# 11

# Grid Integration of Wind Energy Systems

Detlef Schulz

Department of Electrical Engineering,
Electrical Power Engineering,
Helmut-Schmidt-University,
Holstenhofweg 85, D-22043 Hamburg, Germany.
Email: Detlef.Schulz@hsu-hh.de

## 11.1 Introduction

Considering all renewable sources, wind energy has a global share of 42%. The number of Wind Energy Converters (WECs) rapidly increases world-wide. By the end of 2007 a global wind power of nearly 94 GW had been installed [1]. Looking at country-dependent models for improved feed-in tariffs or quota system models the economical position of this energy conversion type has improved significantly over the last ten years. At the same time these different financial conditions has led to diverse installation numbers. As a result Europe has 75% of the installed wind power, America 15%, Asia 10%, Africa 1% and Australia/Pacific 1.5%. Beacuse of this growth, mainly Europe has become a high technology wind energy area with new drive train concepts, high generator powers and high rotor blade lengths. Unit powers increased rapidly from 180 kW in 1992 to 6 MW in 2007, whereas the higher unit powers above 3 MW are exclusively European technology. These high power WECs are mainly designed for offshore installations, which is a European speciality due to the necessary geological and economical conditions. The highest country share of global wind power belongs to Germany with 28%, followed by Spain, USA, India and Denmark. High potential for future years is forecast for USA, Spain, France and Poland. The United States installed 5.2 GW in 2007, the highest share of new wind power [1]. Onshore and offshore installations require different technologies and therefore they are discussed separately.

## 11.2 System Overview

Wind energy converters refers to the technical system for the conversion of wind power into electrical power. A description of wind energy conversion into usable electrical energy requires an explanation of the combined mechanical and electrical components, which are balanced together in control circuits. Relating to the scope of this book, the electrical functionality of the WECs and their interaction with the power system will be in the foreground. In Figure 11.1 an overview of WEC construction types with upwind rotor is given. Figure 11.1a shows a WEC type with gearbox. The rotor speed, which is often in the range of 8–22 rpm, is the input value for the gearbox that usually has a transmission ratio of 1:90. On the output side the speed is around 1,500 rpm, which is the synchronous speed of four-pole generators. The use of standard four-pole induction machines is favored in this WEC type. A drawback of this system is the need of a fast rotation gear that can be a source of mechanical outages over the expected operation time of 20 years. This WEC type can be visual by identified by the long horizontal dimensions of the drive train, resulting in a long nacelle shape. Figure 11.1b shows an other solution without a gearbox.

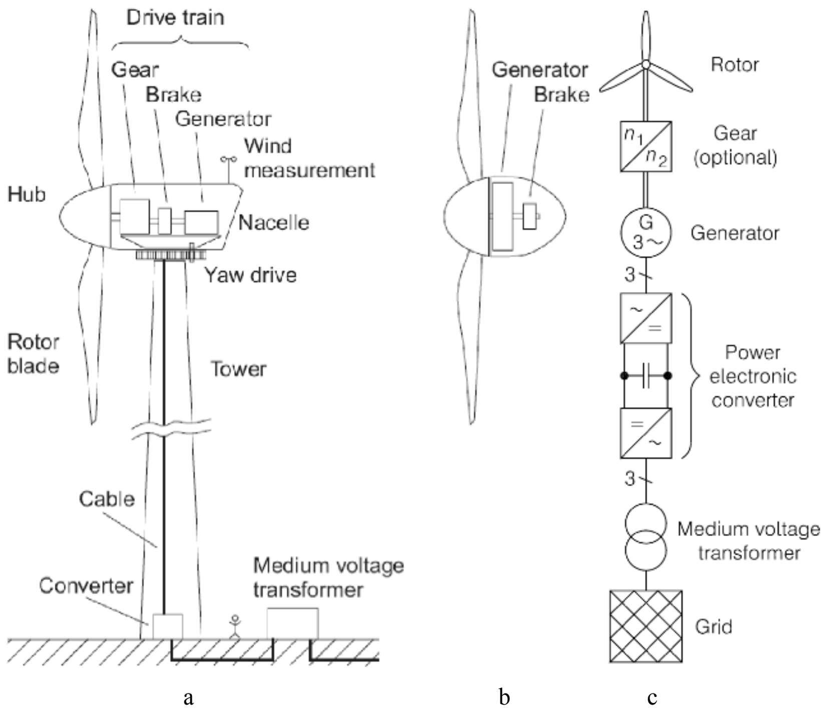



**Figure 11.1.** Principle of a wind energy converter: **a** WEC with upwind rotor, gearbox and four-pole machine; **b** tower head of a gearless type with multi-pole generator; **c** overview of a grid connected WEC

There the pole number of the generator has to be higher for a lower synchronous speed in the range of the mechanical rotor speed. A higher pole number requires more coils in the stator circumference and therefore the diameter of the generator is greater compared to the WEC type with gearbox. The gearless type can be equipped with synchronous machines with electrical or permanent magnet excitation. An advantage of the system is the absence of a high speed gear, in contrast to the disadvantage of the higher weight of the nacelle due to the bigger iron and copper parts of the generator. This type is identifiable from the nacelle shape with its high diameter and short length. Figure 11.1c gives the system overview with focus on the electrical part and grid connection. In this case the generator is connected to a full-size power electronic Voltage Source Converter (VSC), consisting of two back-to-back Voltage Source Inverters (VSI). The converter output is grid connected *via* a medium voltage transformer. Even though a three-phase generator system is depicted, multi-phase systems are also available on the market. For the generator and inverter, low voltage components are used, that require high currents in high power ranges, but reduce the isolation and construction efforts of the components.

Figure 11.2 shows respectively one practical construction example of the two described WEC types. In Figure 11.2a the long nacelle dimension is visible Figure 11.2b shows the gearless type with a higher nacelle diameter. Both described WEC types are in use in power ranges from some hundred kW up to 5 MW. Each type can also be used for higher power ranges in future.


a b

**Figure 11.2.** Exemplary main types of WECs: **a** Nordex N80, fast rotating four-pole generator with gearbox, nominal power 2.5 MW, rotor diameter 80 m (source: Nordex); **b** Enercon E-82, multi-pole generator without gearbox, nominal power 2 MW, rotor diameter 82 m (source: Enercon)

Another type of specially constructed WEC is shown in Figure 11.3. It is totally different from the two systems described so far. The WEC uses a combination of low-speed gearbox and medium voltage multi-pole synchronous generator with permanent excitation. A gear with low speed is not as sensitive as high speed components. Permanent magnet excitated generators have up to 30–40% less volume and weight compared to electrical excitated machines. The medium voltage level allows smaller cross sections for the machine windings and cables. For the grid connection a medium voltage power electronic converter is necessary.

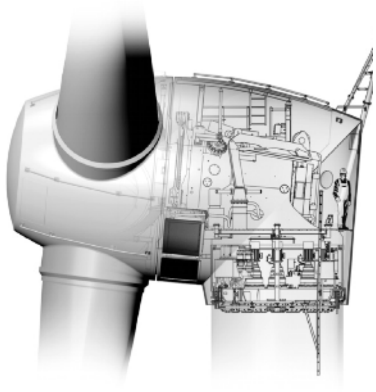


**Figure 11.3.** Half-section drawing of a 5 MW WEC (Multibrid M5000) with permanent magnet excitated synchronous generator and slowly rotating gearbox (source: Multibrid)

## 11.3 Wind Energy Converters

### 11.3.1 Energy Conversion

Wind is caused by temperature and pressure differences in air masses. A change of these parameters alters the air density $\rho$. A volume $V$ causes a force $F$ which, with of $g$ the acceleration of gravity is

$$F = V \cdot g \cdot \Delta\rho \tag{11.1}$$

When this force arises, kinetic energy is produced. It is calculated from the mass $m$ and the velocity $v$

$$E = \frac{1}{2} \cdot m \cdot v^2 \tag{11.2}$$

If an air mass flow $\dot{m}$ instead of a constant mass and a constant velocity is assumed, the wind power $P_w$ results

$$P_W = \dot{E} = \frac{1}{2} \cdot \dot{m} \cdot v^2 \tag{11.3}$$

The air flow $\dot{m}$ can be calculated from the density $\rho$, wind velocity $v$ and the rotor area $A$, which is defined by the rotating blades

$$\dot{m} = \rho \cdot \dot{V} = \rho \cdot A \cdot v \tag{11.4}$$

By insertion of Equation 11.4 into Equation 11.3, the theoretical wind power $P_0$ results

$$P_0 = \frac{1}{2} \cdot \rho \cdot A \cdot v^3 \tag{11.5}$$

This means that power $P$ depends on the third power of the wind speed, and this is mainly influenced by the installation site and the tower height. Of course there is a limit to the convertable wind power. This limit is expressed by the power coefficient $c_p$, also known as the Betz-factor [2]

$$P = \frac{1}{2} \cdot \rho \cdot A \cdot v^3 \cdot c_\mathrm{P}(v) \tag{11.6}$$

The wind speed dependent power coefficient describes the amount of energy converted by the wind turbine. Its theoretical maximum value is $c_p$=0.593. In practice WEC power coefficients occur in the range of $c_p$=0.4–0.5; see Figure 11.4. Below the nominal operation range the factor is smaller. It is highly influenced by the rotor blade profile [3–9].

### 11.3.2 Tip Speed Ratio and Power Curve

The technical applications considered include horizontal axis Wind Turbines (WT) with three blades with electrical powers above 1 MW, which are connected to the electrical transmission system. In almost all of them the rotors are located upwind; only some older devices have downwind rotors. Depending on the nacelle weight the tower is constructed from steel or steel/concrete. Standard tower heights are up to 100 m. Due to height dependent wind speeds, some new devices have lattice towers up to 160 m in height.

Commonly, WT have a high tip speed; the tip speed ratio $\lambda$ is calculated using the tip speed $v_{TS}$ and the speed of the rotor plane $v_{RP}$

$$\lambda = \frac{v_\mathrm{TS}}{v_\mathrm{RP}} = \frac{\Omega \cdot r_\mathrm{R}}{v_\mathrm{RP}}; \quad \Omega = 2 \cdot \pi \cdot n\ . \tag{11.7}$$

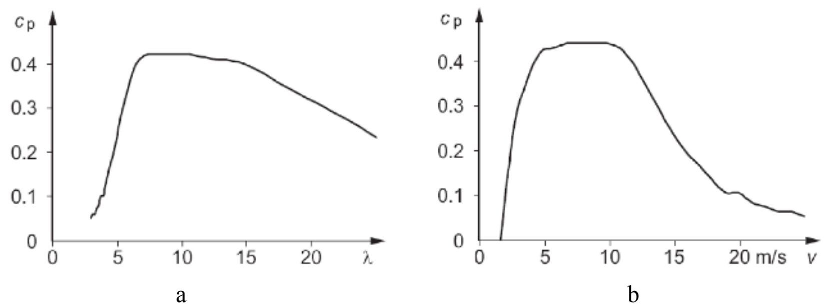



**Figure 11.4.** Power coefficient $c_p$ of a WEC depending on: **a** the tip speed ratio $\lambda$; **b** the wind speed $v$

The rotor speed $\Omega$ is given in rpm, the rotor radius $r$ in m and the speed $n$ in $s^{-1}$. Typical values of the tip speed ratio of three-blade WT are in the range of 8–10. The tip speed ratio influences the power coefficient. Figure 11.4 shows the dependencies of the power coefficient on the tip speed ratio and on the wind speed. Both diagrams deliver a non-linear relation between the depicted values.

Applying the curve of $c_p(v)$ from Figure 11.4 to Equation 11.6, the power-speed curves of a WEC occur as shown in Figure 11.5. These curves show the rotor power over the rotational speed depending on the parameter wind speed. As expressed by Equation 11.6, the power increases non-linearly with increasing wind speed. Obviously the power maxima are dependent on wind speed the rotor speed. For an optimal power yield at variable wind speeds a variable rotor speed is necessary. Therefore variable speed WECs deliver in particular at strong changing wind speeds a higher energy output compared to fixed speed devices.

Attention should be paid to the fact that, due to the wind speed dependency of the power coefficient $c_p$, the tip speed ratio $\lambda$ is also speed dependent; compare with Figure 11.4.

For adaptation of the generator curve to the mechanical trait of the WEC a torque-speed graph is required. Generally the rotor torque $T$ can be derived from the rotor power $P$, the angular frequency $\omega$ in $s^{-1}$ and the rotor speed $n$

$$T = \frac{P}{\omega}; \quad \omega = \frac{2 \cdot \pi \cdot n}{60} \tag{11.8}$$

with $n$ in rpm.

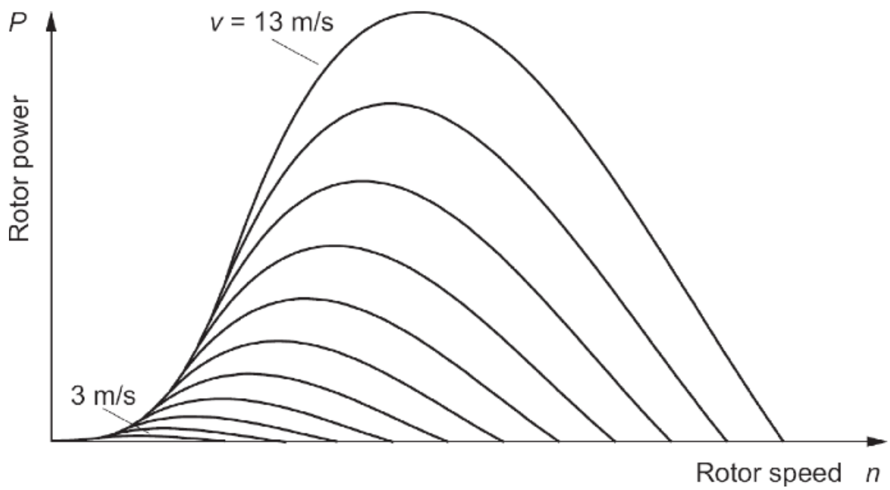



**Figure 11.5.** Rotor power $P$ of a WEC depending on the rotor speed $n$ with the parameter wind speed $v$

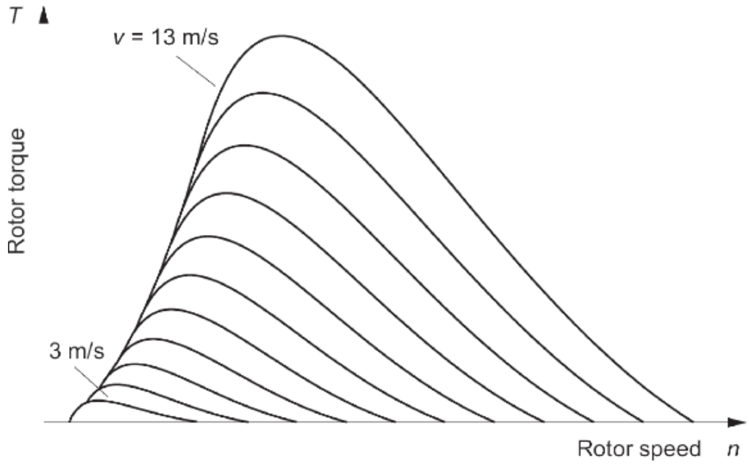



**Figure 11.6.** Rotor torque *T* of a WEC depending on the rotor speed *n* with the parameter wind speed *v*

Using Equation 11.8, the set of curves from Figure 11.5 can be converted to the new array of curves in Figure 11.6. These graphs are useful to determine the working curve of the generators and, based on this, to develop the control circuits and the control strategy of the WEC.

### 11.3.3 Operation Modes

Unlike conventional fossil energy conversion, WECs produce a wind speed dependent output power. The power is calculated according to Equation 11.6, which

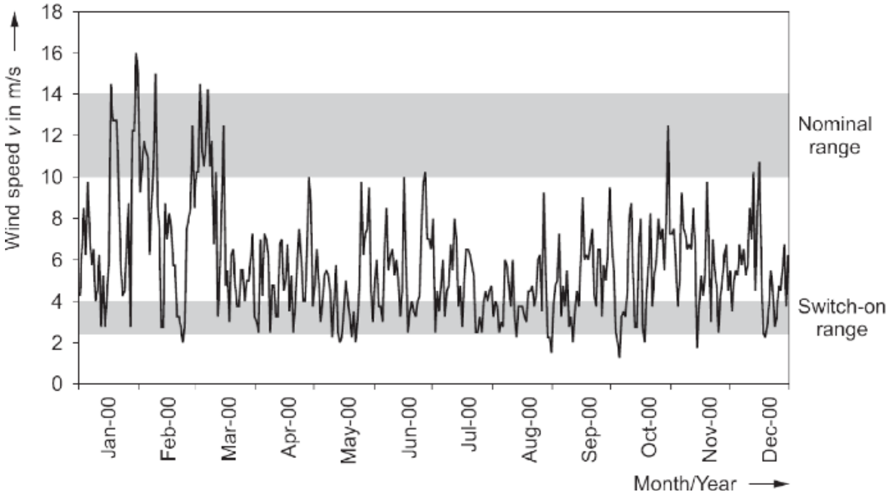



**Figure 11.7.** Daily wind speed values over one year, measured a height of 102 m

describes the strong dependency on wind conditions. From the effective power of the WEC the operation modes can be derived. The switch-on occurs at minimum wind speeds of 2.4–4 m/s. Then the output power increases with increasing wind speed. The nominal WEC power is reached at 11–14 m/s. At higher wind speeds the power is limited to the nominal value. If the cut-off wind speed in the range of 18–25 m/s is reached, the WEC control will decrease the rotor speed and shut down the wind turbine. Wind speed changes occur both over long periods and very quickly within small time intervals of seconds. During some time periods no minimum wind speed is available and the WEC is at a standstill. Figure 11.7 shows daily mean values of wind speed measured over one year. It is clear that high wind speed fluctuations occur and the nominal range is reached only on some days of the year. The mechanical loads on the devices are mainly determined by dynamic forces. Therefore a good knowledge of the dynamic wind behavior is necessary for a component rating. Measurements of short-term wind gusts are shown in Figure 11.8. It is obvious that in very small time intervals fast wind speed changes can arise. Such big speed changes cause strong variations of the output power. They also stress the mechanical components of the WEC. Therefore the mechanical power acting on the device has to be limited in order to protect the WEC.

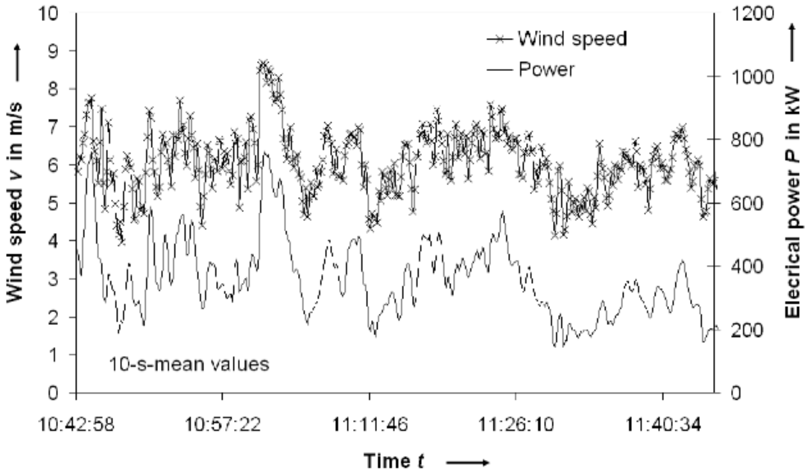



**Figure 11.8.** Wind speed and power values, measured a height of 102 m

### 11.3.4 Power Limitation

Due to the wind gusts described and the resulting mechanical forces acting on the rotor blades, the mechanical power on the WEC must be limited. This can be realised with three approaches, which are depicted in Figure 11.9 [3–9]:

- The stall-effect on fix mounted rotor blades (stall-control): for shut down the rotor blades are braked with adjustable clutches or rotating blade tips (tip spoilers); see Figure 11.9a;

- An adjustable stall-effect, realised with turnable rotor blades (active-stall-control): the blades turn the thin side in the wind direction; see Figure 11.9b;
- The reduction of the effective rotor area by axial rotation of the rotor blade in the wind direction (pitch-control): the turn is opposite to the active-stall-control; it has a higher rotation angle and a higher rotation speed; see Figure 11.9c.

Stall-controlled WECs are limited to power ranges below 2 MW, and active-stall-control is realised by only one manufacturer. In higher power classes all devices are equipped with pitch-control, which enables a fast reaction on high mechanical power spikes and makes exact mechanical dimensioning possible. The power limitation is independent of speed regulation.

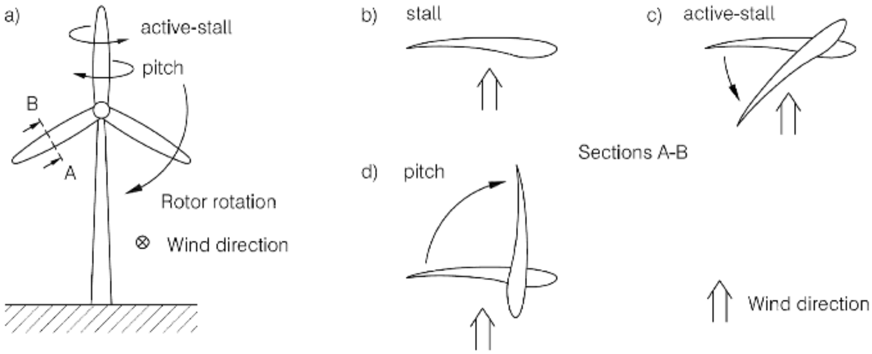



**Figure 11.9.** Aerodynamic limitation of the mechanical power: **a** overview of the WEC; **b** stall-; **c** active-stall-; **d** pitch-control

Depending on the type of power limitation, different power-speed curves of WECs can be observed. Figure 11.10 shows a comparison of the power-speed graphs of three WECs each with 1.5 MW of nominal power. Despite different speed ratings the typical behavior is visible. The stall-controlled WEC in Figure 11.10a shows a small overshoot of the nominal power, followed by a decrease of the power. WECs with active-stall-control do not exceed the nominal power and no power increase arises; see Figure 11.10b.

Pitch-controlled WECs have the same power-speed curve as the active-stall-controlled types; see Figure 11.10c, but they rotate the blade ends in the wind direction and so in the opposite direction compared to the active-stall-control. Another important difference is the faster blade adjustment of the pitch devices. This allows a quick reaction on wind speed changes. A bigger moving angle of the blades makes force reduction on the blades possible up to high wind speed ranges of 25 m/s and so the nominal electric power can be delivered over a wider operation range.

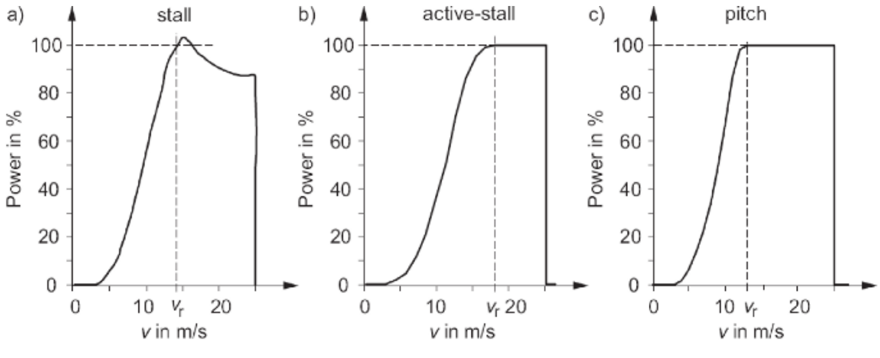



**Figure 11.10.** Power over wind speed of WECs with different power limitation strategies: **a** stall-control; **b** active-stall-control; **c** pitch-control

Basically the energy yield is influenced by the speed control. The reasons for the use of active-stall- and pitch-control are for protection from high mechanical loads. Stall devices make the highest demands on the mechanical components and cause higher noise emissions. Therefore in higher power ranges pitch-WECs are preferably in use. Stall-WECs also cause problems if new demands for grid integration should be applied.

### 11.3.5 Speed Control

The type of speed control usually decides the energy yield of WECs. Figure 11.11 shows the working curves of fixed speed and variable speed generators in combination with the power-speed curves of WECs.

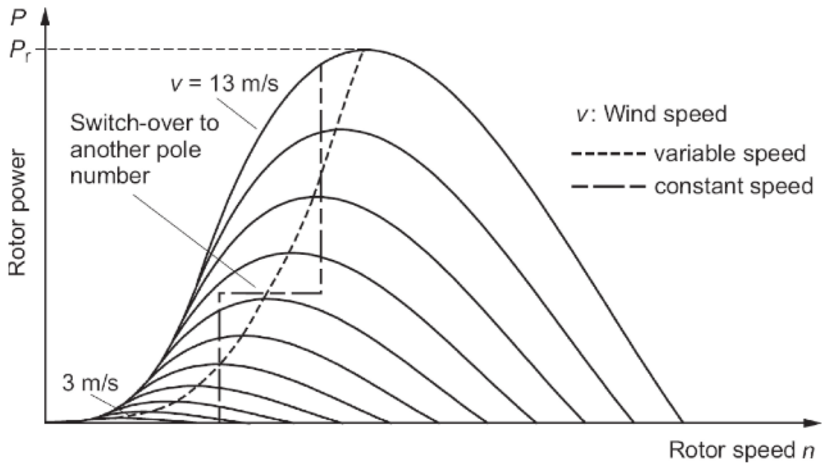



**Figure 11.11.** Working curves of fixed speed and variable speed generators in combination with the power-speed curves of WECs

Generally one can decide easily between single-stage or two-stage fixed speed and variable speed control. Single-stage fixed speed controlled devices cannot adapt their rotor speed to the wind speed and such WECs cannot deliver an optimal energy yield. Two-stage fixed speed WECs are more flexible; they work mostly with two-speed pole-changing generators.

Variable speed generators adapt their speed to the actual power conditions. Their optimal working point is adjusted by using a look-up table or a maximum power tracking method. Variable speed operation enables an optimal energy conversion within the whole speed range. Particularly in time intervals with frequently changing wind speeds; a higher energy yield compared to fixed speed devices is possible. Speed adaptation is realized by the application of power electronic converters.

### 11.3.6 Power Curves of WECs

Depending on the applied power limitation and speed control, resulting power curves can be obtained. Figure 11.12 shows the active power curve given by the manufacturer and the measured power over the wind speed of a WEC with variable speed control as shown in Figure 11.11 [10]. The measured curve lies above the guaranteed power values. Such deviations can result from tolerances of the wind speed measurement, which influence the power curve considerably; see Equation 11.6.

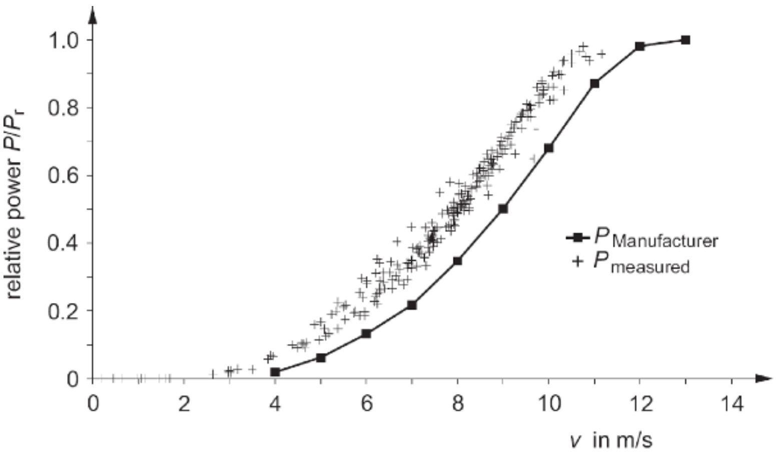



**Figure 11.12.** Relative power of a variable speed WEC given as manufacturer curve and measured curve over wind speed

Figure 11.13 shows the measured apparent power and reactive power of pitch-controlled WECs with double-fed induction generator and nominal powers of 1.5 MW and 600 kW over the relative power. It can be seen that the apparent power increases with increase of the active power, whereas the reactive power is almost constant. The reactive power has to be controlled to a minimum value; the visible part of it is necessary for the magnetization of the generator. If the WEC has a fixed speed control and a generator with two different pole pairs, the reactive power consumption differs compared to a variable speed device [11].

In Figure 11.14 the apparent and reactive power of a fixed speed WEC is depicted. The reactive power consumption increases with increasing apparent power. For all values two curves exist, which represent the WEC behavior depending on the pole pair number used in the two operation modes.

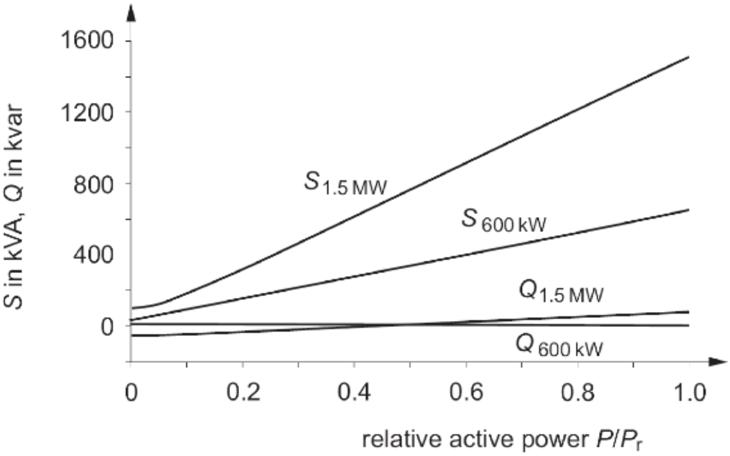



**Figure 11.13.** Measured apparent power $S$ and reactive power $Q$ of pitch-controlled WECs with double-fed induction generator and nominal powers of 1.5 MW and 600 kW over the relative power $P/P_r$

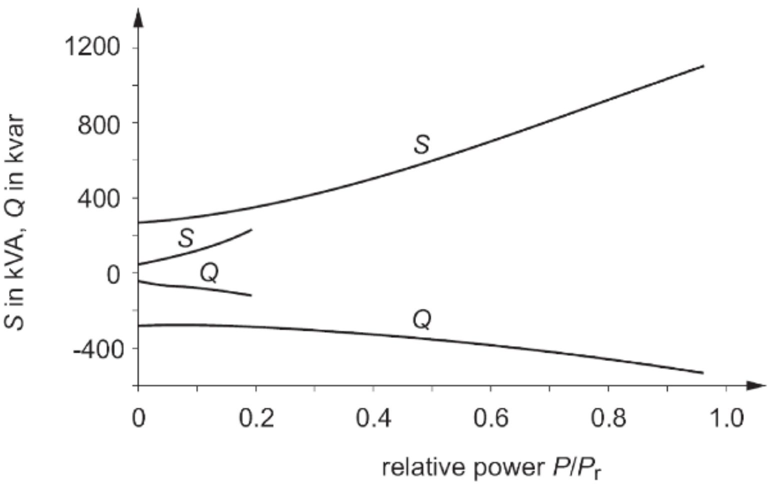



**Figure 11.14.** Apparent and reactive power of a stall-regulated, fixed-speed WT with a nominal power of 1 MW

Because of the mostly simple grid connection of fixed speed WECs (see Section 11.4.3), no improved reactive power control is possible.

## 11.4 Grid Integration

### 11.4.1 Generator Types

Due to the variable wind conditions, the power flow from the WEC to the mains is also discontinuous. The derived operation modes were described in Section 11.3.3. For the conversion of mechanical to electrical power, different generator types are usable; see Figure 11.15 [12]. Their electrical properties strongly influence the behavior of the whole WEC and determine the operation possibilities on the grid. In addition to this, the system features can be improved by using a VSI rated for the full apparent power (full-size) or only the rotor power.

*Direct Coupled Induction Machine (IM)*
In WECs direct coupled induction machines operate mostly as four-pole types. The stator terminals are directly connected to the grid; see Figure 11.15a. A gearbox transforms the mechanical rotor speed into a higher speed for the generator operation in oversynchronous mode. The induction machine consumes reactive power for its magnetization from the grid.

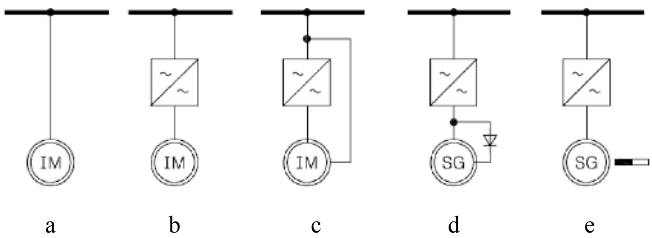



**Figure 11.15.** Generator types: **a** direct coupled induction machine; **b** induction machine with full-size VSI; **c** double-fed induction machine; **d** electrical excited synchronous generator with VSI; **e** Synchronous Generator (SG) with permanent magnet excitation

Therefore this machine type cannot work in islanding mode or build its own grid, *e.g.*, after a blackout. Due to the direct grid coupling, wind dependent power spikes directly produce voltage drops and flicker in the grid; see Section 11.5. The switch-on to the grid is realized with thyristor switches, which are short-circuited after the start. Because the direct grid coupling gives no control of the possible power factor, it depends only on the actual operation point of the generator. Recent grid requirements cannot be met with this system; its use is limited to older WEC types.

*Induction Machine (IM) with Full-size Converter*
The induction machine is connected to the grid with two back-to-back voltage source inverters; see Figure 11.15b. Because of the inverter rating for the full apparent power, the power electronics involve considerably costs. The converter decouples the generator electrically from the mains, and wind dependent power spikes are damped by the DC link. Due to the limited switching frequency of the grid side inverter, harmonics in current and voltage occur; See section 11.5. Because of the high inverter costs this system is not as used much as the next type.

*Double-fed Induction Machine (DFIM)*
In this type the stator terminals of the generator are directly connected to the grid and the rotor is connected with a voltage source converter to the mains; see Figure 11.15c. The energy flow over the rotor converter is bidirectional; in subsynchronous mode energy flows to the rotor and in oversynchronous mode energy flows from rotor to the grid. Over the stator terminals always energy flows to the grid. Because of the shared energy transport the rating of the rotor converter is smaller than for a full-size system. It depends on the speed range of the WEC and is mostly a third of the synchronous value in both directions; that produces a converter rating of a third of the nominal power. This power rating can be calculated as follows. The total power $P$ is the sum of the stator $P_s$ and rotor $P_r$ powers

$$P = P_\mathrm{s} \pm P_\mathrm{r} \tag{11.9}$$

whereas the rotor power is rated with the air gap power $P_a$ and the slip $s$

$$P_\mathrm{r} = P_\mathrm{a} \cdot s \tag{11.10}$$

In the speed range of $n=1\pm0.3\cdot n_\mathrm{s}$, around the synchronous speed the slip $s$ of a four-pole induction machine is

$$s_{-30\%} = \frac{n_\mathrm{s} - \frac{2}{3} n_\mathrm{s}}{n_\mathrm{s}} = 0.\bar{3} \tag{11.11}$$

$$s_{+30\%} = \frac{n_\mathrm{s} - \frac{4}{3} n_\mathrm{s}}{n_\mathrm{s}} = -0.\bar{3} \tag{11.12}$$

The calculations show that, at a speed variation of a third around the synchronous speed, a third of the total power must be transmitted over the VSI. The variable speed control of the machine is realized as shown earlier in Figure 11.11. For an explanation of the DFIM operation, the variable-speed-curve of Figure 11.11 is transformed according to Equation 11.8 into a torque-speed-curve as shown in

Figure 11.16. This curve is tipped over to the left side and added to the torque-speed-curve of the DFIM; see Figure 11.17. Working points result as intersection points of the graphs [13]. The standard operation curve of an induction machine includes the synchronous speed $n_s$ at the synchronous point SP. This point is determined by the grid frequency $f_1$ and the pole number $p$

$$n_s = \frac{f_1 \cdot 60}{p} \tag{11.13}$$

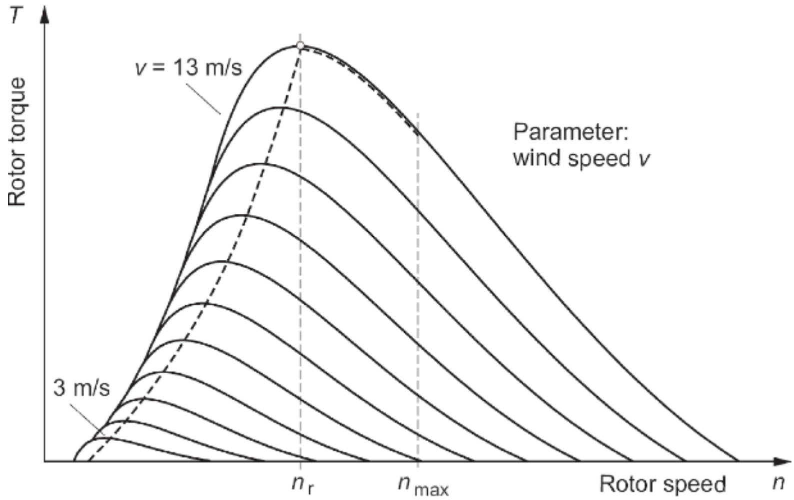



**Figure 11.16.** Variable speed operation curve of a WEC

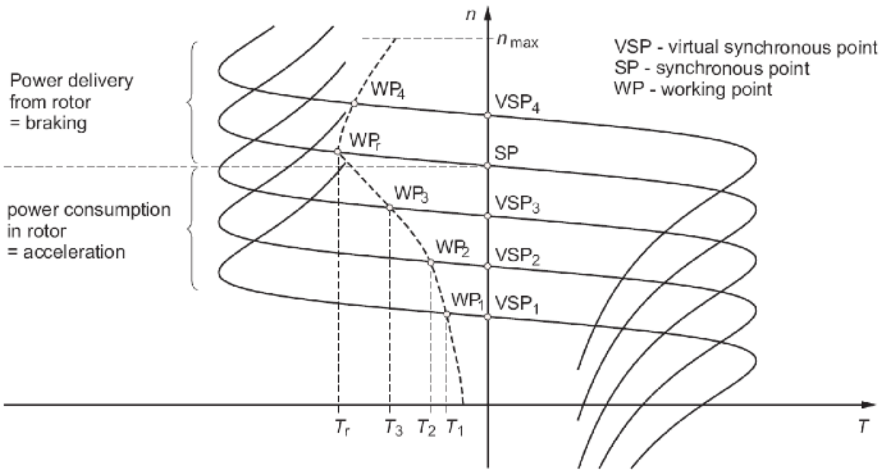



**Figure 11.17.** Array of curves for the double fed induction machine at different synchronous points and working curve of the WEC

Because of the double connection of the stator and the rotor, Equation (11.13) is not applicable; the grid frequency is replaced for further considerations by the virtual frequency $f_v$

$$f_v = f_r \pm f_s \tag{11.14}$$

A positive sign arises for different electrical rotation directions. This virtual frequency is used for the calculation of the synchronous speed

$$n_s = \frac{f_r \pm f}{p} \cdot 60 \tag{11.15}$$

Table 11.1 shows the values for the frequencies and powers in the virtual synchronous points marked in Figure 11.17. Using the control possibility of the rotor converter as shown in Table 11.1, active and reactive power can be controlled independently from each other.

**Table 11.1.** Frequencies and power directions at different synchronous points

| **Synchronous point** | $f_v$ **in Hz** | $f_r$ **in Hz** | $P_r$ | $P_s$ |
|---|---|---|---|---|
| VSP1 | 40 | 10 | + | – |
| SP | 50 | 0 | 0 | 0 |
| VSP2 | 60 | 10 | – | + |

VSP virtual synchronous point, SP synchronous point, $f_v$ virtual frequency, $P_r$ rotor power, $P_s$ stator power

The generator itself has a higher rotor winding number compared to standard machines, which allows the operation of the grid side inverter without transformer. Figure 11.18 shows a measured curve of the stator power of a DFIM, which is compared to the manufacturer curve [11]. The difference must be the rotor power, which is fed to the rotor in the sub-synchronous mode and is obtained from the rotor in the over-synchronous operation range.

*SG with Electrical Excitation and Full-size Converter*

Two systems are on the market: synchronous generators with low pole numbers and speed adaptation with gearbox and devices with high pole numbers without need for gearing. The type without gearbox is especially widespread due to reduced mechanical maintenance requirements. The power factor of the machine is adjustable by the electrical excitation. Because of the frequency adaption the synchronous generator is always equipped with a full-size voltage source converter; see Figure 11.15d. This generator type consumes no reactive power from the grid side; it is only produced with the DC rotor excitation. It can build an islanding grid and therefore also rebuild an electric grid after a blackout. For such purposes it needs a battery charged excitation current source. The excitation power decreases the system efficiency, and therefore permanent magnet excitation is also used.

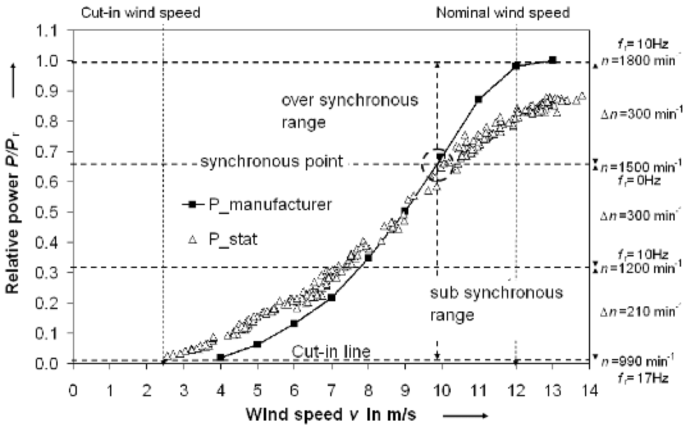



**Figure 11.18.** Array of curves for the double fed induction machine at different synchronous points and working curve of the WEC

*SG with Permanent Magnet Excitation and Full-size Converter*

For this type, permanent magnet excitation is applied. No excitation losses and excitation control exist. Control of the power factor is realized with the grid side inverter. Magnets are mounted on the rotor for the DC excitation. In WECs various hard magnetic materials such as SmCo or NdFeB with high energy production are used. Ferrites only have a low energy density. The magnetic energy density determines the generator volume and weight, higher values causing more magnet costs. If permanent magnets are used, the generator volume increases from 20–40% compared to electrical excitation. The Multibrid-WEC described in Section 11.2 is a special design of a permanent magnet excited generator type.

### 11.4.2 Types of Common Grid Coupling

If the common generator types are combined with the common power limitation methods, three main classes of WEC types result for the power class above 1 MW; see Figure 11.19 [13]. Older systems as shown in Figure 11.19a work with direct grid coupling and a thyristor start switch. They are not more acceptable because of their bad power quality parameters; see Section 11.5. The WEC types in Figure 11.19b,c are widely spread, the latter technology having the highest installation numbers. Mostly two back-to-back inverters are used, whereas the generator inverter controls the generators in an optimum working point with high efficiency and the grid side inverter controls the power quality properties of the WEC. Table 11.2 shows the electrical properties of some power electronic switches which are used in WECs. The most important values are the blocking voltage and kW-standard-units allow a flexible power adaptation. Only one WEC-application exist in the medium voltage range; see Section 11.2. Mostly low voltage converters are installed, and therefore high currents arise in the megawatt-range. A subdivision into 600 voltage applications are known from other technologies, such as oil and gas extraction or railway drive trains.

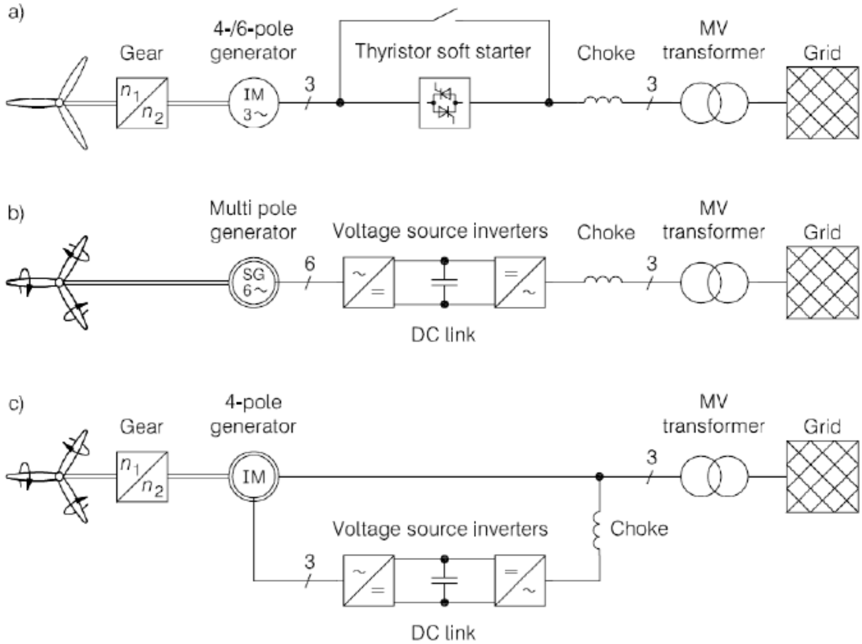



**Figure 11.19.** WEC types in the power range above 1 MW: **a** stall-regulated, constant-speed controlled WEC with direct grid connection; **b** pitch-regulated, gearless WEC with variable speed control with multi-pole synchronous generator and voltage-source converter; **c** pitch-regulated, variable speed controlled WEC with double-fed induction machine and voltage-source converter

**Table 11.2.** Power electronic switches for the use in WECs

| Switch | Blocking voltage in kV | Maximum current in A | Pulse frequency used in WECs in Hz |
|---|---|---|---|
| Thyristor | 12 | 5,000 (at 5 kV) | 50 |
| GTO | 6 | 6,000 | 200–1,000 |
| IEGT | 6.5 | 1,200 (at 6.5 kV) [14] | 2,000–20,000 |
| IGBT | 6.5 | 1,200 (at 3.3 kV) [15] | 2,000–20,000 |
| IGCT | 10 | 3,000 (at 6.5 kV] [16] | 150–500 |

GTO gate turn-off thyristor, IEGT injection enhancement gate transistor, IGBT insulated gate bipolar transistor, IGCT insulated gate commutated thyristor

### 11.4.3 Wind Park Design and Energy Management

Wind energy converters operate mostly concentrated in wind parks. This allows the joint use of local wind conditions and of the medium voltage structure on the electrical side. Almost all WECs work with low voltage generators and voltage-source power electronic converters. The wind turbines are connected to a medium voltage transformer. The medium voltage level of the wind park power is then connected to a high voltage transformer in a transformer station; see Figure 11.20.

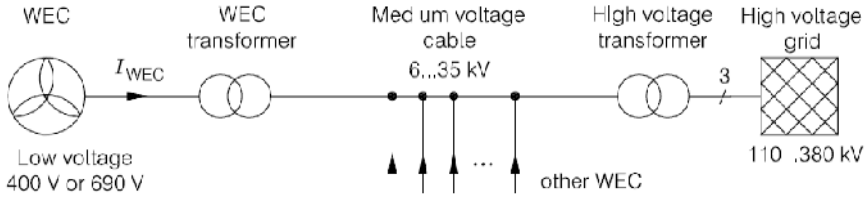



**Figure 11.20.** Principle of the grid connection of WECs in a wind park

Figure 11.21 shows an example structure of a wind park with 56 wind turbines with a total power of 95.2 MW. Beside the WECs, transformers and cables are installed, which contribute to the reactive power consumption.

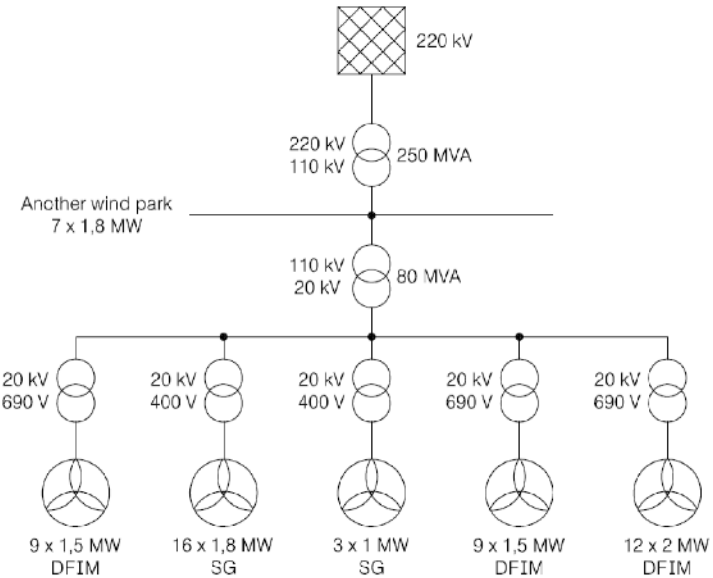



**Figure 11.21.** Example structure of a wind park with low voltage WECs DFIM double-fed induction machine, SG synchronous generator

### 11.4.4 Reactive Power Management in Wind Parks

WECs are equipped with a standard power control that adjusts the power factor $\lambda$ to unity, because only the active power feed-in into the grid is remunerated. This is a proper solution for stand-alone WECs, but not for wind parks. There the Power Factor (PF) must be controlled to unity at the PCC. Reactive power management can be realised if the characteristics of all transmission elements are known.

Passive components, such as transformers and cables, also contribute to the reactive power balance of wind parks. Therefore they have to be considered in the calculation of the total power share. Based on the given wind park structure of Figure 11.21, Figure 11.22 shows an equivalent circuit of a WEC with low voltage generator, connected to the ultra high voltage level of the wind park. The WEC is the only active element and is simulated as a current source. All other parts are passive components, which are simulated with their geometry-dependent parameters. With these values the load dependent reactive power shares of the transformers and cables are calculated.

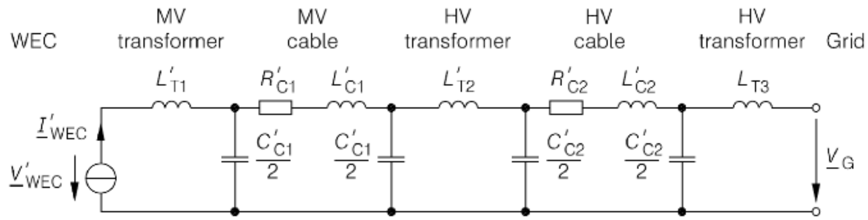



**Figure 11.22.** Equivalent circuit of a WEC with low voltage (LV) generator, medium voltage (MV) transformer and cable, high voltage (HV) transformer and cable and ultra high voltage (UHV) transformer

*Transformers*

For the calculation of the reactive power $Q$ of the transformers the relative short-circuit voltage $v_{sc}$, the transmitted active power $P$ and the rated apparent power $S_r$ is used

$$Q_{\mathrm{T}} = v_{\mathrm{sc}} \frac{P^2}{S_{\mathrm{r}}} \tag{11.16}$$

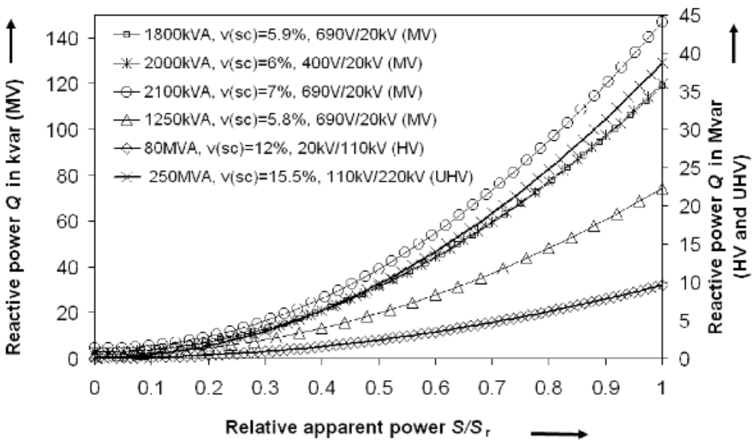



**Figure 11.23.** Load dependent reactive transformer power, left axis: medium voltage (MV); right axis: high (HV) and ultra high voltage (UHV)

With Equation 11.16 the reactive power consumption over the whole power range of the wind park is calculated for all medium voltage (MV) device transformers, the high voltage (HV) substation transformer and the ultra high voltage (UHV) transformer at the PCC. Between the HV and UHV transformer is an additional feeding from another wind park.

The calculation results are shown in Figure 11.23. It is indent, that the derived curves always show a square dependency over the relative apparent power [17, 18].

*Medium and High Voltage Cables*

Cables have both inductive and capacitive components; resistive parts can be neglected. The inductive $Q_{C,\,ind}$ and capacitive $Q_{C,\,ca}$ reactive parts are calculated from the cable length $l$ and the inductance layer $L^{'}$ or capacitive layer $C^{'}$ per length unit

$$Q_{C,ind} = 3 \cdot I^2 \cdot 2\pi f \cdot L' \cdot l \tag{11.17}$$

$$Q_{\mathrm{C,cap}} = V_{\mathrm{LL}}^{\;2} \cdot 2\pi f \cdot C' \cdot l \tag{11.18}$$

The total reactive power of the cable is then calculated

$$Q_{\mathrm{C}} = \left|Q_{\mathrm{C,ind}}\right| - \left|Q_{\mathrm{C,cap}}\right| \tag{11.19}$$

For the calculations of the reactive powers, manufacturer equivalent circuit cable data are used as summarised in Table 11.3. The reactive power consumption of medium and high voltage wind park cables over the transmitted active power is shown in Figure 11.24. It is seen, that the lowest total reactive power occurs at full load. The capacitive reactive power of the high voltage cable is higher compared to

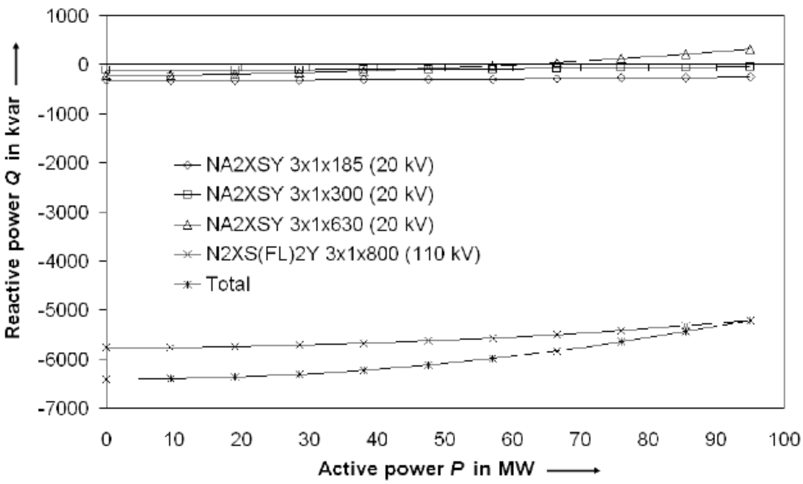



**Figure 11.24.** Reactive power consumption of medium and high voltage cables

that of medium voltage cables and determines the total cable characteristic in the wind park.

**Table 11.3.** Manufacturer equivalent circuit data of medium voltage and high voltage cables

| Voltage in kV | Cable description | Cross section in $mm^2$ | *R'* in Ω/km | *L'* in mH/km | *C'* in μF/km |
|---|---|---|---|---|---|
| 20 | NA2XSY | 3×1×185 | 0.410 | 0.37 | 0.27 |
| 20 | NA2XSY | 3×1×300 | 0.195 | 0.35 | 0.325 |
| 20 | NA2XSY | 3×1×630 | 0.063 | 0.315 | 0.43 |
| 110 | N2XS(FL)2Y | 3×1×800 | 0.03 | 0.4 | 0.22 |

*Wind Park Power Balance*

An optimised active power transmission between WEC and PCC in a wind park requires equal inductive and capacitive reactive power parts. This is not easy to realise because the reactive power share is not constant, but load dependent, and results from the summation of the reactive powers of the passive transmission elements that are represented by the transformer curves and cable curves in Figures 11.23 and 11.24. The wind park reactive power balance is calculated according to the equivalent circuit of Figure 11.22 with the reactive powers of the transformers (index T) and cables (index C). For the wind park as shown in Figure 11.21 the total balance is calculated

$$Q_{\mathrm{WP}} = Q_{\mathrm{WT}} + Q_{\mathrm{T1}} + \left|Q_{\mathrm{C1,ind}}\right| - \left|Q_{\mathrm{C1,cap}}\right| + Q_{\mathrm{T3}} + \left|Q_{\mathrm{C2,ind}}\right| - \left|Q_{\mathrm{C2,cap}}\right| + Q_{\mathrm{T3}} \qquad (11.20)$$

The complete wind park transmission system includes three transformers and two cables

$$Q_{\mathrm{TL}}(P) = \sum_{1}^{3} Q_{\mathrm{T}n}(P) + \sum_{1}^{2} Q_{\mathrm{C}n}(P) \qquad (11.21)$$

A calculation of the load-dependent reactive powers according to Equations 11.20 and 11.21 leads to the curve in Figure 11.25. It is shown that the reactive power consumption and the PF of the wind park are strongly load-dependent. A PF of unity is only reached at 50% of nominal output power. Therefore the wind park works over a wide range not optimally and reaches an optimal PF only accidentally. This leads to an unfavorable PF on the PCC and results in loss of revenue. The WECs are the only flexibly adjustable devices in the wind park. All transmission elements deliver load-dependent reactive power shares. Only a permanent PF adjustment of the WECs can guarantee the highest active power at the PCC.

Figure 11.26 shows as an example the consumed reactive power of the wind park for a flexible adjustment of the power factor on the WECs. Now is it possible to control the reactive power to zero in a wide range of relative power. The effectiveness of this control depends on the control range of the power factor of the single WECs, which may vary for different WEC technologies and manufacturers.

In Figure 11.27 the calculated control range of some WEC types with an adjustable power factor of cosφ=±0.966 is applied to the considered wind park. In this case, the reactive power can be held at zero between 34% and 84% of the rated wind park power [11].

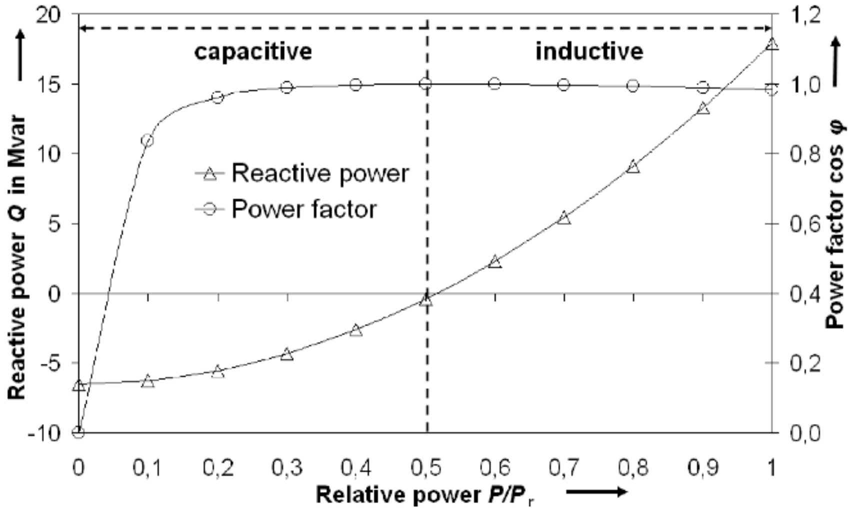



**Figure 11.25.** Reactive power consumption and power factor of the investigated wind park over relative power $P/P_r$

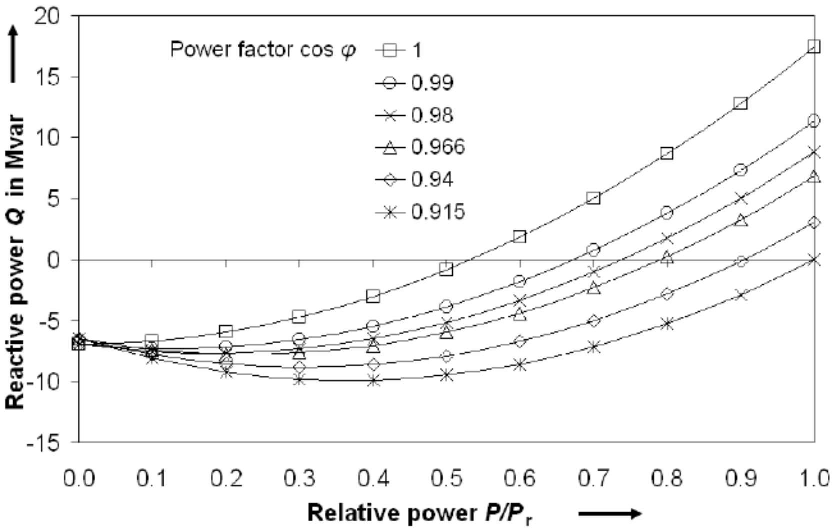



**Figure 11.26.** Calculated reactive power consumption of the wind park at variable power factor of the WECs

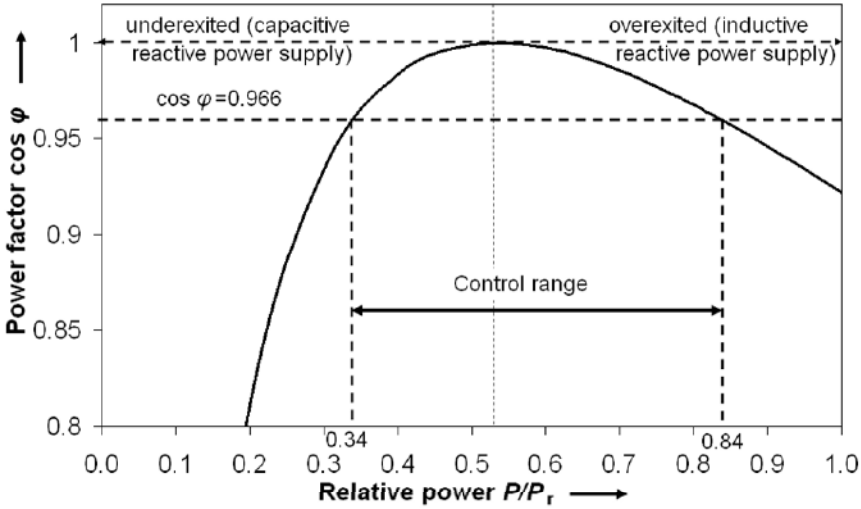



**Figure 11.27.** Control range of the wind park with flexible power factor adjustment of WECs

Meanwhile, reactive power management is state-of-the art in big wind parks with long cable distances. Before the first systems come into operation, measurements must remove all technical doubts. The results of such joint test measurements between wind park operator and utility are shown in Figure 11.28 [11]. This test should prove some defined tasks:

- Consumption of reactive power for voltage control on demand;
- Bisection of the reactive power on demand;
- Reduction of the active power generation from a current value to a defined value;
- Increase of active power after power reduction.

In Figure 11.28 the active power is visible; it doesn't changes during the reactive power change as shown in Figure 11.28b. Of course the power factor in Figure 11.28c decreases during the reactive power increase. The power quality was not reduced during the measurement interval; see Figure 11.28d,e. This topic is later considered in more detail; see Section 11.5.

For the permanent use of load dependent power management an automated control circuit is necessary. Input is the set-value of the PF. The superposition of the wind-dependent WEC, cable and transformer curves gives the actual PF. A practical implementation also requires the consideration of economic aspects. This is realised by selective use of the WECs for participation in power control, depending on their current nominal power and possible losses of active power. This idea is expressed by the box "*Economic WEC selection*"; see Figure 11.29.

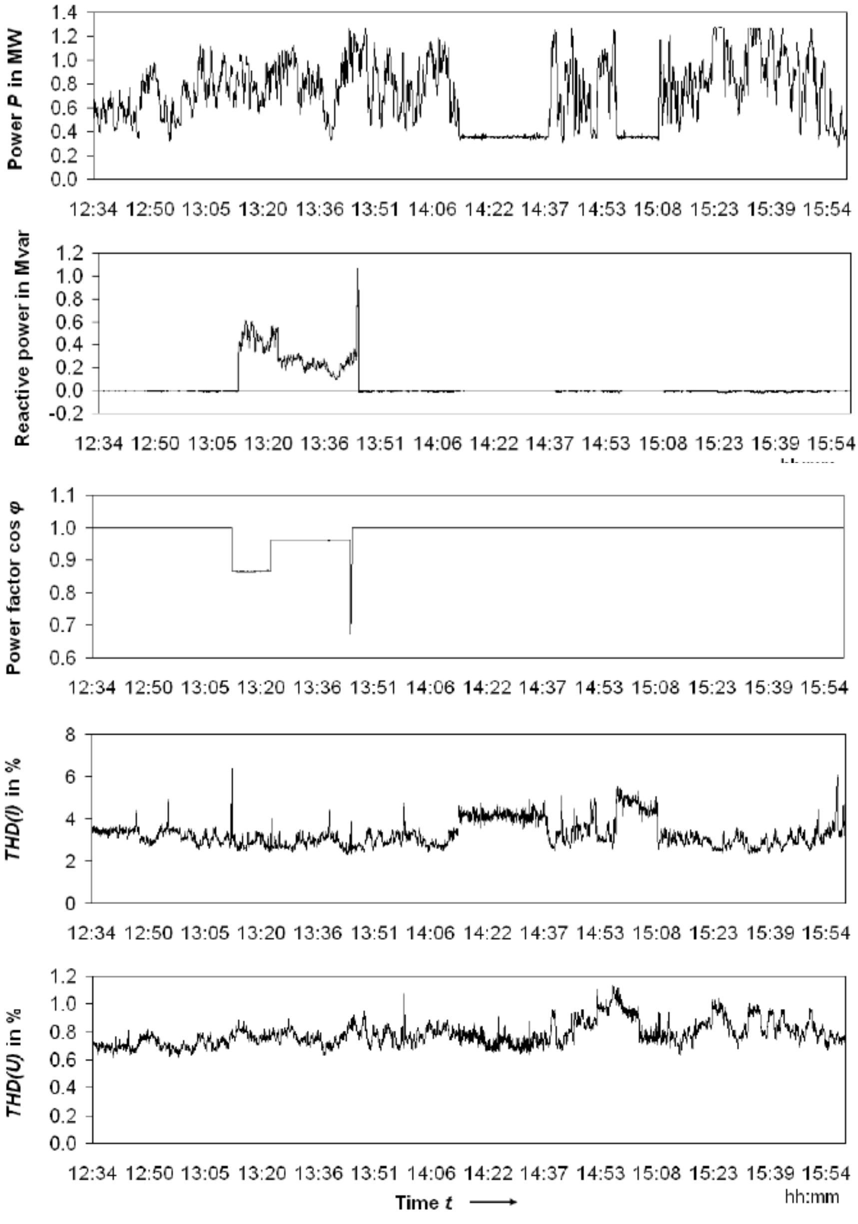



**Figure 11.28.** Measurements of active and reactive power adjustment of a WEC with a rated power of 1.5 MW. From above: active power; reactive power; power factor; total harmonic distortion of current; total harmonic distortion of voltage

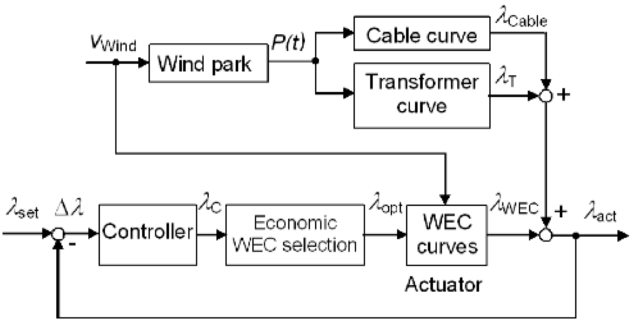
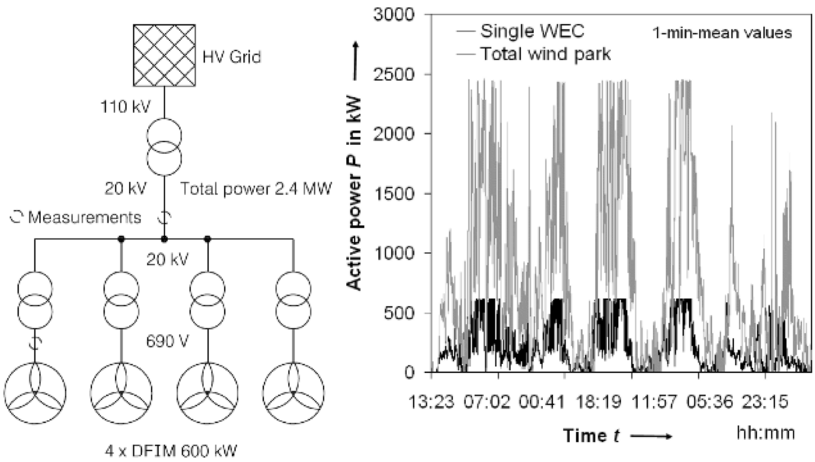



**Figure 11.29.** Structure of a load-dependent reactive power wind park management with flexible WEC power factor

# 11.5 Power Quality on WECs

## 11.5.1 Power Fluctuations and Flicker

Depending on the wind speed variation, power fluctuations occur in WECs; compare with Figures 11.7 and 11.8 in Section 11.3.3. Power smoothing arises only in a wide area. In small wind parks the total output power is mostly discontinuous; see Figure 11.30. For the depicted wind park the distance between the WECs is only 200 m.




a b

**Figure 11.30.** Power fluctuations in a small wind park: **a** wind park structure with measurement points; **b** power of a pitch-controlled 600-kW-WEC with double-fed asynchronous generator and total power of all four devices over 13 days

If the power changes, the variable current flow causes voltage drops on the grid impedance. These voltage changes cause, *e.g.*, light density changes on bulbs, which is called flicker. Hence, the magnitude of the voltage change depends on the values of the current and the grid impedance. Large power fluctuations cause large current changes; the flicker effect is strongly influenced by the power class of WECs. When a load with power $P$ is connected to the grid, current $I$ flows

$$I = \frac{P}{V \cdot \cos\varphi} \tag{11.22}$$

Every power change per time unit is equivalent to a current change $\Delta I$

$$\Delta I = \frac{\Delta P}{V \cdot \cos\varphi} \tag{11.23}$$

The resulting current through the grid impedance causes a voltage drop, which reduces the grid voltage and causes several effects on the consumer, such as power decrease or malfunction. Such voltage drops are easily visible in light sources.

*Evaluation of Flicker*

Flicker is a voltage change in the frequency range between 0.005 Hz and 35 Hz, which is evaluated with the light density changes of a 60-W-bulb visible to the human eye [19]. The light density of bulbs is proportional to the square of the supply voltage. Hence, the flicker intensity depends on the frequency and amplitude of the voltage change. It is evaluated according to the standards EN 61000-3-3, -4-7, -4-15 and IEC 1000-3-5 [20–23]. In order to understand in the next pages the most important parameters are discussed here.

Short voltage variations are detected by short-term flicker $P_{st}$, which is calculated with the flicker causing time $t_f$ in the calculation period $T_p$ of 10 min; the exponent is a standardization factor

$$P_{st} = \left( \sum t_f / T_p \right)^{1/3.2} \tag{11.24}$$

Measurement devices use weighting factors $a_i$ for the cumulative distribution of the power quantils $P_{i\%}$

$$P_{st} = \sqrt{\sum_i a_i \cdot P_{i\%}} \tag{11.25}$$

Corresponding to the standard EN 61000 the short-term flicker must not exceed the value of $P_{lt}=1$.

The long-term flicker $P_{lt}$ is calculated by a cubical smoothing of the short-term flicker over $N$=12 intervals of 10 min; it must be in line with the standard EN 61000 and not exceed the value of $P_{lt}$=0.65

$$P_{\mathrm{lt}} = \sqrt[3]{\frac{1}{N}\sum_{i=1}^{N} P_{\mathrm{st},i}^{3}} \tag{11.26}$$

Some countries, *e.g.*, Germany, have additional local regulations for flicker evaluation. There exists a limit for the long-term flicker of grid connected power plants on the low and medium voltage level of $P_{lt}$=0.46, considering the superposition effect from multiple flicker sources [24]. Corresponding to the standard EN 50160 [25] the long-term flicker during a weekly interval must be, for 95% of the time, maximal $P_{lt}$=1. Utilities are responsible for limiting the long- term flicker in their grid sections below this value independent of the number of flicker sources.

For the practical evaluation of flicker limits, the curves according to EN 61000-3-3 as shown in Figure 11.31 are applied. The flicker limits depend on the value and the repetition rate and, in addition to this, on the shape of the voltage changes. Rectangular changes cause more visible flicker effects than sinusoidal voltage deviations. Generally the curves have the same trend; this is caused by the characteristical sensitivity of the human eye. The most disturbing frequency of light density changes is at 8.8 Hz; therefore this frequency range has the lowest flicker. This flicker frequency is equivalent to a repetition rate per half period of the grid voltage of $r$=1056 min$^{-1}$

$$r = 2 \cdot f \cdot 60 \frac{s}{\min} = 2 \cdot 8.8 \frac{1}{s} \cdot 60 \frac{s}{\min} = 1056\,\min^{-1}$$

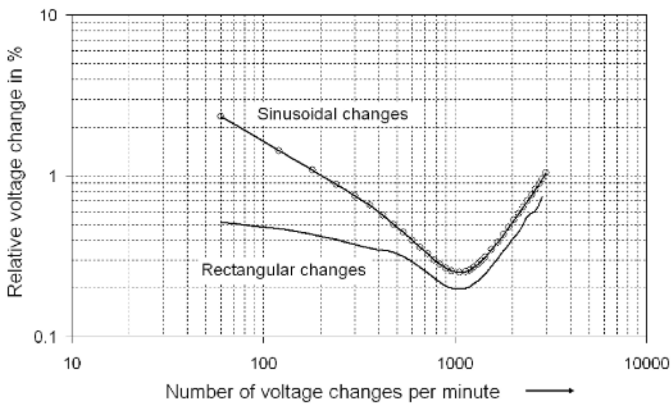



**Figure 11.31.** Flicker tolerance curve according to EN 61000-3-3, IEC 1000-3-3 for periodic rectangular and sinusoidal voltage changes (CENELEC-curve)

Flicker relevant frequencies $f_r$, caused by the tower shadow effect of a WEC with $b$=three blades at a speed of $n_r$, are calculated according to

$$f_{\mathrm{r}} = b \cdot n_{\mathrm{r}} \tag{11.27}$$

To minimize the risk of financial losses for WECs a pre-evaluation of the possible flicker emissions is required. This procedure follows the standard IEC 61400-21 [26]. It will not be amplified here; a remarkable fact is the simulation of the WEC on a fictive grid with defined properties. A variation of these properties is realized by the choice of the resistive and inductive impedance parts. Also, for WEC power quality testing, local regulations exist, *e.g.*, the FGW-standards [27]. Some of these different standards are unified to a MEASNET standard for the power quality evaluation of WECs [28].

*Flicker Characteristic of WECs*

Basically the flicker effects of WECs are influenced by the device power, the generator type and its kind of grid coupling. Flicker is generally caused by load changes due to wind speed variations, wind shear between lower and upper rotor blade tip and tower shadow effects. The last two items are only important for high rotor diameters in the megawatt power class. In the 5-MW-class the WECs are equipped with a single blade control to minimize the tower shadow effect.

Stall-regulated, constant-speed devices (see Figure 11.19a) transmit all wind changes as power changes to the grid. Therefore this WEC type causes the highest flicker emissions, which do not exceed the flicker limit values only in small power classes below 1 MW. Modern WECs with pitch-regulated power limitation and variable speed control have typical curves of voltage changes as shown in Figure 11.32 for a 600-kW WEC.

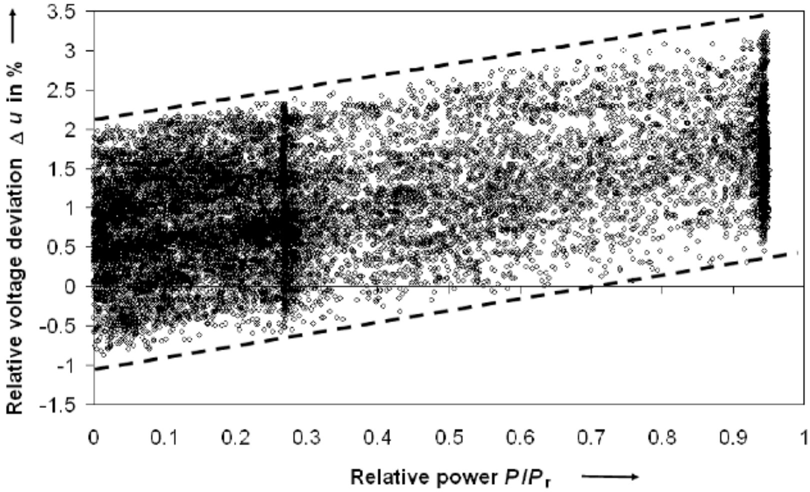



**Figure 11.32.** Typical curve of the relative voltage deviation over the relative power, measured on the 690 V level of a pitch-controlled 600-kW WEC with double-fed induction machine, 1-min mean values, measured over 13 days

Other WEC types in the megawatt power classes show similar trend curves to the measured wind turbine. With increasing relative power increases the relative voltage deviation $\Delta U$

$$\Delta u = \frac{u(t) - u_{\mathrm{rG}}}{100} \tag{11.28}$$

For an estimation of the grid disturbance potential the *k*-factor is used, which is calculated from the maximal current $I_{max}$ and the rating current $I_r$

$$k = \frac{I_{\max}}{I_{\mathrm{r}}} \tag{11.29}$$

With this factor the stress on the transmission elements and also the potential flicker load can be estimated. The *k*-factor is set to one if the generator is a synchronous type or the WEC is grid connected with a power electronic converter. For directly grid connected induction machines with speeds of 95–105% of the synchronous speed, *k* is set to four. The value is *k*=8, if the starting current is unknown; for a known starting current *k* is calculated from the ratio of the starting and the rating current.

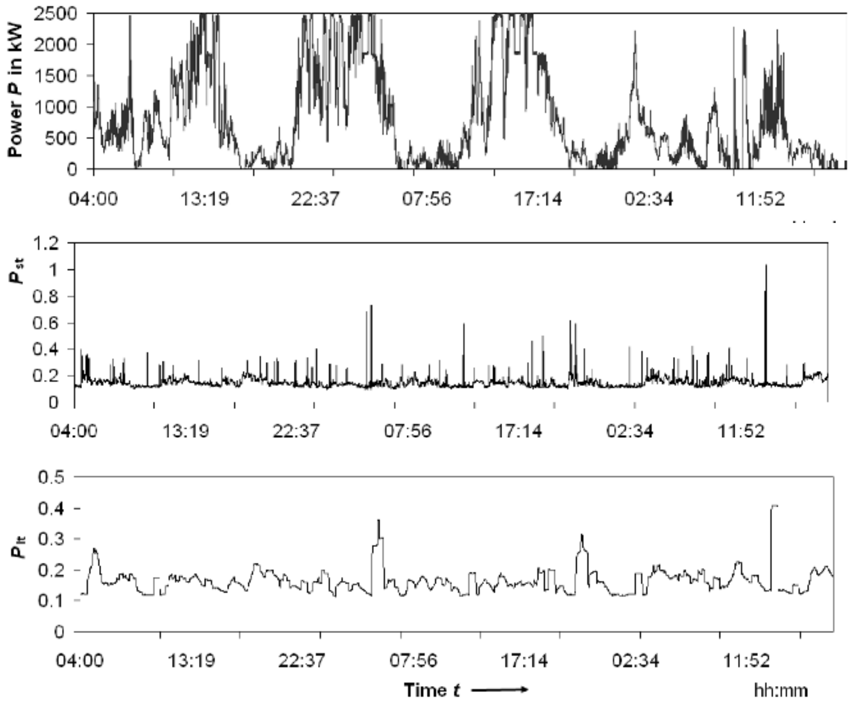



**Figure 11.33.** Measurements over 10 days on the 20 kV-level of a wind park with a total power of 2.4 MW, see Figure 11.29a, 1-min-mean values. *From the top*: power; short-term flicker (limit value $P_{st}$=1); long-term flicker (limit value $P_{lt}$=0.46)

The flicker generation is also influenced by the grid impedance, the value of which depends strongly on the voltage level. The grid impedance decreases with increasing voltage level. A guiding value of the ratio between the relative impedances of the low, medium and high voltage level is 100:10:1, which may vary depending on the installed components. Compared to the low voltage connection, the flicker values of WECs are always smaller on the medium voltage side because of the lower grid impedance and the low currents. Figure 11.33 shows measurement results of a 10-day measurement interval on the 20-kV level of a wind park with 2.4 MW power. In Figure 11.33a the power over time is depicted. This curve shows some strong fluctuations, which result in short-term flicker values according to Figure 11.33b. It can bee seen that the long-term flicker in Figure 11.33c is always smaller than the short-term values because of the cubical smoothing in its calculation according to Equation 11.27. The measured wind park does not exceed the flicker limits. In practical grid measurements it is mostly difficult to assign the measured flicker values clearly to their sources. A promising method is the measurement of the existing flicker level in the grid with disconnected WEC. If a power quality assessment is necessary, such pre-measurements should be carried out over the full planned time interval to avoid later misinterpretations of the results and proposals for supposed improvements. A possible feature for the detection of the flicker direction is currently not applied in the existing measurement devices.

*Reduction of Flicker*

There are possible measures on the grid side and on the consumer side to reduce the flicker level within technical limits. On the PCC the following conditions should be considered during the planning of a wind park project:

- Sufficient short-circuit power on the PCC;
- Distribution of fluctuating loads to different PCCs;
- No simultaneous load deviations on the same PCC;
- Limitation of power oscillations between wind parks.

Often the grid conditions are fixed due to limited installation area of a wind park. Then the only choice is to find a more distant PCC with a higher short-circuit power. This will result in higher costs. A split of the wind park to different PCCs is also applicable to limit the simultaneous power changes.

Basically the flicker is reduced by the decrease of the grid impedance and a decreasing current change. A lower grid impedance can be realized by:

- Increased grid meshing: not used practically because of high costs;
- Use of transformers with higher short-circuit power: used if the operation losses do not increase;
- Applying a higher voltage level: frequently used for WECs in high power classes or wind parks.

On the side of the (active) consumers, such as WECs, the flicker effect in the grid can be reduced by limitation of the current fluctuations during starting events and the power fluctuations caused by wind changes. These demands require their consideration in the technical concepts of the WECs, which therefore can be equipped with:

- Soft starters for WECs with constant speed control: they use mostly thyristor circuits; see Figure 11.19a;
- Voltage-source power electronic converters with high capacity values in the DC link for the damping of power fluctuations;
- Zero-current synchronisation control during the grid switch-on;
- Dynamic compensation of load changes with several kinds of active filters; this methods is technical possible, but not applied practically because of the high costs.

A high flicker level is often a reason for the non-approval of wind parks by the utilities. Sometimes they give only a time-limited grid connection allowance until a measurement certificate exists.

### 11.5.2 Harmonics

Non-sinusoidal functions can be split with the FOURIER-transformation into parts of sine and cosine functions. These shares are multiples of the basic oscillation and are called harmonics. In the European transmission system the fundamental frequency of 50 Hz is the first harmonic. The *n*-th integer multiple of the basic frequency is the *n*-th harmonic. If the multiplier is a fraction, the result is an interharmonic. The interharmonic parts below the basic frequency are called subharmonics. Even though all kinds of harmonics are only results of a mathematical split time function, in practice "*measured*" harmonics are referred to because of device internal calculations. The harmonic content describes the deviation from the ideal sinusoidal function.

*Cause of Harmonics*
Harmonics occur if the current or voltage is non-sinusoidal. Basically non-linear loads, pulsed voltages of converters with PWM or switching events in general are the reason for such function shapes. Because of the direct relation between some kinds of harmonic types and their causes, it is possible to draw conclusions about the cause from the measured harmonics.

Even numbered harmonics arise only if the time function is half-wave unsymmetrical. Such asymmetries appear as transient stages at fast load changes or as permanent effects at unsymmetrical control of power electronic converters. Faulty current measurements can also generate such problems. All these described possibilities can arise in WECs. Subharmonics are produced by periodical switching events with variable frequency. Interharmonics are generated by periodical switching processes, when the frequency is not synchronized to the fundamental frequency. This happens at low and high frequency switching, asynchronous switching of power electronic converters, matrix converters or devices with burst firing control.

Some relations between the signal properties and the result of the harmonic analysis can be seen:

- The steeper the signal the higher the generated frequencies;
- Periodic signals deliver discrete spectra;
- Non-periodic signals deliver continuous spectra.

*Evaluation of Harmonics*

Current and voltage harmonics are evaluated according to IEC 61000-3-4 [29]. The most important IEEE power quality standards are also listed in the references [30–34]. Relevant harmonic parameters are:

- Values of the single harmonics;
- THD of current or voltage;
- Partial Weighted Harmonic Distortion (PWHD) of current or voltage.

Beside these parameters, sum parameters for the separated evaluation of the even and uneven harmonic parts also exist, which are not considered here because of their absence in the power quality standards for WECs.

Whereas the THD of current shows the influence of the whole-numbered current multiples of the base frequency, the PWHD of current evaluates the influence of the current harmonics of higher orders. These sum parameters are calculated with the single harmonic current parts $I_n$ and the first harmonic current $I_1$, the same calculations are possible for the voltage

$$THD(I) = \frac{\sqrt{\sum_{n=2}^{40} I_n^2}}{I_1} \tag{11.30}$$

$$PWHD(I) = \frac{\sqrt{\sum_{n=14}^{40} n \cdot I_n^2}}{I_1} \tag{11.31}$$

Up to now, no international standard exists with defined sum parameters for interharmonic evaluation; they are only considered as flicker relevant voltages in IEC 61000-2-4 and -2-12 [35, 36]. Only some countries have local standards for the limitation of interharmonic currents and voltages.

If measurements are applied, attention should be paid to the maximum frequency resolution of the device and the current and voltage probes, which should be at least twice as high as the fastest measurement value. Corresponding to IEC 61000-4-30 [37], the measurement interval must be over 10 periods of the grid voltage.

The internal Fast Fourier Transformation calculates the multiples of the device basic frequency. This basic frequency $f_b$ is derived from the sampling frequency $f_{sa}$ and the storage depth $d$. For a typical storage depth of 1920 points and a sampling frequency of 9.6 kHz we obtain a frequency resolution of 5 Hz

$$f_b = \frac{f_{sa}}{d} = \frac{9.6\,\text{kHz}}{1920} = 5\,\text{Hz} \tag{11.32}$$

A frequency resolution of a tenth of the grid frequency is useful because of the required 10-period-interval. If the measurement channels use a joined analog/digital converter, the frequency resolution decreases with increasing channel use. For long-term measurements the storage capacity of the device is important, depending on the selected frequency resolution and the measurement time.

*Harmonic Generation Rules and WEC Specialities*

The generation of harmonics follows known basic rules:

- Characteristic harmonics as multiples of the pulse frequency of PWM converters;
- Grid commutated power electronic converters produce current harmonics depending on their pulse number $p$;

  $$I_n = m \cdot (p \pm 1) \quad m = 1, 2, 3, \ldots \tag{11.33}$$

- Harmonic side bands by amplitude modulation of basic and pulse frequency in self and grid commutated power converters;
- Interharmonics $f_\mu$ arise as side bands of characteristic harmonics of PWM converters, they are calculated with the pulse number $p$, the load frequency $f_l$ and the harmonic order $n$;

  $$f_\mu = n \cdot 50\,\text{Hz} \pm k \cdot p \cdot f_l, \quad k = 1, 2, 3, \ldots \tag{11.34}$$

- Even harmonics due to asymmetries, caused by control faults;
- Interharmonics due to control actions;
- Interharmonics with the frequency $f_{n,m}$ due to the back-to-back configuration of two converters, calculated in line with IEC 61000-2-4 with the power converter pulse numbers $p_1$ and $p_2$ and the input $f$ and output $F$ basic frequency, for $k_2$=0 is $f_{n,m}$=$f_n$ and only harmonics arise;

  $$f_{n,m} = \left[(p_1 \cdot k_1) \pm 1\right] \cdot f \pm (p_2 \cdot k_2) \cdot F \quad k_1, k_2 = 0, 1, 2, 3, \ldots \tag{11.35}$$

- 5/7 harmonics as compensation effect of standard three-phase PWM converters, if the grid voltage is distorted [38].

In addition to the basic rules, specific harmonics often arise, which are typical, but not limited to WECs:

- Interharmonics due to generator pole switching, if generators with two pole pairs are applied;
- Interharmonics due to the speed-depending frequency conversion between rotor and stator of DFIM [39];
- Harmonics due to the slot numbers of the generators, if one part of the generator is directly connected to the grid, depending on the speed; 1.5

MW-generators have, *e.g.*, slot numbers of $N_s$=72 on the stator and $N_r$=60 on the rotor;

- Harmonics due to resonance effects [40];
- Non-characteristic harmonics due to grid impedance unbalance [41].

*Harmonic Characteristic of WECs*

The limited switching frequencies of the frequency converters causes distortions on the output currents of the WECs. These distortions are evaluated with Equation 11.28. Its height is proportional to the ratio of the grid impedance values $R_G/X_G$ and inversly proportional to the PMW pulse frequency. If the THD of current values of a PMW converter are allocated to the relative output power, we obtain a curve as depicted in Figure 11.34. It shows a characteristic graph with the function

$$THD(I) \sim \frac{1}{P} \tag{11.36}$$

This typical curve shape occurs independently of the voltage level and is valid for single WECs and also for wind parks. It is caused by the structure of the calculation formula in Equation 11.30, because the harmonic content is always referred to the fundamental wave, which increases with increasing output power. For the mathematical description of the typical measured curve shape of the THD of current over the relative power of PWM converters, the parameters *a* and *m* can be used [11]

$$THD(I) = f(P) = ax^{-m} \text{ with } x = \frac{P}{P_r} \tag{11.37}$$

The parameters *a* and *m* are variable; they are influenced by the value of the grid impedance, the PWM converter switching frequency, installed grid chokes and filters. Table 11.4 shows the calculated parameters of five WECs. The allocation of such trend functions is only possible if the THD of current varies only slightly.

**Table 11.4.** Parameters *a* and *m* according to Equation 11.37 obtained from measured THD(*I*) curves of 1.5 MW WECs

| WEC type | Generator type | $THD(I)_{max}$ in % | $THD(I)_{min}$ in % | *a* | *m* |
|---|---|---|---|---|---|
| 1 | DFIM | 90 | 4 | 2.29 | 0.97 |
| 2 | DFIM | 50 | 1 | 0.99 | 1.10 |
| 3 | DFIM | 100 | 3 | 2.80 | 0.89 |
| 4 | DFIM | 450 | 8 | 4.46 | 1.12 |
| 5 | SG | 130 | 5 | 3.93 | 0.75 |

DFIM double-fed induction machine, SG synchronous generator, Total Harmonic Distortion of current

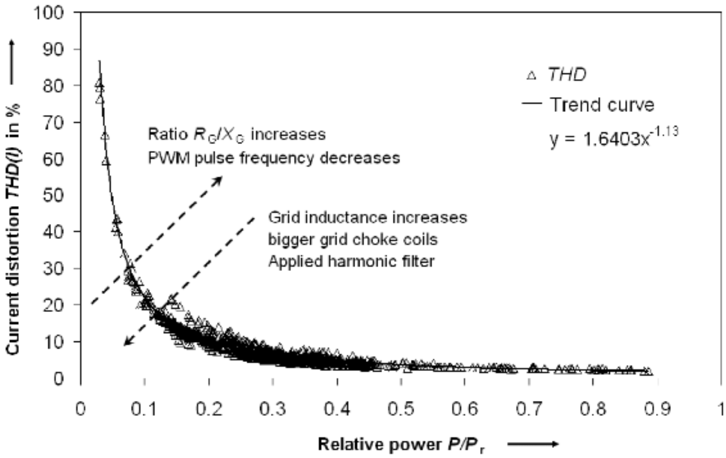



**Figure 11.34.** Total harmonic distortion of the current THD(*I*) on the 20 kV-level of a wind park

All described effects are visible in Figure 11.34, which also shows the calculated trend curve of the measured values. If the trend curves of WECs are known, countermeasures can be applied more easily, *e.g.*, the rating of passive harmonic filters or the design and programming of active filters.

*Use of Harmonic Superposition Effects*

Harmonics can be minimised by using the superposition effects. If harmonics are shifted to each other, their sum may be reduced or reinforced. Therefore the superposition of two sinusoidal functions with the same normalised amplitude of one is considered

$$f_{\Sigma} = y_1 \sin(\omega t) + y_2 (\sin \omega t + \varphi) \qquad (11.38)$$

These functions can be shifted against each other in small time or angular steps. Depending on the shifting angle $\varphi$, the sum of the two single amplitudes is calculated. This is realised for the fundamental wave and also for their harmonic frequencies. Figure 11.35 shows the calculation results for the fundamental frequency and the harmonics of order $n$=3, 5, and 7. It is very clear that the sum of the two fundamental waves from angles between zero and 120° is higher than the single wave amplitude and from 120° to 180° it decreases. As a general result, the calculated sum function has spans with decreased and increased amplitude, compared to the amplitudes of the single functions. The range, in which the amplitude sum of the two normalised functions increases, can be described using the periods $T_n$ of the harmonics [42]

$$m \cdot \left( -\frac{T_n}{3} \right) \leq f_{\sum n} \leq m \cdot \left( \frac{T_n}{3} \right) \text{ with } \; n \in \Re, m = 1, 3, \ldots . \qquad (11.39)$$

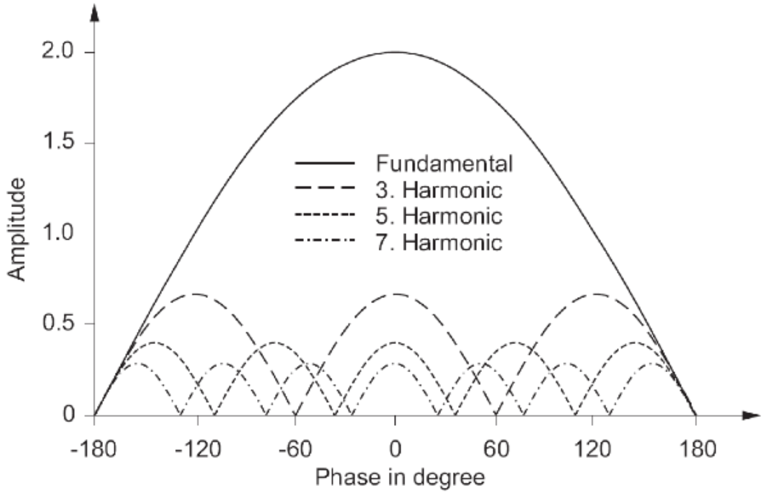



**Figure 11.35.** Amplitude sum of respectively two functions with normalised amplitudes *vs* shifting angle $\varphi$, results for the 1st, 3rd, 5th and 7th harmonic

A decrease of the sum amplitude of the respectively two amplitudes occurs in the remaining ranges

$$f_{\sum_n} \leq \pm\ m \cdot \left( \frac{T_n}{3} \dots \frac{2T_n}{3} \right) \text{ with } n \in \Re, m = 1,3,\dots. \tag{11.40}$$

The resulting superposition rule of two functions with the same period is obvious

$$f_{\sum_n}(t) = 2 \cdot \left| \sin\left( \left( 0.5 \cdot \omega \cdot t \right) \cdot n \right) \right| , n \in \Re \tag{11.41}$$

This function is valid for the superposition of two equal functions of any frequency. From Figure 35 it can be concluded that the attenuation of harmonics at small shifting angles is more probable if the order and therefore the frequency is higher. For that reason the third or fifth harmonic will not be so attenuated at small shifting angles as high order harmonics.

If the number of harmonic sources is higher than two, the problem becomes more complex. The variance increases with the number of connected harmonic sources. Whereas the sum of two independent functions delivers definite results, the sum of more magnitudes with independent shifting angles brings scattered results. The reasons for different shifting angles and different power factors cosφ of more functions can be, *e.g.*, two-point current control with different bandwidth, different control modes or load changes. To obtain values for these cases, the probability of increase and decrease must be calculated.

A popular empiric relation used for the superposition of multiple harmonic sources of WECs is given by [43]

$$THD(I)_{\Sigma} = THD(I)_n \cdot \frac{1}{\sqrt{n}} \tag{11.42}$$

Generally the harmonic superposition delivers effects due to the shifting angle arising between harmonic current sources. This may be caused by the complex grid impedance between two sources or by the phase shifting of the sources itself. Both effects can be used for the decrease of current harmonics. A typical application of the shifting of harmonic sources is the use of phase-shifting medium voltage transformers in WECs. Then the superposition problem is always reduced to a two-source problem with the alternating use of different transformer vector groups Dyn5 and Dzn6. This causes a phase shift of $\varphi$=30°. In wind parks this procedure is often applied because the WECs are mostly of the same power class and deliver a similar output power. Due to the fact that the superposition of harmonics is described algebraicly, it can be considered during the wind park planning.

*TSO Requirements*
Because of the increasing power share of the wind energy, more and more Transmission System Operators (TSO) demand a participation of the WECs in additional grid services. These requirements are country dependent; only the standard IEC 61400-21 gives consistant frame of technical demands [26]. In addition to this, the local utilities are free to issue other additional technical guidelines. Some basic features are:

- Frequency dependent control of the active power flow;
- External control possibility of the active power by the TSO;
- Grid voltage control by adjustable reactive power flow;
- Low-voltage ride-through during grid short-circuit events.

All these demands are fixed in diagrams which are part of the technical guidelines. Figure 11.36 shows an example for some grid system services demanded by German transmission system operators. In Figure 11.36a is the power curve over the frequency shown. WECs must not disconnect from the grid within the frequency range between 47.5 Hz and 51 Hz. The minimum duration of the power generation during grid frequency deviations is depicted in Figure 11.36b; Figure 11.36c shows the voltage dependent reactive power supply.

Also the WEC-behavior during grid short-circuit events is clearly defined in the local TSO guidelines. Figure 11.37 shows the low-voltage ride-through curves as required for the passing of grid failure events. The reason for such demands is the desired grid assistance by the WECs. At falling frequency a certain output power must supplied by the devices; see Figure 11.37a. Depending on whether the grid short-circuit is close to the generator terminals or remote at the wind turbine, the reaction on the resulting voltage drop must be different; see Figure 11.37b,c.

Such demands anticipate the necessary properties of completely decentralized energy systems with a high supply share from renewable systems in the future. Especially the possible voltage control is a useful feature of the decentralised power generation with WECs [47, 48], because the voltage cannot be controlled centralised. In future the participation on the primary grid frequency control is also foreseen.

All additional grid service requirements cause additional technical efforts for the WEC manufacturer. If a voltage control is applied, the necessary reactive power must flow over the grid side frequency converter. This means that this converter has to be rated higher compared to only the active power supply. Therefore the amount of reactive power is given exactly for each operation point of the WEC; see Figure 11.38.

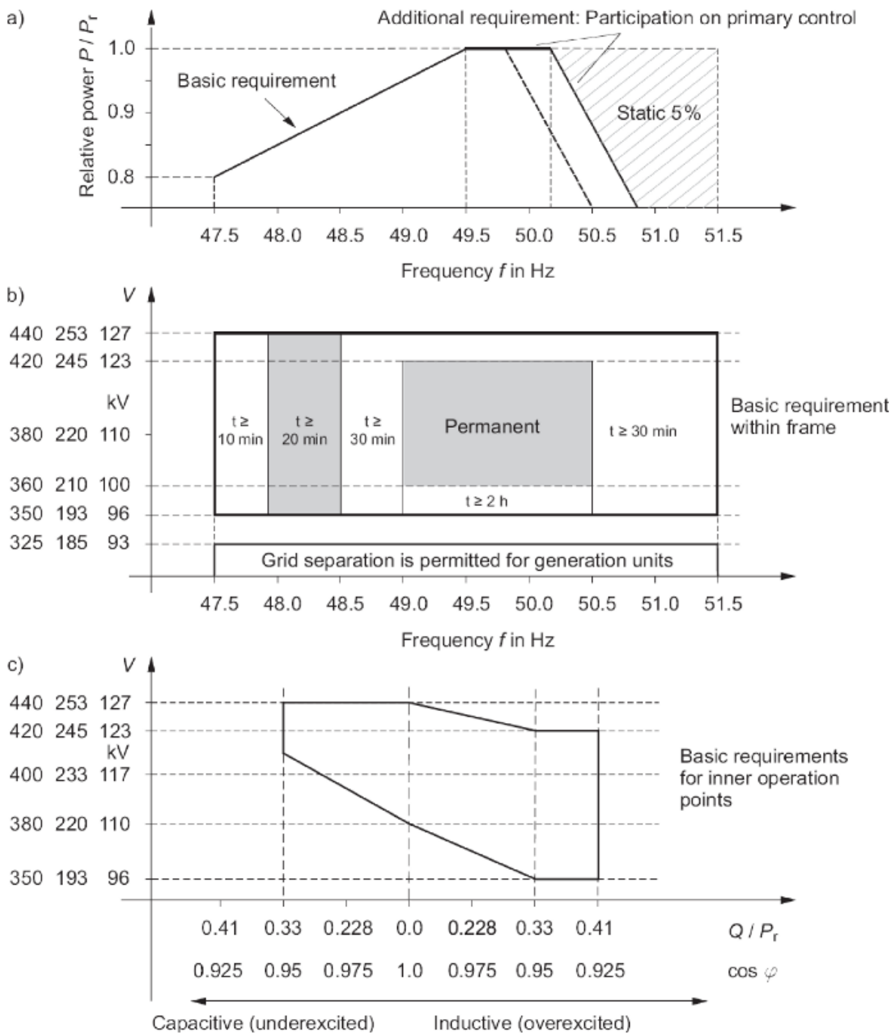



**Figure 11.36.** TSO requirements for WECs as applied in Germany [44]: **a** power curve; **b** supply duration; **c** reactive power supply

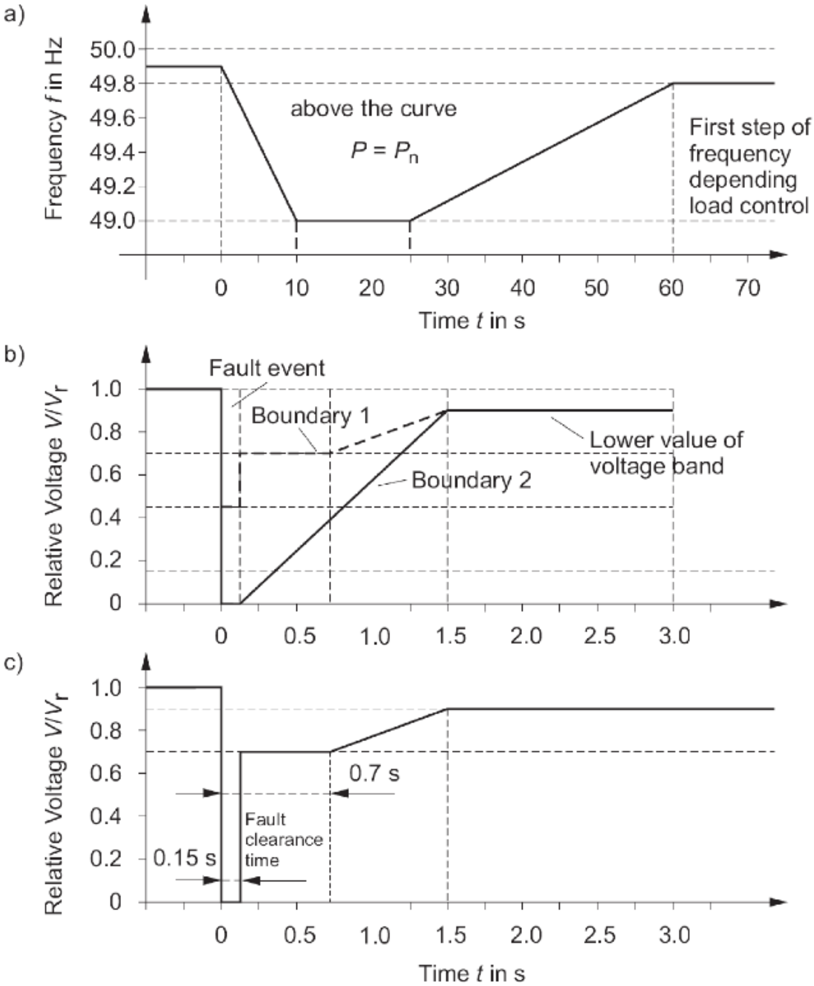



**Figure 11.37.** German ride-through guidelines for: **a** low frequency; **b** low-voltage [44]; **c** short-circuit close to generator [45]

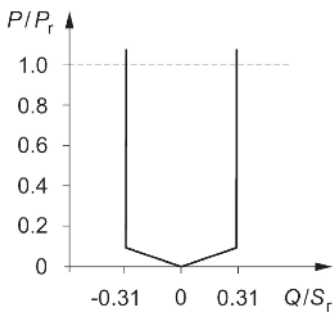



**Figure 11.38.** Reactive power range of a WEC [46]

## 11.6 Offshore Wind Energy

### 11.6.1 Installation Numbers and Conditions

In 2007 a global capacity of over 827 MW was installed in offshore wind parks, most of them in Europe. More than 45 GW are planned in Europe, thereof over 27 GW in Germany and over 10 GW in Great Britain. Also in North America a capacity of 1 GW is planned. These numbers show that the offshore market can be one of the most successful energy stories of the current century. A reason for the present global offshore power distribution with a European preponderance is the necessary occurrence of some good offshore conditions: good wind speeds, flat shore grounds, near grid connection points and adequate feed-in tariffs.

The high economic interest in WEC offshore technology is triggered by the good wind conditions on sea, which allows a doubling of the yearly energy generation compared to onshore wind parks and also the use of new installation areas. In contrast the installation effort is much higher and requires, unlike onshore WECs, special sea cranes.

### 11.6.2 Wind Park Design

Depending on the installation place, different technical requirements for the WECs occur. Offshore devices are evaluated corresponding to their:

- Reliability: failure frequency, maintenance efforts;
- Life time: erosion, corrosion resistance, load limitation;
- Technical risk: use of approved concepts;
- Installation costs: possibly low nacelle weights for low grounding efforts, low technical complexity;
- Energy yield: use of pitch-controlled wind turbines;
- Control possibilities: active and reactive power, grid services;
- Power quality properties: harmonics, flicker.

There are diverse possibilities for internal grid structures in wind parks. The design is influenced by the voltage type and level of the existing PCC and the installed generator type and voltage level of the WECs. Usable combinations of these three technical degrees of freedom result in the following five systems:

- Low voltage (LV) generators, connected to a medium voltage (MV) wind park grid with fixed grid frequency, high voltage (HV) AC onshore connection;
- As the first bullet with an HVDC land connection;
- As the first bullet with MV generator; for the generator see Figure 11.3;
- As the first bullet with MV generator;
- As the first bullet with a variable frequency in the internal wind park grid.

Also the speed control can be varied for fixed or variable speed system and it can be realised as a single or group control with to relatively smooth wind conditions. Radial or ring distribution systems similar to land installations are used as internal wind park grids. Up to a wind park power of 120 MW, two-winding transformers are used; above 120 MW up to 300 MW three-winding types are applied.

### 11.6.3 Transmission Types

For the energy transmission between offshore wind park and land substation, three systems are usable: the three-phase HVAC, a multi-phase HVAC or the HVDC connection. Their technical properties are listed in Table 11.5. Figure 11.39 shows the principle drawing of the three transmission systems. With the idea of six-phase HVAC systems the limited transmission capacity can be doubled [49]. This is only possible up to a maximum transmission distance due to the reactive cable power.

**Table 11.5.** Parameters of the transmission systems [50]

| Parameter | HVAC three-phase | HVDC |
|---|---|---|
| Power per cable in MW | 180–250 | 300–350 |
| Maximum distance in km | 80–120 | Unlimited |
| Economical transmission voltage in kV | 150 | 150 |
| Cable available for voltage in kV | 170 | 150 |
| Cable diameter in mm | 200 for three conductors | 90 for one conductor |

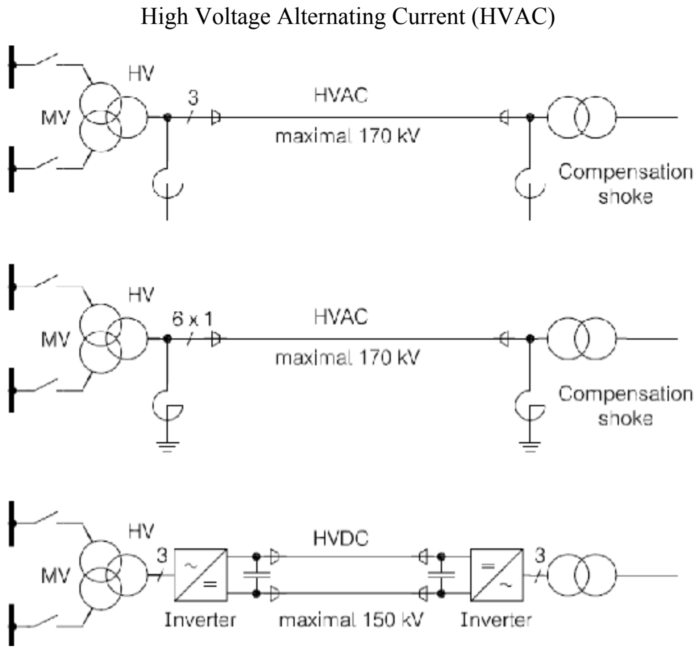



**Figure 11.39.** Transmission systems between offshore wind park and land substation. *From the top*: three-phase HVAC; six-phase HVAC; HVDC

**Table 11.6.** Advantages and disadvantages of high voltage AC and DC transmission systems

| System | Advantage | Disadvantage |
|---|---|---|
| HVAC | • Proven technology<br>• Low space required<br>• No cost intensive power electronics<br>• High reliability | • High cable costs<br>• Reactive power of cable causes losses, requires compensation<br>• Ground heating<br>• Harmonics transmission<br>• Limited length |
| HVDC | • Unlimited length<br>• Low cable costs<br>• No compensation required<br>• Usable as static compensator<br>• Electrical decoupling of systems<br>• Free choice of wind park frequency<br>• Independent active and reactive power control<br>• High power quality<br>• Black start (grid building) capability | • No reference for wind parks<br>• High costs for power electronics<br>• Power electronic losses<br>• No electrical coupling between wind park and grid, no contribution to grid stability possible<br>• A lot of space necessary |

In Table 11.6 the advantages and disadvantages of the HVAC and HVDC systems are compared. Both transmission types are planned for future offshore wind parks, depending on their distance to the land substations. A wind park project mostly starts with a small pilot project with some WECs and will then be finished with full power in a second stage if the pilot project was successful. This makes the decision for the suitable transmission system difficult at the beginning.

## 11.7 Future Requirements and Developments

### 11.7.1 WEC Types

Considering future developments, voltage level, generator design, power electronic design and energy conversion strategy can be discussed. Of course the low voltage WEC types existing today will be further developed in future. This means novel generators and power electronic converters with higher output power will be on the market.

If the unit power increases up to 8 MW or 10 MW either the current or the voltage may increase. A conventional solution is the system development at the low voltage level by upscaling the generators and PWM converters. Medium voltage solutions bring decreasing currents, a smaller generator design and a lower nacelle weight which is important mainly for offshore wind parks. Currently the available medium voltage equipment for WECs is limited to only some supplies.

This hinders the development from the low voltage to medium voltage system approach.

In addition to this, special designed generators are mostly used in WECs. Double-fed induction generators or synchronous generators with electrical or permanent magnet excitation dominate the market. Whether costly special generators should be used or standard generators in combination with costly power electronics, see Section 11.4.1. The use of completely new generator designs, like transversal flux machines, has to now not been convincing in terms of manufacturing costs and efficiency. WEC concepts equipped with multi generators have also been discussed, but not realised yet.

Considering the energy conversion chain, only one conversion step between mechanical and electrical energy is necessary in WECs. Following this idea, the combination of a hydraulic gearbox with a simple standard synchronous generator seems to be a promising concept for the future. In this case no special designed generator or power electronic is necessary, but the gearbox efficiency has to be as high as for conventional gears.

### 11.7.2 Energy Management, Storage and Communication

The aim of a large-area Energy Management System (EMS) is to optimize power flow in the transmission system. This includes the control of power generation, power consumption, import and export of power and energy storage. This can only work properly if the different generation units cooperate within the electrical grid. With increasing power generation from renewable units a transformation of the transmission system is necessary. Beside the construction and modernization of the grid the implementation of "intelligent" properties is also required to reach the "*SmartGrid*" status. All system services have to be carried out by the decentralized power units.

If the EMS cannot adapt the generated and consumed power, energy storage is required. For use in transmission systems, high storage capacities are necessary. Such energy amounts can be handled today only from pumped-storage power stations or compressed air storage. High storage potential can be made available if consumer control is applied. This is mainly usable with industrial cooling in cold storage houses. By controlled disconnection and connection of such units, a storage capacity of some 10 GW is disposable, *e.g.*, only in Germany 40 GW [49]. This method should be used if the storage requirements hinder the further development of a necessary transfer of the energy supply [51].

In a future grid every unit should be able to work in four states: generator, load, flushing storage or charging storage. Between all units there must be an information exchange to secure the system stability. WECs are able to meet external control requirements and participate in the grid control; see Figure 11.28 in Section 11.4.4. For the participation in the grid services a controllable interface is necessary. In addition to this, the external control requirements may call for a communication interface. Both have to be consistent for all generation units. The communication standard IEC 61850 [52] for substations is not sufficient for WECs; because of this a separate standard IEC 61400-25 [53] and a draft for the control and monitoring of decentralised generation units IEC 57/660/NP are in cause of preparation.

## 11.8 Economics and Reimbursement

Two economic strategies for the remuneration of energy feed-in compete; first, the increased feed-in tariff based on certain laws as in Germany, Spain or France and, second, the quota system model for energy projects as applied in Great Britain. The most important value is the realised feed-in payment per kWh. Law-based tariffs generate a high increase of the installed wind power capacity. Because of a higher technical and financial risk the offshore installations stay behind expectations. Within the last 15 years the costs per kilowatt have been reduced by 50% from 1,600 to 800 €/kW. This concerns standard wind turbines in the megawatt power range. New developed devices, especially offshore WECs, are more costly because of their improved technology and more auxiliary components. Generally, within the last two years, a cost increase due to a higher market demand and increasing material costs has been observed. Currently the energy generation costs of WECs are in the range of 8–9 €cent/kWh for onshore and 6–8 €cent/kWh for offshore installations. At the same time, the European feed-in tariffs differ significantly for onshore and exceptionally for offshore wind parks. Figure 11.40 shows a comparison of the feed-in tariffs of different European countries. In the newest German amendment of the renewable energy law an additional bonus is foreseen with 0.7 €cent/kWh on the medium voltage level and 1.4 €cent/kWh on the high voltage level for system services like participation in grid voltage control.

The difference between the feed-in tariffs and the energy generation costs, reduced by interest payments and maintenance costs, is the estimated net profit. Naturally wind park projects with higher net profit are preferably installed. In the offshore market there is also a high financial imbalance. According to a study by a

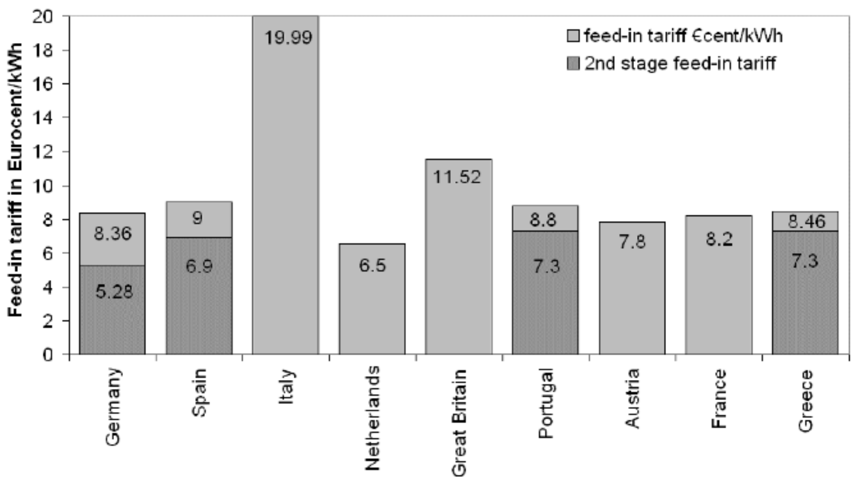



**Figure 11.40.** European feed-in tariffs of onshore WECs

European accounting company, is the imbalance for future offshore projects is very high with an average internal rate of return of 1.2% in Germany and 19.5% in Great Britain [54]. Such financial imbalances lead to supplier concentration in countries with advantageous conditions. Due to limited manufacturer capacities this can hinder offshore development in countries with lower rates of return.

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