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Energy Yield, Power Quality and Grid Integration of Wind Energy Converters

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Abstract - Because of the limited fossil resources and the need to avoid emissions and toxic waste the future energy supply will be based on a large portion of renewable energies: wind-, solar-, biomass- and geothermal energy. Focus is on the utilization of wind energy coming from onshore- and offshore-sites. Generating electricity from wind is state of the art and feeding large amounts of wind power into the electrical grid will create some additional problems. Suggestions concerning energy storage will be made and the problem of power quality is discussed.

Keywords: wind energy, wind park, energy yield, total harmonic, distortion, power quality

1. Introduction

The acquisition of wind energy is encouraged by EU authorities in a variety of European countries [1]. In total about 24 GW of generating capacity are presently installed. By the end of 2004 more than 16 GW of wind energy converter power has been installed in Germany. The future potential for onshore systems is 12 GW plus 7 GW from repowering. For comparison: All 19 nuclear power plants in Germany have a total installed power of 19.4 GW.

If we assume for the full-load-hours per year an average figure of 1500 h, the total energy is about 20 TWh/a or close to 4 % of electricity generation in Germany.

As most of the favourable wind sites are already exploited the focus is now on offshore wind farms. The advantages of going offshore are that the wind speed is higher, the wind is blowing steadier and visual impact is much smaller. Examples of offshore wind park exist in Denmark and Sweden, but these wind parks are close to the shore [2].

Planning is under progress for more than 30 wind parks in the German parts of the North Sea and the Baltic Sea. A grand total of 60 GW is envisaged. All these systems will be installed outside the twelve-sea-miles zone where water depth is 40 m [3].

World-wide about 260 wind energy converters have been installed offshore and the total installed power of these systems is in the range of 450 MW.

For new offshore sites large wind energy converters with a power of 5 MW are foreseen. A 4.5 MW system was built and is now under test in onshore conditions. In 2004 a novel 5 MW wind generator with permanent magnet excitation has been assembled and is now tested.

2. Technical Parameters

The planning of a wind park is a rather complex topic especially for offshore sites. We have to distinguish between:

- WEC and internal wind park grid
- Energy transfer via sea cable and land cable to the grid
- Connection to public grid following guidelines of utilities.

A number of problem areas are not solved and many questions have to answered such as:

a) Which innovative generator concept in the MW range is best?
b) Which cable technology is most economical?
c) Where is the break even point between ac-cable and dc-cable energy transport?
d) Should there be a standard for the voltage level of the internal wind park grid? Voltage levels between 20 kV and 36 kV are under discussion.

From table I and table II it can be taken that a variety of possible solutions exist depending on the site and therefore the energy transport path.

Table 1 Grid and generator features for offshore wind parks

Parameter	A	B
1 Generator voltage	Low voltage (LV)	Medium voltage (MV)
2 Generator frequency	Fixed	Variable
3 Energy transport	AC cable	DC cable

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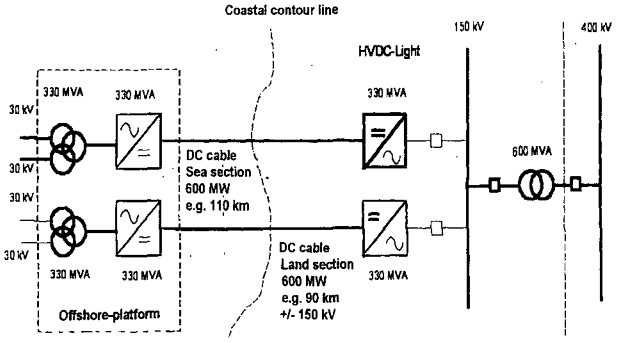

Fig. 1 HDVC cable for energy transport.

In the case of an AC/DC inverter in combination with the wind energy converter (WEC) the energy transport can be realized with a HVDC-cable. For this specific approach the voltage level of the MV wind park grid and also the frequency can be selected freely. A frequency lower than 50 Hz will help to minimize the losses within the cable grid and a higher frequency will reduce the size of the devices e.g. transformers.

Table 2 Structures For Offshore Wind Parks

Generator Concept	Low voltage Generator	Medium voltage Generator
f = const	Connection to medium voltage wind park grid. High voltage energy cable to shore.	Connection to wind park MV-grid. High voltage energy AC cable to shore.
	Connection to medium voltage wind park. Rectifier and HV-DC cable to shore.	Connection to wind park MV-grid. Rectifier and HV-DC line to shore.
f ≠ const	-	Connection to wind park MV-grid. Rectifier and HV-DC cable to shore.

With Fig. 1 such a HVDC cable system is presented.

Offshore wind parks in the future will have a power of 100 MW up to 1000 MW and therefore also a three-phase AC energy transport is feasible.

For wind parks close to the shore with a cable length around 20 km the voltage will be e.g. 35 kV for a small wind park with a total power of 25 MW.

New developments take place in order to cut down the costs for cable-laying, because remote control of the WEC's is essential for offshore systems. Therefore it is almost logical to combine the energy cable and the glass fibre cable into one system.

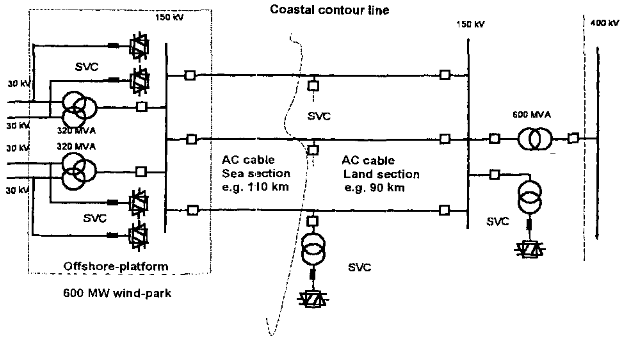

Fig. 2 AC cable for energy transport.

For a wind park power level of 600 MW the grid voltage should be 400 kV, but often these lines are far away from the coast. A combination of cable and overhead transmission line is then the best solution. However, the charge current of the ac-cable creates technical problems for cable length of about 150 km. Static reactive power compensation (SVC) is then a necessity. Fig. 2 gives an overview of such a system lay-out.

3. Control Problems

A special feature of wind energy utilization is that wind power and grid load are not correlated in time. As we see from Fig. 3 and Fig. 4 the fluctuation of the wind speed for onshore sites is quite high [4, 5].

The stochastic nature of wind energy requires a certain amount of balancing power for frequency control and stabilization of the voltage.

We need therefore supplementary power with specific features:

1. Positive control power is needed during periods of low wind
2. Negative control power is required during intervals of high wind speed when the grid cannot take the surplus power.

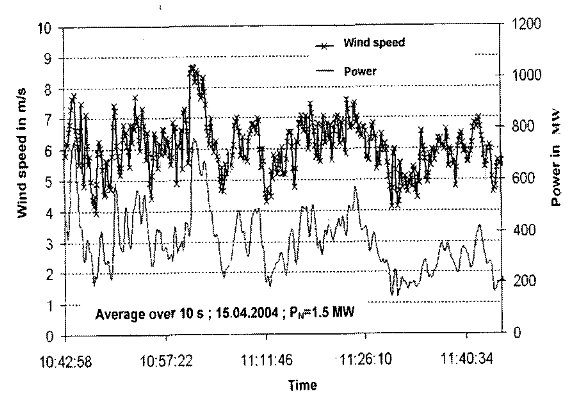

Fig. 3 Wind speed and power fluctuations.

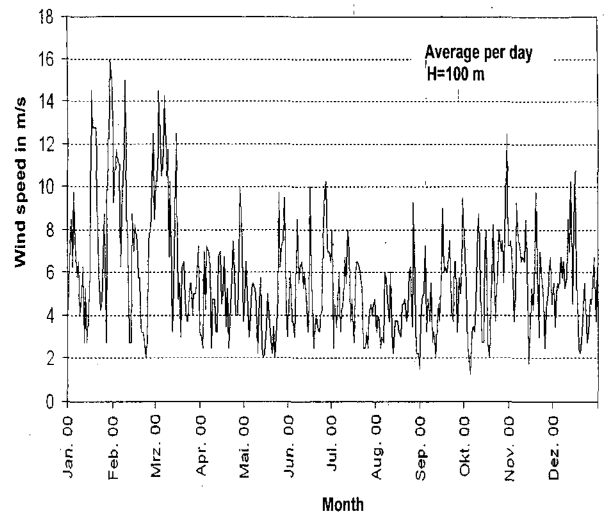

Fig. 4 Wind speed distribution for one year (Uckermark/Brandenburg).

This energy should be stored and preserved for later use according to the grid requirements. A number of solutions are under discussion: pumped hydro, compressed air storage, batteries, fly wheels and electrolysis systems to produce hydrogen [6, 14].

One candidate to provide positive power is biomass. A power plant based on biomass could have 7500 h of operation under full load compared to a wind energy converter system which will have about 1500 h of full load operation.

Also fuel cells could be implemented to offer positive power. However, the dynamic behaviour of fuel cells has to be improved.

4. Energy Yield

Instead of building just one WEC there is today the approach to create wind parks. Typical structures are shown in Fig. 5 and Fig. 6.

If we assume a constant wind speed v the power P_o of a WEC can be calculated according:

$$P_o = 0.5\ \rho \cdot A \cdot v^3 \tag{1}$$

A ... area (rotor swept area)
ρ ... specific air density (10°C: 1.23 kg/m^3)
v ... wind speed

In order to get an impression about the wind power, the specific power for an air temperature of 10°C and three different wind speeds are calculated [12, 13]:

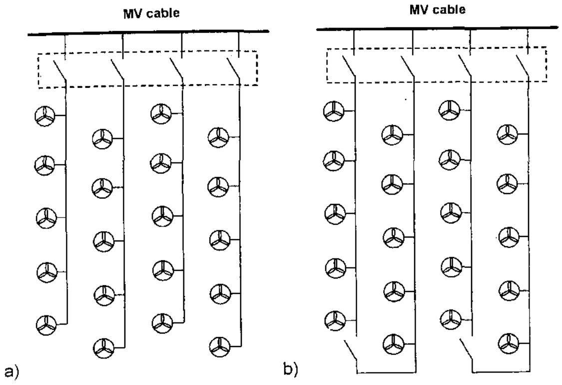

Fig. 5 Wind park structures
a) radial feeder
b) ring feeder.

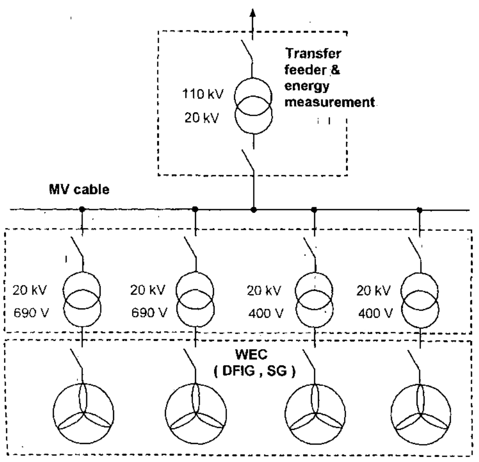

Fig. 6 Wind park structure and transformers.

Table 3 Specific power as a function of wind speed

P/A W/m^2	v m/s	Descriptive term
16600	30	violent storm
600	10	fresh breeze
0.6	1	very light breeze

From the result it is clear that the average wind speed should be in the range of at least 4 m/s. If we utilize the wind power with a turbine the Betz-power coefficient c_p must be introduced:

$$c_p = 0.5\ (1 + r)\ (1 - r^2) \qquad \text{with } r = v_2/v_1 \tag{2}$$

$$P = c_p \cdot P_o \tag{3}$$

The ideal coefficient $c_{pi} = 0.593$ is obtained for $r = 1/3$. To date, no Wind turbine has been designed which is capable of exceeding this limit. The reason is, that the stream-tube has to expand upstream of the actuator disc and so the cross section of the tube where the air is at the full, free-stream velocity is smaller than the area of the disc. For real applications the power coefficient is in the range between 0.4 and 0.5.

In the wind power industry different developments can be observed:

Route I is characterized by large tower heights of about 100 m and a power level of 3 to 5 MW with rotor diameters of 80 m up to 112 m.

Route II is characterized by the fact that the low wind speeds between 2.0 and 6.0 m/s are utilized. The power level of these systems is between 3 kW and 8 kW and the tower height ranges from 10 m to 20 m. Rotor diameter for the larger systems is below 13 m. Some of these systems are tailored for grid connection while others work as stand alone e.g. in combination with irrigation systems [7, 9]. The expected energy yield for a 6.4 kW system with a cut-in wind speed of 2 m/s is given in table IV [8].

Table 4 Energy yield per year of wind energy converter for low wind speeds (Route II)

Wind speed m/s	Energy/year KWh
2.5	8600
3.0	12700
3.5	16700
4.0	20300
4.5	23400

All the wind energy systems looked at above work with a horizontal axis. There is a niche market for wind turbines with a vertical axis.

Route III includes turbines with a vertical axis and a tower height often below 10 m [10]. There is the choice between a gearless- and a gear box-system. The power level is in the range from 500 W to 10 kW. Turbine speed can reach more than 200 rpm [10].

When a large turbine extracts energy from the wind, it leaves behind it a wake characterized by reduced wind speeds and increased level of turbulence. Another turbine operating in this wake, or deep inside a wind park where the effects of a number of wakes may be felt simultaneously, will therefore produce less energy than a turbine operating in the free stream. In addition these turbines suffer a greater structural loading. With table V this effect is underlined. The specific energy yield for turbines operating in two different wind parks is given and differences of up to 10 % can be observed.

Table 5 Energy yield from wind parks. Schneverdingen and Krusemark (ENERCON 1.8 MW) in 2003

System No.	Energy 2003 kWh/a	Specific energy kWh/m²a
S 1	1,760280	457.5
S 2	1,897320	493.0
S 3	1,942020	504.7
S 4	1,942380	504.8
K 1	1,887960	490.6
K 2	1,882440	489.0
K 3	1,844280	479.3
K 4	1,862280	484.0

It is also of interest to study the relationship between rated power and swept area for turbines. The mean specific power for a large number of WEC's is 405 W/m^2.

The aim of the wind turbine operator is the production of energy at minimum cost, however, environmental impact considerations cannot be ignored. Beside noise the aspect of power quality is of interest.

5. Power Quality

This term is used to describe how closely the electrical power delivered by WEC's to customers corresponds to the appropriate standards. In the following table VI origin and power quality issues are summarized:

Table 6 Power quality issues

Network influence on WEC	WEC influence on network
Voltage sags/swells	Harmonic currents
Harmonic voltage	Active power
Distortions	Reactive power
Voltage unbalance	Flicker
Transient interruption	Fault-level contribution

Main power quality issues occur when a large number of WEC's in a wind park create a steady-state voltage rise or for individual large turbines connected to a weak network the transient voltage changes dur to rapid changes of wind speed [16, 17, 18].

The total harmonic distortion is a parameter to describe the harmonic contents.

For the current we can write:

$$\mathrm{THD}_I = \frac{\sqrt{\sum_{n=2}^{40} I_n^2}}{I_1} \tag{4}$$

On the low voltage side this parameter might exceed the limits, however, on the high voltage side – due to the damping of the transformer – the THD_I is within the limits. Figure 7 shows the THD_I-factor versus normalized power. Also the approximation function is provided, which shows that the total harmonic distortion of the current is inversely proportional to the relative power P/P_n. Parameters such as grid impedance $Z_G = R_G + jX_G$, coupling reactance, filter and pulse frequency of the inverter have an influence on the curve.

Beside the total harmonic distortion also the partial weighted harmonic distortion (PWHD) and the interharmonics are of interest.

Voltage deviations arise in the grid, if the current flow I_G over the grid impedance fluctuates. Depending on speed and magnitude of current changes fast or slow voltage changes with different amplitudes occur. The relative voltage change ΔU is calculated by using the measured voltage U_M and the nominal voltage U_n:

$$\Delta U = (U_M - U_n)/U_n \tag{5}$$

Data from a 600 kW wind energy converter are presented in Fig. 8.

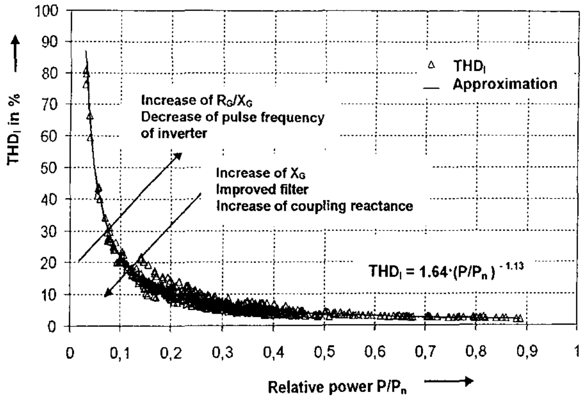

Fig. 7 Total harmonic distortion of the current on the 20 kV level of a wind park.

Voltage deviations are limited to 3 % on the low voltage and 2 % on the medium voltage level. These voltage changes may cause distortions of consumers in the grid. Its influence on other devices is described by the evaluation of light intensity changes of bulbs, the flicker.

The limit lines of flicker are fixed in standards:

IEC 1000-3-5 (1994), EN 50160 (2000).

6. Grid Integration

The focus is on the variable-speed type WEC's, because these devices are preferred in the megawatt-power-range. These systems also cause reduced grid interaction compared to stall-controlled devices and deliver a higher energy yield combined with a more smooth power flow.

Grid connection of variable speed wind turbines is realized with a series connection of voltage source inverters (VSI). Although the inverter dc link capacitor bank reduces dynamic generator current changes, this system shows current distortions because of the limited switching frequency of the power electronic devices. Typical switching frequencies are between 2 and 10 kHz. The lower the switching frequency, the worse is the shape of the inverter output current on the low voltage side, e.g. 400 V or 690 V. Due to the damping characteristics of the transformers between low voltage and 20 kV level, the requirements of the utilities can be fulfilled [19, 20].

It is essential that wind turbines do not degrade the power quality of the distribution network. New standards are being developed to get information of wind turbines concerning:

- maximum output power (10 min average, 60 s average, 200 ms average)
- reactive power (10 min average) as a function of active power
- maximum number of wind turbine starts within 10 min and 120 min periods
- flicker coefficient for continuous operation as a function of network source impedance phase angle.

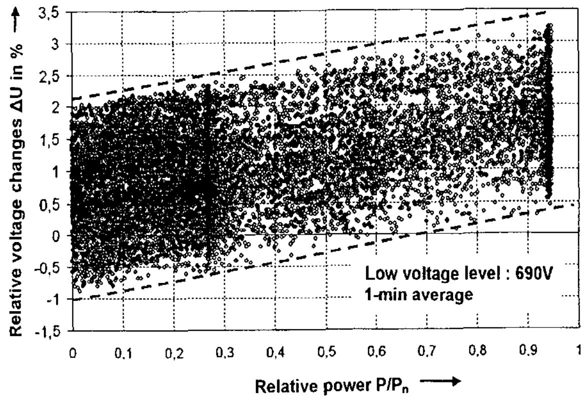

Fig. 8 Voltage changes on the low voltage level of a pitch controlled WEC with 600 kW.

The main sources of power fluctuations are: wind turbulence, blade passing and blade pitching. Major effects – mainly due to turbulence – were found at wind speeds of 9-10 m/s.

The effect of embedded generation systems on a distribution network will vary according to circumstances and therefore each project must be evaluated individually.

7. Emissions

Wind energy utilization, solar energy and the use of biomass contribute to CO_2-savings. As a guideline it can be assumed that the specific CO_2-emissions from a coal fired power plant are 0.85 kg CO_2/kWh [11]. A wind energy converter will deliver per installed kW and 1500 h of full load operation a specific CO_2-reduction of 1275 kg CO_2 per year. This situation will improve for offshore sites.

8. Summary

During recent years a strong increase of power from renewable energy sources occurred. Because of advantageous feed-in tariffs based on national laws focus is on wind energy parks. However, grid connection points are limited by the existing grid structure. There is a demand for new strategies to reduce harmonics and flicker. Future wind parks should have the capability of self-starting of the whole park for the supply and voltage stabilization of parts of the electrical network. This requires the mix of different WEC-types: variable speed WEC's with pitch-control with focus on synchronous generators but also doubly fed induction generators and energy storage units.

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