low cost. Other variations are a conventional high-speed synchronous or asynchronous squirrel-cage induction generator connected to the turbine's rotor through a gear box and to the grid by a power electronics converter of the full rating of the generator.

Note that directly grid-coupled synchronous generators, being used in the majority of conventional power stations, are not used in wind turbines. Although wind turbines with directly grid-coupled synchronous generators were built in the past, this generator type is not applied anymore. Its unfavorable dynamic characteristics when used in combination with a fluctuating prime mover cause high structural loads and a risk of instability during wind gusts. Further, a synchronous generator must be synchronized before connecting, which is also problematic.

Wind Versus Conventional

As can be concluded from the above, there are fundamental differences between wind power and conventional generation.

- ✔ In wind turbines, generating systems different from the synchronous generator used in conventional power plants are applied.
- ✔ The prime mover of wind turbines (i.e., the wind) is hardly controllable and fluctuates randomly.

These differences between conventional and wind power generation are reflected in a different interaction with the power system.

In the analysis below, a distinction is made between local and system-wide impacts of wind power. *Local* impacts of wind power are impacts that occur in the (electrical) vicinity of a wind turbine or wind farm and can be attributed to a specific turbine or farm. Local impacts occur at each turbine or farm and are largely independent of the overall wind power penetration level in the system as a whole. When the wind power penetration level is increased, the local impacts occur in the vicinity of each turbine or farm, but when the (electrical) distance is large enough, adding wind power on one location does not affect the local impacts of wind power elsewhere. Only adding turbines locally increases the local impacts. Further, due to the differences between the applied generating systems, the local impacts differ between the three main wind turbine types.

figure 4. King Mountain Wind Range, consisting of 214 1.3-MW wind turbines in Upton County, West Texas. (Courtesy: Bonus Energy Systems A/S.)

figure 5. Utgrunden off-shore wind farm, consisting of seven 1.5-MW wind turbines erected for the Swedish coast. (Courtesy: GE Wind Energy.)

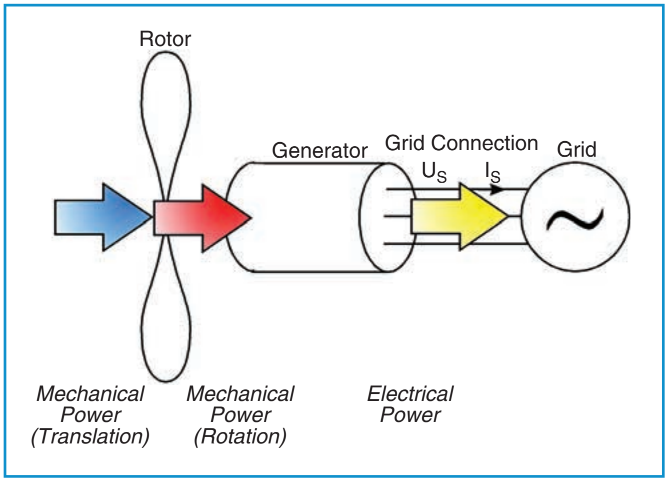

figure 6. General working principle of wind turbines.

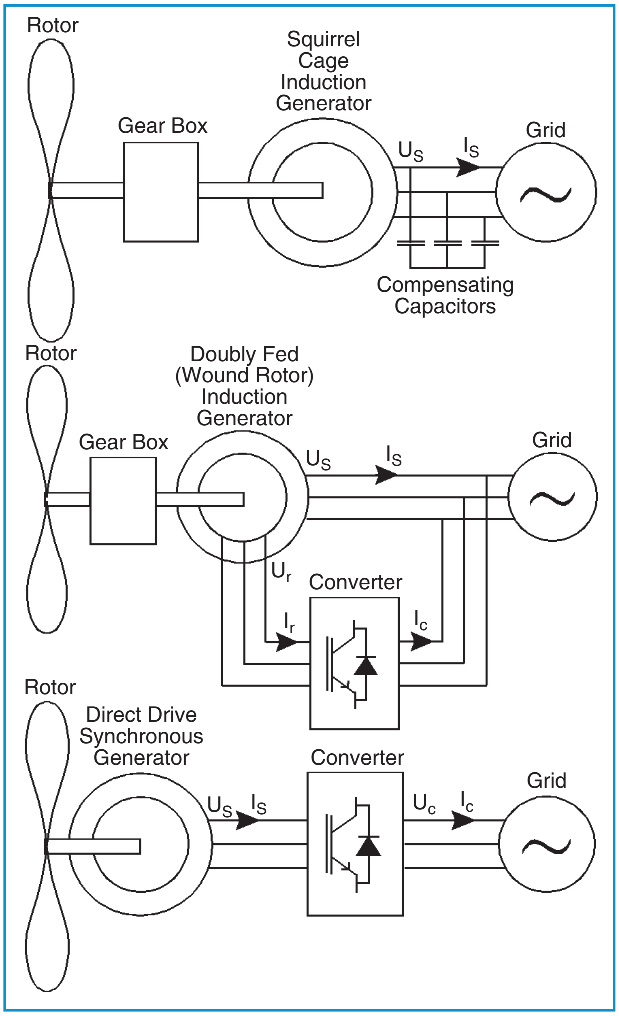

figure 7. Generating systems used in wind turbines: (top) squirrel-cage induction generator, (middle) doubly fed (wound rotor) induction generator, and (bottom) direct drive synchronous generator.

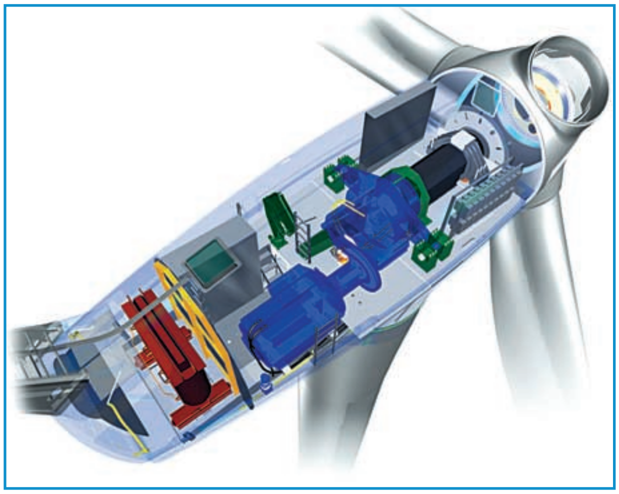

figure 8. Technical drawing of the nacelle of a wind turbine with a gearbox and a squirrel cage or wound rotor induction generator. (Courtesy: NEG Micon A/S.)

System-wide impacts, on the other hand, are impacts that affect the behavior of the system as a whole. They are an inherent consequence from the application of wind power but cannot be attributed to individual turbines or farms. Further, they are strongly related to the wind power penetration level in the system; i.e., the contribution of wind power to the actual load. In opposition to the local effects, however, the level of geographical spreading of the wind turbines and the applied wind turbine type are less important, although they still have some impact.

Local Impacts

Wind power locally has an impact on the following aspects of a power system:

- ✔ branch flows and node voltages
- ✔ protection schemes, fault currents, and switchgear ratings
- ✔ harmonic distortion
- ✔ flicker.

The first two topics must always be investigated when connecting new generation capacity. This applies independently of the prime mover of the generator and the grid coupling, and these issues are therefore not specific for wind power. The third topic, harmonic distortion, is particularly of interest when generators that are grid coupled through a power electronic converter are used. For wind power, it does therefore mainly apply to variable-speed turbines. Further, it applies to other converter connected generation, such as photovoltaics and small-scale CHP (combined heat and power) systems that are often based on high-speed synchronous generators interfaced with power electronics. The last topic, flicker, is specific for wind power.

The way in which wind turbines locally affect the node voltages depends on whether constant-speed or variable-speed turbines are used. The squirrel-cage induction generator in constant-speed turbines has a fixed relation between rotor speed, active power, reactive power, and terminal voltage. Therefore, it cannot affect node voltages by adapting the reactive power exchange with the grid. To this end, additional equipment for generating controllable amounts of reactive power would be necessary. On the other hand, variable-speed turbines have, at least theoretically, the capability of varying reactive power to affect their terminal voltage. Whether this is indeed possible in practice depends, however, on the rating and the controllers of the power electronic converter.

The contribution of wind turbines to the fault current also differs between the three main wind turbine types. Constant-speed turbines are based on a directly grid-coupled squirrel-cage induction generator. They therefore contribute to the fault current and rely on conventional protection schemes (overcurrent, overspeed, over- and undervoltage). Turbines based on the doubly fed induction generator also contribute to the fault current. However, the control system of the power electronics converter that controls the rotor current measures various quantities, such as the grid voltage and the rotor cur-

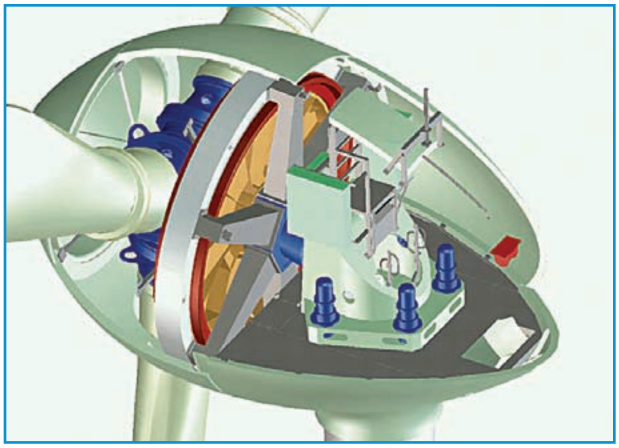

figure 9. Technical drawing of the nacelle of a wind turbine with a direct-drive synchronous generator. (Courtesy: Enercon GmbH.)

rent, at a very high sampling rate (several kHz). A fault is therefore observed very quickly. Due to the sensitivity of power electronics to overcurrents, this wind turbine type is currently quickly disconnected when a fault is detected. Wind turbines with a direct-drive generator hardly contribute to the fault current because the power electronics converter through which the generator is connected to the grid is not capable of supplying a fault current. Normally, these are also quickly disconnected in case of a fault.

The third topic, harmonic distortion, is mainly an issue in the case of variable-speed turbines because these contain power electronics, an important source of harmonics. However, in the case of modern power electronics converters with their high switching frequencies and advanced control algorithms and filtering techniques, harmonic distortion should not be a principal problem. Well-designed, directly grid-coupled synchronous and asynchronous generators hardly emit harmonics. Harmonic distortion is therefore not an issue for constant-speed wind turbines based on directly grid-coupled asynchronous generators.

The last topic, flicker, is a specific property of wind turbines. Wind is a quite rapidly fluctuating prime mover. In constant-speed turbines, prime mover fluctuations are directly translated into output power fluctuations because there is no buffer between mechanical input and electrical output. Depending on the strength of the grid connection, the resulting power fluctuations can result in grid voltage fluctuations, which can cause unwanted and annoying fluctuations in bulb brightness. This problem is referred to as *flicker*. In general, no flicker problems occur with variable-speed turbines, because in these turbines wind speed fluctuations are not directly translated to output power fluctuations. The rotor inertia acts as an energy buffer. The local impacts of the various wind turbine types are summarized in Table 1.

System-Wide Impacts

Apart from the local impacts, wind power also has a number of system-wide impacts because it affects:

- ✔ power system dynamics and stability
- ✔ reactive power and voltage control
- ✔ frequency control and load following/dispatch of conventional units.

The impact on the dynamics and stability of a power system is mainly caused by the fact that, in wind turbines, generating systems are applied that are not based on a conventional synchronous generator. The specific characteristics of these generating systems are reflected in their response to changes in terminal voltage and frequency, which therefore differs from that of a grid-coupled synchronous generator. In order to investigate the impact of wind power on power system dynamics and stability, adequate wind turbine models are essential. This often poses problems, because in many software packages for the simulation of power systems, no wind turbine models are currently incorporated. This is in turn caused by the fact that generally accepted wind turbine models seem not to exist yet. Nevertheless, it is possible to comment on the impact of the three main wind turbine types on power system dynamics and stability in a qualitative sense by analyzing their properties.

Squirrel-cage induction generators used in constant-speed turbines can lead to voltage and rotor-speed instability. During a fault, they accelerate due to the unbalance between mechanical power extracted from the wind and electrical power supplied to the grid. When the voltage restores, they consume much reactive power, impeding voltage restoration,

table 1. Local grid impacts for main wind turbine types.

Local impact	Constant speed	Doubly fed	Direct drive
Voltage control	Only possible with additional equipment; e.g., capacitor banks, SVCs or STATCOMs	Theoretically possible but dependent on converter rating and controller	Theoretically possible but dependent on converter rating and controller
Harmonics	Hardly of interest	Theoretically of interest but should not be a problem	Theoretically of interest but should not be a problem
Flicker	Important, particularly in weak grids	Unimportant due to functioning of rotor as energy buffer	Unimportant due to functioning of rotor as energy buffer
Contribution to fault currents	Yes	Yes, but turbine is presently quickly disconnected	No, converter not capable of carrying fault current, turbine is presently quickly disconnected

> When the output of conventional synchronous generators is replaced by wind turbines at remote locations on a large scale, the voltage control aspect must be taken into account explicitly.

as can be seen in Figure 10. When the voltage does not return quickly enough, the wind turbines continue to accelerate and to consume large amounts of reactive power. This eventually leads to voltage and rotor-speed instability. Opposite to what applies to synchronous generators, whose exciters increase reactive power output at low voltage and thus accelerate voltage restoration after a fault, squirrel-cage induction generators hence tend to slow down voltage restoration.

With variable-speed turbines, the sensitivity of the power electronics to overcurrents caused by voltage drops can have problematic consequences for the stability of the power system. When the penetration level of variable-speed turbines in the system is high and they disconnect at relatively small voltage drops, as is the case nowadays, a voltage drop in a wide geographic area could lead to a large generation deficit. Such a voltage drop could, for instance, be caused by a fault in the transmission grid. To prevent this, some grid companies and transmission system operators facing a high contribution of wind power in their control area are currently changing their connection requirements. They prescribe that wind turbines must be able to withstand voltage drops of certain magnitudes and durations, in order to prevent the disconnection of a large amount of wind power at a fault. In order to meet these requirements, manufacturers of variable-speed wind turbines are implementing solutions to reduce the sensitivity of variable-speed wind turbines to grid voltage drops.

The impact of wind power on reactive power generation and voltage control originates first from the fact that not all wind turbines are capable of varying their reactive power output, as stated above when discussing the local impacts of wind power. However, this is only one aspect of the impact of wind power on voltage control in a power system. Apart from this, there are two other issues that determine the impact of wind power on reactive power generation and voltage control.

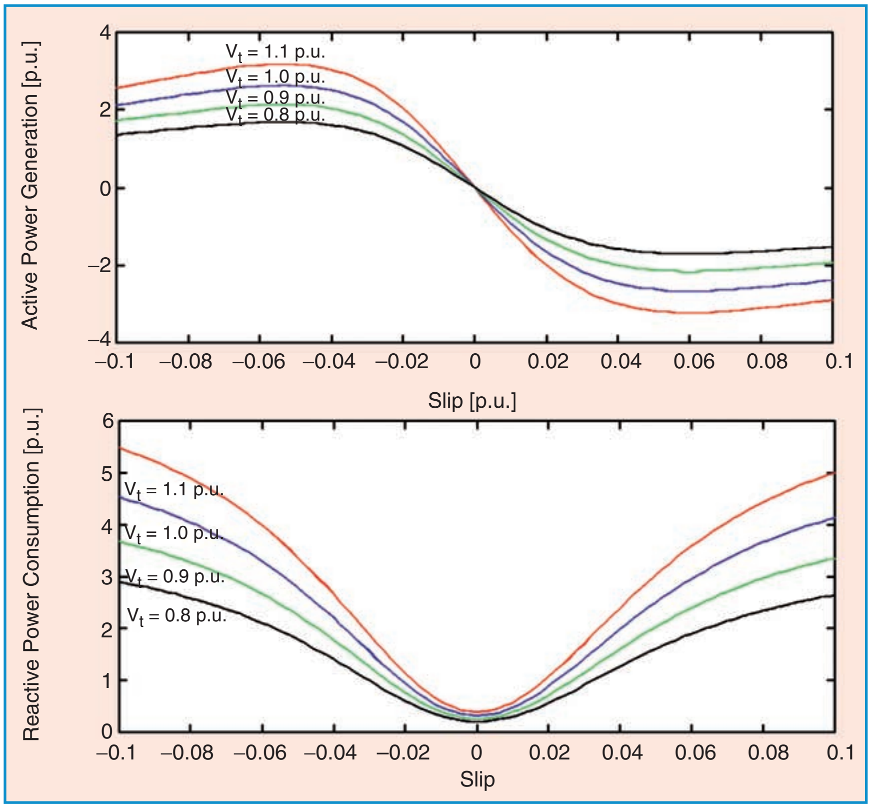

figure 10. Technical drawing of the nacelle of a wind turbine with a direct-drive synchronous generator. (Courtesy: Enercon GmbH.)

First, wind power cannot be very flexibly located when compared to conventional generation. As mentioned above, wind power affects the scenery and can hence only be constructed at locations at which this is not considered a major problem. Further, it must be erected at locations with a good wind resource. The locations that meet these two conditions are not necessarily locations that are favorable from the perspective of grid voltage control. When choosing a location for a conventional power plant, the voltage control aspect is often easier to consider because of the better location flexibility of a conventional plant. Second, wind turbines are relatively weakly coupled to the system because their output voltage is rather low and because they are often erected at distant locations. This further reduces their contribution toward voltage control. When the output of conventional synchronous generators is replaced by wind turbines at remote locations on a

The aggregated short-term output power fluctuations of a large number of wind turbines are generally not considered problematic, except for storm-induced outages.

large scale, the voltage control aspect must therefore be taken into account explicitly.

The impact of wind power on frequency control and load following is caused by the fact that the prime mover of wind power is uncontrollable. Therefore, wind power hardly ever contributes to primary frequency regulation. Further, the variability of the wind on the longer term (15 minutes to hours) tends to complicate the load following with the conventional units that remain in the system, as the demand curve to be matched by these units (which equals the system load minus the wind power generation) is far less smooth than would be the case without wind power. This heavily affects the dispatch of the conventional generators.

Note that the aggregated short-term (<1 min) output power fluctuations of a large number of wind turbines are very much smoothed and are generally not considered problematic. These fluctuations are induced by turbulence, which is a stochastic quantity that evens out when many turbines are considered. An exception, however, is formed by storm-induced outages that occur when the wind speed exceeds the cut-out value. These are not induced by stochastic turbulence but by storm fronts and can therefore affect a large number of turbines simultaneously.

The impact of wind power on frequency control and load following becomes more severe the higher the wind power penetration level is. The higher the wind power penetration level, the larger the impact of wind power on the demand curve faced by the remaining conventional units, resulting in and fewer remaining units. Thus, the requirements on the ramping capabilities of these units must be be stricter in order to match the remaining demand curve and to keep the fluctuations of the system's frequency, caused by unbalances between generation and load, within acceptable limits. It is, however, impossible to quantify the wind power penetration level at which system-wide effects start to occur because of the differences in, for example, conventional generation portfolio, wind speed regime, and geographical spread of the turbines, demand curve, and network topology between various power systems.

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