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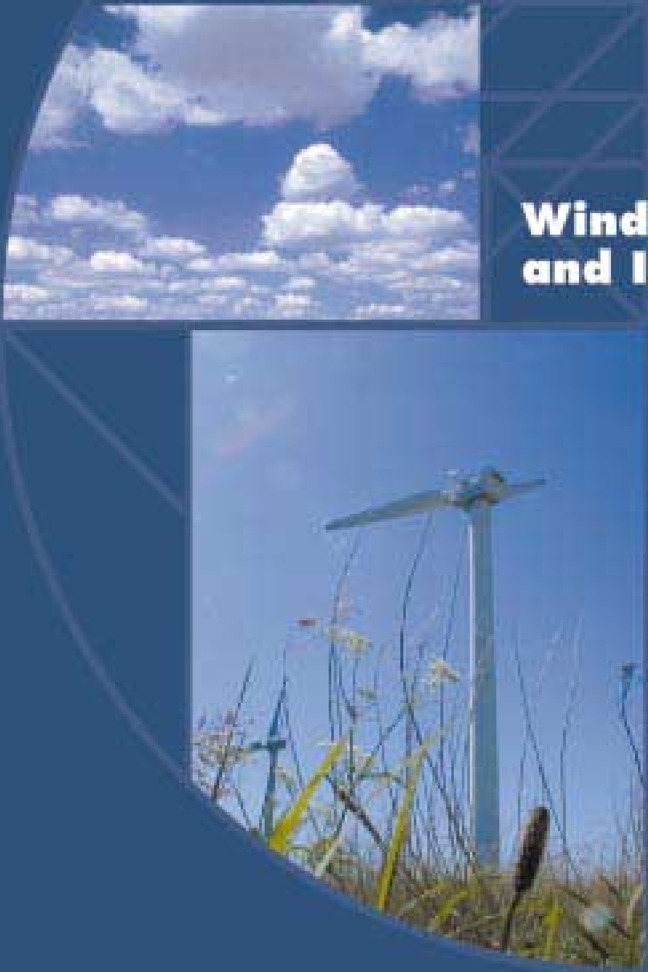

Wind Turbine Grid Connection and Interaction

Deutsches Windenergie-Institut
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1 Introduction

Wind energy is now firmly established as a mature technology for electricity generation and over 13,900 MW of capacity is now installed, worldwide. It is one of the fastest growing electricity-generating technologies and features in energy plans across all five continents, both in the industrialised and the developing world.

It differs, however, in several respects from the „conventional“ thermal sources of electricity generation. Key differences are the small sizes of individual units, the variable nature of the wind and the type of electrical generator. Each is considered in this brochure.

Small unit sizes: The small unit sizes mean that both wind farms and individual wind turbines (WT) are usually connected into low voltage distribution networks rather than the high voltage transmission systems and this means that a number of issues related to power flows and protection systems need to be addressed. Electrical safety is an important issue under this heading.

Variability: The variable nature of wind is often perceived as a difficulty, but in fact poses few problems. The variations in output do not cause any difficulty in operating electricity systems, as they are not usually detectable above the normal variations in supply and demand. With significant amounts of wind power – roughly 30 % or more of demand - low cost solutions can be found and some island systems operate with high proportions of wind energy. Variability also needs to be taken into account at the local level, to ensure consumers are not affected by „flicker“. Appropriate care in electrical design, however, can eliminate this problem.

Electrical properties: Early WT followed steam turbine practice with synchronous generators, but many modern WT have induction generators. These draw reactive power from the electricity network, necessitating careful thought to electrical power flows. Other machines, however, are capable of conditioning the electrical output and providing a controllable power factor. This is an asset, especially in rural areas, where it may be undesirable to draw reactive power from the network.

Advances in wind-turbine technology and the results of nearly two decades of research mean that the integration of WT and wind farms into electricity networks generally poses few problems. The characteristics of the network and of the turbines do nevertheless need to be evaluated but there is now a wealth of experience upon which to draw. The fact that Denmark is planning to supply 30 percent of its electricity needs from wind energy is testimony to the fact that its potential is considerable.

2 Overview of Wind Power Generation and Transmission

WT convert wind energy into electrical energy, which is fed into electricity supply systems. The connection of WT to the supply systems is possible to the low voltage, medium voltage, high voltage as well as to the extra high voltage system. While most of the turbines are nowadays connected to the medium voltage system of the grid future large offshore wind farms will be connected to the high and extra high voltage level.

2.1 Components of the System

The three main components for energy conversion in WT are rotor, gear box and generator. The rotor converts the fluctuating wind energy into mechanical energy and is thus the driving component in the conversion system.

The generator and possibly an electronic inverter absorb the mechanical power while converting it into electrical energy, fed into a supply grid. The gear box adapts rotor to generator speed. The gear box is not necessary for multipole, slow running generators.

The main components for the grid connection of the WT are the transformer and the substation with the circuit breaker and the electricity meter inside it. Because of the high losses in low voltage lines, each

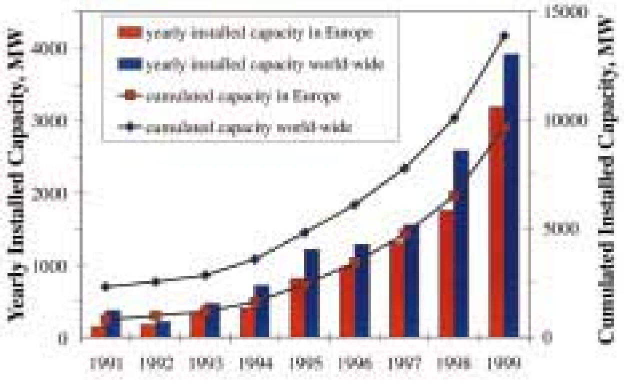


Figure 1.1: Yearly installed capacity of wind energy in Europe and wold-wide

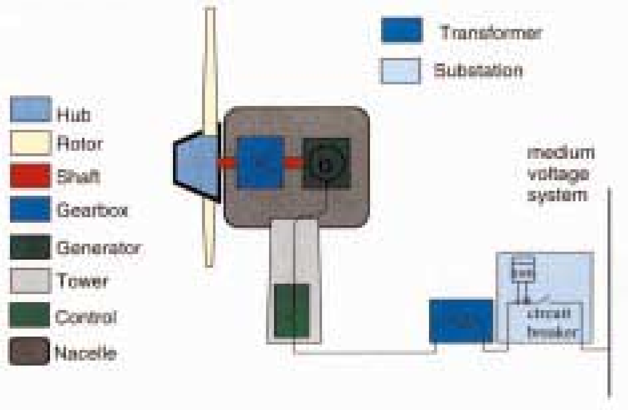


Figure 2.1: Components of the WT and for the grid connection of a WT

of the turbines has its own transformer from the voltage level of the WT (400 or 690 V) to the medium voltage line. The transformer are located directly beside the WT to avoid long low-voltage cables. Only for small WTGS it is possible to connect them directly to the low voltage line of the grid without a transformer or, in a wind farm of small WT, to connect some of the small WT to one transformer. For large wind farms a separate substation for transformation from the medium voltage system to the high voltage system is necessary.

At the point of common coupling (PCC) between the single WT or the wind farm and the grid a circuit breaker for the disconnection of the whole wind farm or of the WT must exist. In general this circuit breaker is located at the medium voltage system inside a substation, where also the electricity meter for the settlement purposes is installed. This usually has its own voltage and current transformers.

The medium voltage connection to the grid can be performed as a radial feeder or as a ring feeder, depending on the individual conditions of the existing supply system. Fig. 2.1 gives an overview of the necessary components in case of connection of the WTGS to the medium voltage system.

2.2 Supply Network

The power supply system is divided into:

- LV: low voltage system
  (nominal voltage up to 1kV)
- MV: medium voltage system
  (nominal voltage above 1kV up to 35kV)
- HV: high voltage system
  (nominal voltage above 35kV)

Small consumers like households are connected to the low voltage system. Larger consumers like workshops and medium size industries are connected to the medium voltage system, while larger or heavy industries may be connected to the high voltage system. Conventional power stations are connected to the high voltage or extra-high voltage system.

The power transmission capacity of the electricity supply system usually decreases with falling population density. Areas for WT are generally located in regions with low population density and with low power transmission capacity.

The transmittable power for connection to different levels of the electrical network are listed in table 2.1.

2.3 Offshore grid connection

Offshore wind power holds the promise of very large - in Denmark figures of up to 1800 MW are mentioned - geographically concentrated wind power installations placed at great distances from the nearest point where it can be connected to the electric transmission system. For large onshore wind farms, i.e. 100-200 MW, high voltage overhead lines above 100kV are normally used in this situation. For offshore wind farms however this option is not available as a large part of the distance to the connection point necessarily must be covered by a submarine cable. The distances can be considerable, depending on local conditions, water depth and bottom conditions in particular. Too deep water increases the cost for foundations and too shallow water makes construction difficult due to limited access for barges, floating cranes and jack-

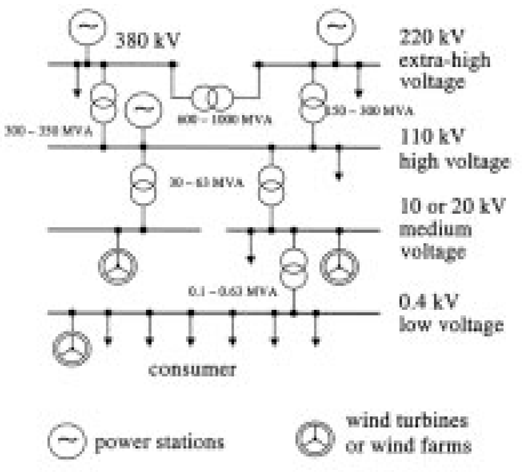


Figure 2.2: Power supply system in Germany

Voltage system	Size of wind turbine or wind farm	Transmittable power
Low voltage system	For small to medium wind turbines	up to ≈ 300 kW
Feeder of the medium voltage system	For medium to large wind turbines and small wind farms	up to ≈ 2–5 MW
Medium voltage system, at transformer substation to high voltage	For medium to large onshore windfarms	up to ≈ 10–40 MW
High voltage system	Clusters of large onshore windfarms	up to ≈ 100 MW
Extra high voltage system	Large offshore wind farms	> 0.5 GW

Table 2.1: Transmittable power and connection of wind turbines to different levels of the electrical network

up platforms for ramming or drilling foundation poles. In Danish coastal waters, where shallow areas are abundant, the wind farms will be placed far from the shore in order to minimise visual impact. Probable distances from the shore ranges from 5 -10 km to 50 km or more.

The principal lay-out of a grid connection scheme for an offshore wind farm follows very much the same lines as for a large onshore installation as the basic functional requirements are the same - to transmit the energy produced to a point where the electric transmission grid is strong enough to absorb it. A typical layout for such a scheme is shown in Figure 2.4. As shown, clusters of WT are each connected to a medium voltage ring. This principle deviates from normal onshore practice where the WT are connected to a number of radial cables from the medium voltage switch gear in the transformer station. The reason for this is the vulnerability of the submarine cables to anchors and fishing activities. It must be anticipated that sections of the ring may be out of service for repair or exchange for long periods if weather conditions makes repair work impossible. With a ring connection, production can continue upheld in the repair periods thus - at a small extra cost - reducing the economic consequences of a cable fault. The choice of voltage level within the wind farm is purely a matter of economy. Each WT is equipped with a transformer stepping up from the generator voltage - typically low voltage, i.e. below 1 kV - to a medium voltage below 36 kV. Transformers going directly from low voltage to voltages higher than 36 kV are not standard products and hence far more expensive, if technically feasible at all. The choice between 20-24 and 30-34 kV is determined by an evaluation minimum lifetime cost; that is the net present value of losses in the two alternatives is weighed against equipment cost.

The transformer station is an offshore structure, from a civil engineering viewpoint much like other structures used in the oil and gas industry, although at lower water depths. A design found feasible is a one pole foundation with a top section containing the equipment. The construction procedure envisages the foundation being established first on the site, while the top-section is finished onshore. This is completely equipped and tested and then is transported to the site and placed by a floating crane on the foundation, and the external cables connected. The main function of the transformer station is to increase the voltage to a level suitable for transmitting the energy produced to the connection point. Depending on the size of the installation this could be anything from the medium voltage level in the farm - in this case the transformer is not needed - to the highest transmission voltages used in the connecting transmission grid, i.e. up to 400 kV. A transformer of this size will be oil-cooled/insulated, possibly with two secondary windings, each with half the nominal rating of the transformer, in order to keep the short circuit power level at medium voltage down to a manageable level, seen from the side of selection of medium voltage equipment.

The medium voltage switch gear could be air or gas insulated but reliability and size considerations will probably favour the gas insulated alternative. The high voltage breaker shown in the transformer station could under certain conditions be omitted. Certain types of faults, such as over voltages due to excessive reactive power production, are difficult to detect onshore. If fast redundant channels permitting opening of the on-shore circuit breaker on a signal from the platform are available the offshore circuit breaker is superfluous and can be replaced by a isolator. Equipment not normally associated with transformer stations is necessary - in particular an emergency supply.

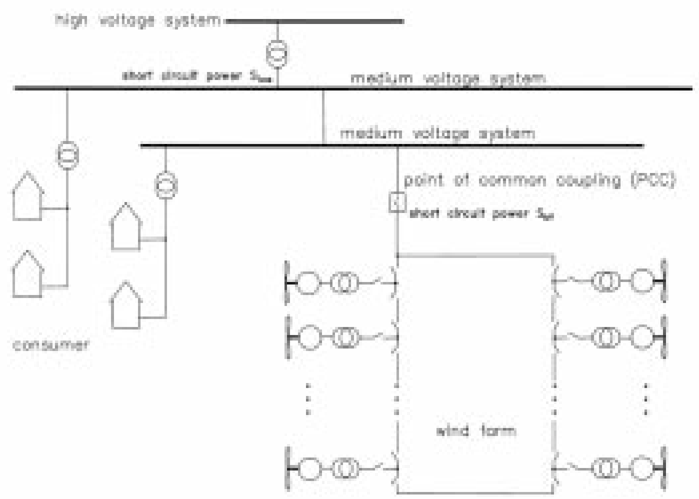


Figure 2.3: Internal and external grid connection of a wind farm

The submarine cable to the shore is subject to a number of threats from anchoring and fishing as already mentioned. Depending on weather, which can be severe for long periods during the winter season, repair can be difficult if not impossible until weather conditions improve. In such periods the voltage to the WT and the transformer station itself must be upheld for service, maintenance and possibly operation of internal climate conditioning equipment. An emergency diesel generator is needed for this purpose with necessary fuel supply to operate for an extended period. The size in kW of the generator is probably fairly small but as the reactive power production in the cables in the wind farm is considerable (compared to the active emergency power needed) measures such as the installation of reactors and possibly an oversize generator on the diesel set are necessary to be able to control the voltage in the wind farm in this situation. As will be discussed later the amount of reactive power the submarine cable to the shore produces is very high - and depending on the voltage squared - reactors will be needed to compensate this as well.

The transmission line from the transformer station to the grid connection point is a project in itself. It can be split up in two parts, a submarine cable and a section onshore which can be a cable buried in the ground or an overhead line.

Submarine cables are in principle ordinary underground cables but equipped with a lead sheath and steel amour to make it watertight and to protect it from mechanical damage. The extra weight also helps to keep it in place in water where there are strong currents. If possible at all, burial by washing down or digging is recommended to protect the cable. For the submarine section four different types of cables are available and for an AC transmission three parallel conductors are needed. The types are single or three conductor oil-insulated cables and single or

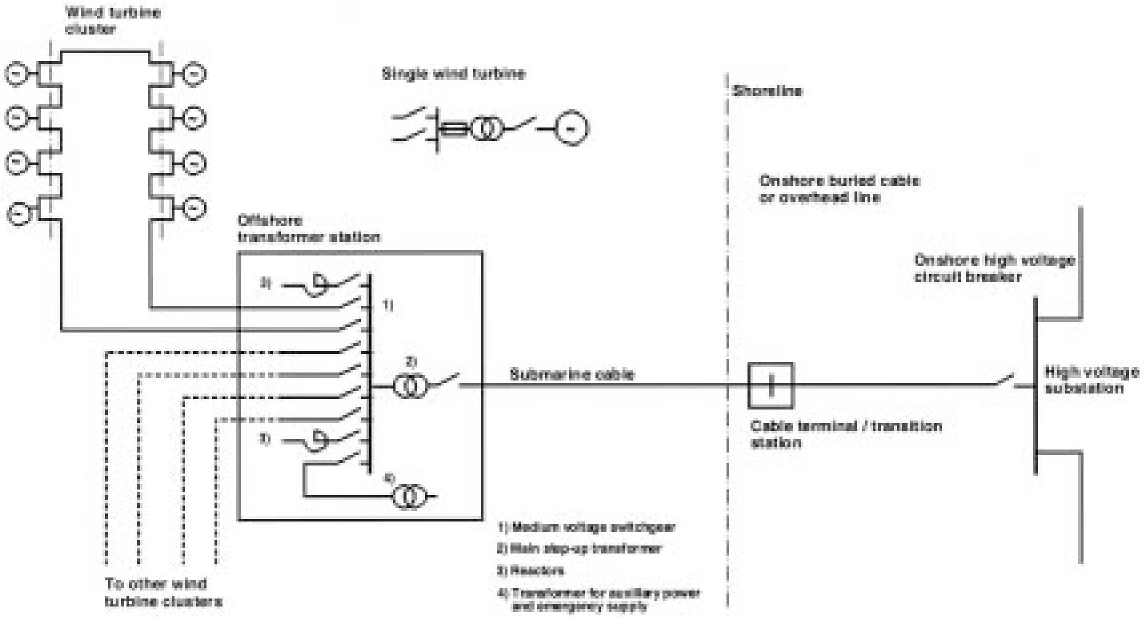


Figure 2.4: AC offshore grid connection

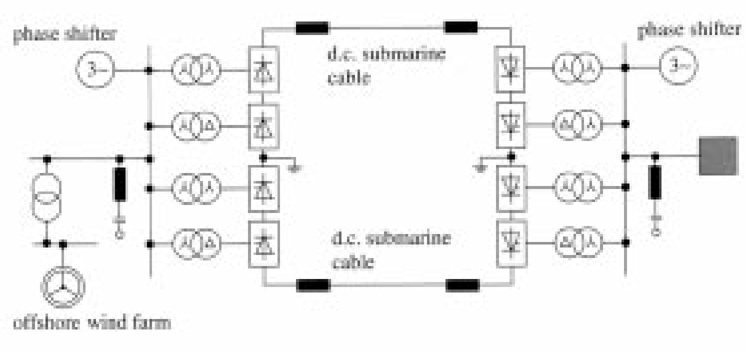


Figure 2.5: Principle sheme of the high-voltage D.C. transmission (HVDCT) with thyristor technique

three conductor PEX-insulated cable. If cables with a single conductor are used the transmission system will comprise three parallel cables. In this case the distance between the individual cables must be great enough to allow for a repair loop as the cables must not cross. They cannot be laid down in one operation and as laying out and subsequent burial of the cables are major cost items, single conductor cables are only used where transmission capacity requirements dictate the use of very large conductor cross sections or high voltages. In general transmission capacities of up to around 200 MVA are possible with three conductor oil-insulated cables at 150kV and a cable with this capacity would have cross section of 800 mm^2. Three conductor submarine PEX-insulated cables are available for up to 170 kV and with corresponding transmission capacities.

A cable is a capacitor with a much higher capacity than an overhead line. The reactive power production in a cable is considerable and a 40 km long cable at 150 kV would produce around 100 Mvar, that is more or less the reactive power used by a 150 MW wind farm with induction generators, - depending on the type of cable. The high voltage grid will probably not be able to absorb this amount in all operating conditions and since the demand of the WT is zero when they are disconnected from the grid in periods with low wind speeds reactors will have to be installed to compensate for this reactive power production.

For very long cables, the loading current from the reactive power production may take a considerable part of its transmission capacity and in this situation high voltage direct current (HVDC) transmission techniques may be economically feasible. Two different converter technologies are used. The traditional thyristor based technology used for some decades, and a new transistor based one. The traditional technology requires an AC voltage at both ends of the DC line and would thus - for an offshore wind farm application - require an extra AC cable parallel to the DC line. It furthermore produces large amounts of harmonics and needs large filters to remove the harmonics. The new technology - which is on the brink of commercial breakthrough - overcomes these two difficulties and will furthermore open new possibilities for obtaining dynamic stability for the wind farm as it will be possible to uphold voltage in the wind farm during the time needed to clear faults and fast reclosures in the onshore transmission system.

2.4 Losses

The electrical losses can be divided into losses due to the generation of power and into losses, which occur independently of the power production of WT. These are losses like the no-load losses of the transformer, but also losses for lights and for heating (needed for protection against frost damages at the substation). The losses due to the generation of power of the WT are mainly losses in the cables and copper losses of the transformer.

In general one of the main losses is the no-load loss of the transformer. Thus it is important, that the no-load loss of the installed transformer is low. Additionally the low-voltage cable between the WT and the transformer should be short to avoid high losses. In general, at the medium voltage lines the losses are low due to the low currents. Only for large wind farms or for long distances are the losses of the medium voltage lines important. In general the electrical losses are in the range 1%–2%of the energy yield of the WT or of the wind farm.

3 Generator systems for Wind Turbines

The energy conversion of most modern WT can be divided into two main concepts, fixed speed machines with one or two speeds and variable speed machines. If the number of machines designs in a given category can be taken as a guide, the preferred concepts are the variable speed and the two speed machines, see figure 3.1.

3.1 Fixed Speed wind turbines

In fixed speed machines the generator is directly connected to the mains supply grid. The frequency of the grid determines the rotational speed of the generator and thus of the rotor. The low rotational speed of the turbine rotor n_{rotor} is translated into the generator rotational speed $n_{generator}$ by a gear box with the transmission ratio r. The generator speed depends on the number of pole pairs p and the frequency of the grid f_{grid}.

$$n_{rotor} = \frac{n_{generator}}{r}$$

$$n_{generator} = \frac{f_{grid}}{p}$$

$$n_{rotor} = \frac{f_{grid}}{r \cdot p}$$

The details on fixed speed machines are depicted in the figure 3.2. The greatest advantages of WT with induction generators is the simple and cheap construction. In addition no synchronisation device is required. With the exception of bearings there are no wearing parts.

The disadvantages of induction generators are high starting currents, which usually are smoothed by a thyristor controller, and their demand for reactive power.

3.2 Variable Speed Wind Turbines

In variable speed machines the generator is connected to the grid by an electronic inverter system. For synchronous generators and for induction generators without slip rings this inverter system is connected between the stator of the generator and the grid like fig. 3.3, where the total power production must be fed through the inverter. For induction generators with slip rings the stator of the generator is connected to the grid directly. Only the rotor of the generator is connected to the grid by an electronic inverter, see fig. 3.4. This gives the advantage, that only a part of the power production is fed through the inverter. That means the nominal power of the inverter system can be less than the nominal power of the WT. In general the nominal power of the inverter is the half of the power of the WT, enabling a rotor speed variation in the range of half the nominal speed.

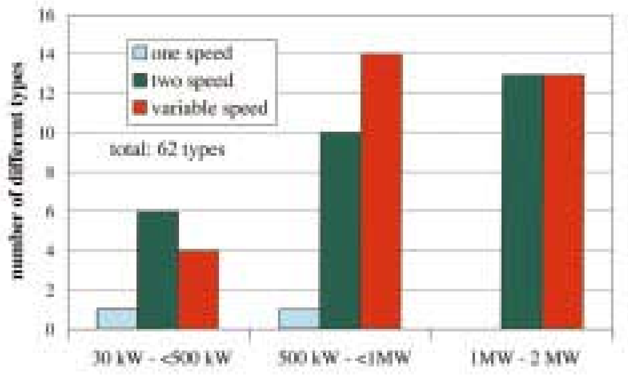
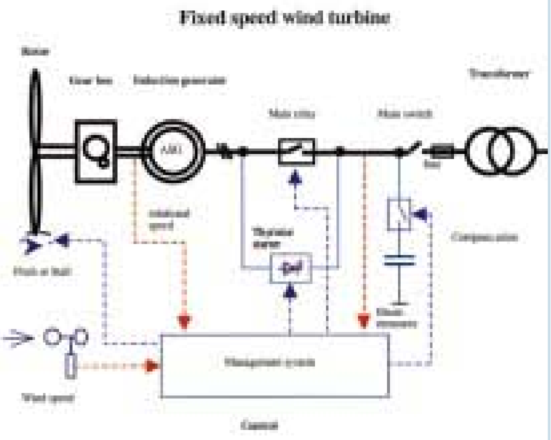


Figure 3.1: Number of different types of WT in the German market in the year 2000



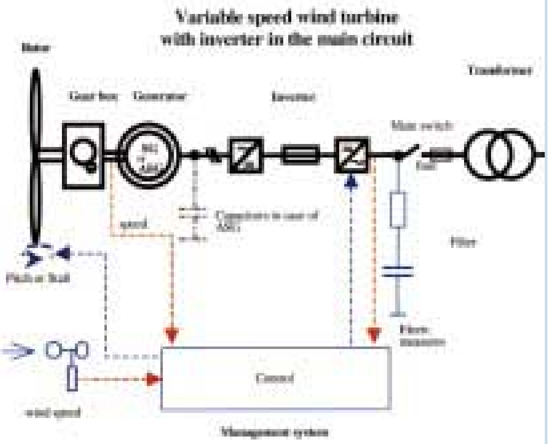
rotational speed:	constant + slip range
grid coupling:	rigid, with low elasticity
excitation:	by the grid
control:	power control by stall or pitch speed control by pitch
advantage:	simple and cheap construction no synchronisation with the grid required
disadvantage:	production of reactive power generation of power peaks, only low compensation of wind speed fluctuations power generation only controllable by pitch

Figure 3.2: Details of the fixed WT

By the control of active power of the inverter, it is possible to vary the rotational speed of the generator and thus of the rotor of the WT.

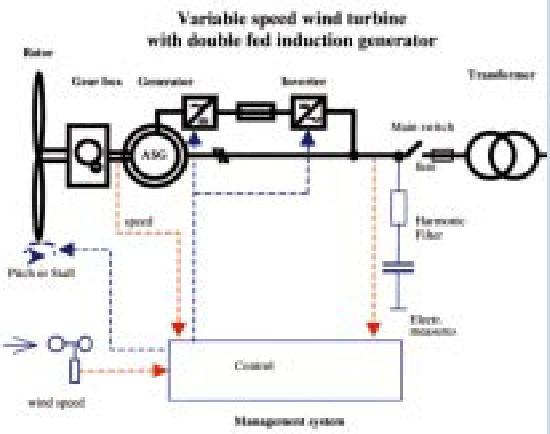
3.3 Inverter systems

If the WT operates at variable rotational speed, the electric frequency of the generator varies and must therefore be decoupled from the frequency of the grid. This can be achieved by an inverter system. There are two different types of inverter systems: grid commutated and self commutated inverter systems. The grid commutated inverters are mainly thyristor inverters, e. g. 6 or 12 pulse. This type of inverter produces integer harmonics like the 5th, 7th, 11th, 13th order etc (frequencies of 250, 350, 550, 650 Hz,...), which in general must be reduced by harmonic filters. On the other hand thyristor inverter are not able to control the reactive power.



rotational speed:	variable
grid coupling:	soft, not coupled to grid frequency
control:	power control by stall or pitch speed delimitation by pitch speed control by power regulation of the inverter system
advantage:	smoothing of power output and loads, compensation of wind speed fluctuations controllable production of reactive power operation at optimal power coefficient c_p due to variable speed
disadvantage:	expensive construction generation of harmonics

Figure 3.3: Details of the variable speed WT with inverter in the main circuit



rotational speed:	variable
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control:	power control by stall or pitch speed delimitation by pitch speed control by power regulation of the inverter system
advantage:	smoothing of power output and loads, compensation of wind speed fluctuations controllable production of reactive power operation at optimal power coefficient c_p due to variable speed
disadvantage:	expensive construction generation of harmonics

Figure 3.4: Details of the variable speed WT with double fed induction generator

Their behaviour concerning reactive power is similar to the behaviour of an induction generator they consume inductive reactive power.

Self commutated inverter systems are mainly pulse width modulated (PWM) inverter, where IGBTs (Insulated Gate Bipolar Transistor) are used. This type of inverter gives the advantage, that in addition to the control of the active power the reactive power is also controllable. That means the reactive power demand of the generator can be delivered by the PWM-inverter. One disadvantage is the production of interharmonics. In general these interharmonics are generated by the inverter in the range of some kHz. Thus filters are necessary to reduce the interharmonics. But due to the high frequencies, in general the construction of the filters is easier.

In modern WT generally use is made of transistor based inverter systems only.

4 Interaction with the Local Electricity Network

The modern electricity supply network is a complex system. The somewhat vague term “power quality” is used to describe the interaction between traditional producers operating fossil fired, nuclear, or hydro power plants and consumers. The latter may be large (heavy industry - metal melting) or small (private homes) consumers. In the last 10 years, a steadily increasing number of renewable energy sources such as wind or solar (photovoltaic) powered generating systems have been added to the systems. A distinctive feature of electricity is that it cannot be stored as such - there must at any instant be balance between production and demand. “Storage” technologies such as batteries, pump storage and fuel cells all have one common characteristic i.e. the electric energy to be stored is converted to other forms, such as chemical (batteries), potential energy in form of water in high storage (pump storage) and hydrogen (fuel cells). All renewable resources produce when the source is available - for wind power, as the wind blows. This characteristic is of little if any importance when the amount of wind power is modest compared to the total installed (and spinning) capacity of controllable power plants, but it changes into a major technical obstacle as the renewable part (termed penetration) grows to cover a large fraction of the total demand for electric energy in the system.

On the local level, voltage variations are the main problem associated with wind power. Normal static tolerances on voltage levels are ±10%. However, fast small variations become a nuisance at levels as low as 0.3% and in weak grids - as is often found in remote areas where the wind conditions are best. This can be the limiting factor on the amount of wind power which can be installed. In the following, a short introduction is given to each of the electrical parameters which taken together are used to characterise power quality - or more correct, voltage quality - in a given point in the electricity supply system.

4.1 Short circuit power level

The short circuit power level in a given point in the electrical network is a measure of its strength and, while not directly a parameter in the voltage quality, has a heavy influence. The ability of the grid to absorb disturbances is directly related to the short circuit power level of the point in question. Any point (p) in the network can be modelled as an equivalent circuit as shown in Figure 4.1. Far away from the point the voltage can be taken as constant i.e. not influenced by the conditions in p. The voltage in this remote point is designated U_{SC} and the short circuit power level S_{SC} in MVA can be found as U_{SC}^2 / Z_{SC} where Z_{SC} is the line impedance. Variations in the load (or production) in p causes current variations in the line and these in turn a varying voltage drop (ΔU) over the line impedance Z_{SC}. The voltage in p (U_L) is the difference between U_{SC} and ΔU and this resulting voltage is seen by - and possibly disturbing - other consumers connected to p. Strong and/or weak grids are terms often used in connection with wind power installations. It is obvious from figure 4.1, that if the impedance Z_{SC} is small then the voltage variations in p will be small (the grid is strong) and consequently, if Z_{SC} is large, then the voltage variations will be large. Strong or weak are relative terms. For any given wind power installation of installed capacity P(MW) the ratio $R_{SC} = S_{SC} / P$ is a measure of the strength. The grid is strong with respect to the installation if R_{SC} is above 20 to 25 times and weak for R_{SC} below 8 to 10 times. Depending on the type of electrical equipment in the WT they can sometimes be operated successfully under weak conditions. Care should always be taken, for single or few WT in particular, as they tend to be relatively more disturbing than installations with many units.

Flicker severity factor	Planning levels		Emmission levels
	MV	HV	MV and HV
P_{st}	0.9	0.8	0.35
P_{lt}	0.7	0.6	0.25

Table 4.1: Flicker planning and emission levels for medium voltage (MV) and high voltage (HV)

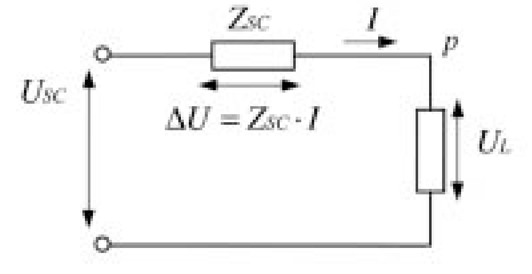

Figure 4.1: equivalent circuit

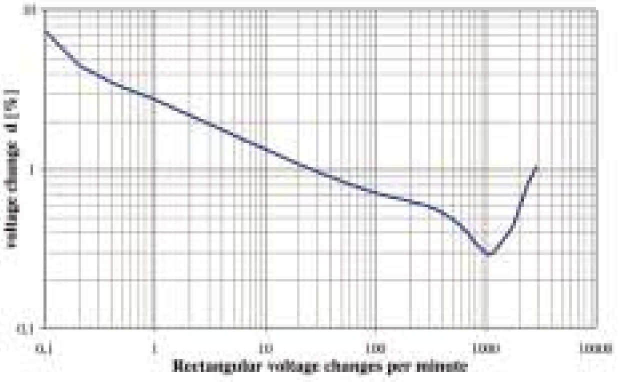

Figure 4.2: $P_{st} = 1$ curve for regular rectangular voltage changes

4.2 Voltage variations and flicker

Voltage variations caused by fluctuating loads and/or production is the most common cause of complaints over the voltage quality. Very large disturbances may be caused by melters, arc-welding machines and frequent starting of (large) motors. Slow voltage variations within the normal -10+6% tolerance band are not disturbing and neither are infrequent (a few times per day) step changes of up to 3%, though visible to the naked eye. Fast and small variations are called flicker. Flicker evaluation is based on IEC 1000-3-7 which gives guidelines for emission limits for fluctuating loads in medium voltage (MV, i.e. voltages between 1 and 36 kV) and high voltage (HV, i.e. voltages between 36 and 230 kV) networks. The basis for the evaluation is a measured curve (figure 4.2) giving the threshold of visibility for rectangular voltage changes applied to an incandescent lamp. Disturbances just visible are said to have a flicker severity factor of $P_{st} = 1$ (P_{st} for P short term). Furthermore, a long term flicker severity factor P_{lt} is defined as:

$$P_{lt} = \sqrt[3]{\frac{1}{12}\sum_{j=1}^{12} P_{stj}^{3}}$$

Where P_{st} is measured over 10 minutes and P_{lt} is valid for two hour periods. IEC 1000-3-7 gives both planning levels, that is total flicker levels which are not supposed to be exceeded and emission levels, that is the contributions from an individual installation which must not be exceeded. The recommended values are given in table 4.1

Determination of flicker emission is always based on measurement. IEC 61000-4-15 specifies a flickermeter which can be used to measure flicker directly. As flicker in the general situation is the result of flicker already present on the grid and the emissions to be measured, a direct measurement requires a undisturbed constant impedance power supply and this is not feasible for WTGS due to their size. Instead the flicker measurement is based on measurements of three instantaneous phase voltages and currents followed by an analytical determination of P_{st} for different grid impedance angles by means of a "flicker algorithm" - a programme simulating the IEC flickermeter.

4.3 Harmonics

Harmonics are a phenomenon associated with the distortion of the fundamental sinewave of the grid voltages, which is purely sinusoidal in the ideal situation.

The concept stems back to the French mathematician Josef Fourier who in the early 1800 found that any periodical function can be expressed as a sum of sinusoidal curves with different frequencies ranging from the fundamental frequency - the first harmonic - and integer multiples thereof where the integer designates the harmonic number. Figure 4.3 shows the distortion to the fundamental 50 Hz voltage by adding 20% third harmonic (150 Hz) to the wave form.

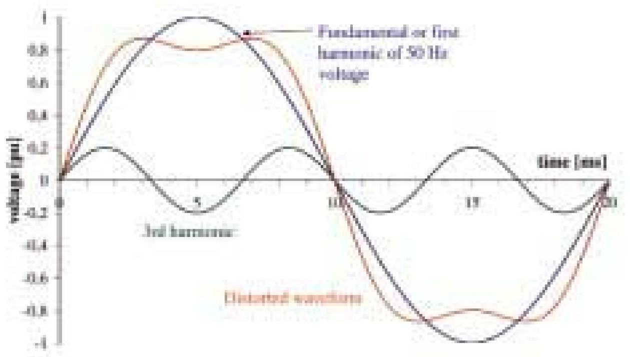

Figure 4.3: Distortion by 3^{rd} harmonic

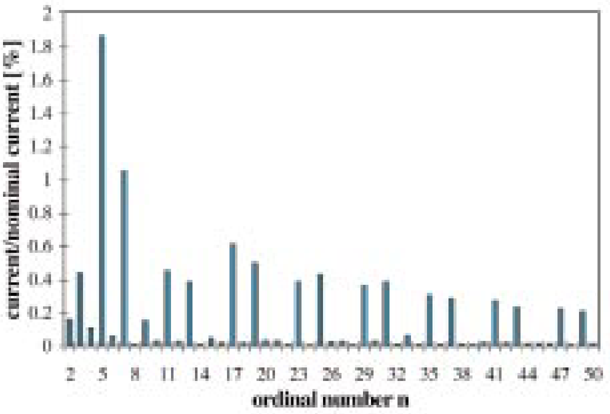

Figure 4.4: Harmonic currents of a 6pulse thyristor inverter with filter

Harmonic disturbances are produced by many types of electrical equipment. Depending on their harmonic order they may cause different types of damage to different types of electrical equipment. All harmonics causes increased currents and possible destructive overheating in capacitors as the impedance of a capacitor goes down in proportion to the increase in frequency. As harmonics with order 3 and odd higher multiples of 3 are in phase in a three phase balanced network, they cannot cancel out between the phases and cause circulating currents in the delta windings of transformers, again with possible overheating as the result. The higher harmonics may further give rise to increased noise in analogue telephone circuits.

Highly distorting loads are older unfiltered frequency converters based on thyristor technology and similar types of equipment. It is characteristic for this type that it switches one time in each half period and it may generate large amounts of the lower harmonic orders, i.e. up to N=40, see figure 4.4.Newer transistor based designs are used in most variable speed WT today. The method is referred to as Pulse Width Modulation (PWM). It switches many times in each period and typically starts producing harmonics where the older types stop, that is around 2 kHz. Their magnitude is smaller and they are easier to remove by filtering than the harmonics of lower order. Figure 4.5 gives an example of the harmonics of a WT with PWM inverter system.

IEC 1000-3-6 put forward guidelines on compatibility and planning levels for MV and HV networks

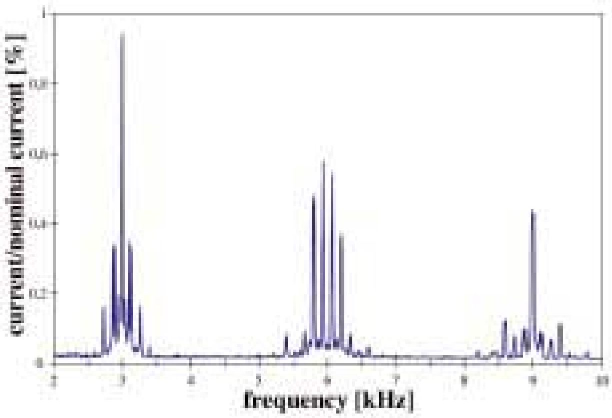

Figure 4.5: Frequency Analysis of current of a WT with PWM inverter system without filter

and presents methods for assessing the contribution from individual installations to the overall disturbance level.

The distortion is expressed as Total Harmonic Distortion (THD) and the recommended compatibility level in a MV system is 8 % whereas the indicative Planning levels for a MV system is 6.5 % and 3 % in a HV system. Based on the amplitudes (or RMS values) of the harmonics present in the voltage, THD can be found as:

$$THD = 100\sqrt{\sum_{n=2}^{40} \frac{U_n}{U_1}}\ \%$$

where U_n are the individual harmonics and U_1 the fundamental amplitude (or RMS value).

4.4 Frequency

The electrical supply and distribution systems used world-wide today are based on alternating voltages and currents (AC systems). That is, the voltage constantly changes between positive and negative polarity and the current its direction. The number of changes per second is designated the frequency of the system with the unit Hz. In Europe the frequency is 50 Hz whereas it is 60 Hz in many other places in the world. The frequency of the system is proportional to the rotating speed of the synchronous generators operating in the system and they are - apart from an integer even factor depending on machine design - essentially running at the same speed: They are synchronised. Increasing the electrical load in the system tends to brake the generators and the frequency falls. The frequency control of the system then increases the torque on some of the generators until equilibrium is restored and the frequency is 50 Hz again.

The requirements to frequency control in the West European grid are laid down in the UCPTE (Union for the Co-ordination of Production and Transmission of Electricity) rules.

The area is divided in a number of control zones each with its own primary and secondary control. The primary control acts on fast frequency deviations, with the purpose of keeping equilibrium between instantaneous power consumption and production for the whole area. The secondary control aims at keeping the balance between production and demand within the individual zones and keeping up the agreed exchange of power with other zones.

The power required for primary control is 3000 MW distributed throughout the control zones whereas the frequency control related to keeping the time for electric grid controlled watches is accomplished by operating the system at slightly deviating frequencies in a diurnal pattern so that the frequency on an average is 50 Hz.

In the Scandinavian grid a similar scheme is operated in the NORDEL system.

4.5 Reactive Power

Reactive power is a concept associated with oscillating exchange of energy stored in capacitive and inductive components in a power system. Reactive power is produced in capacitive components (e.g. capacitors, cables) and consumed in inductive components (e.g. transformers, motors, fluorescent tubes). The synchronous generator is special in this context as it can either produce reactive power (the normal situation) when overmagnetised or consume reactive power when undermagnetised. Voltage control is effected by controlling the magnetising level of the generator i.e. a high magnetising level results in high voltage and production of reactive power.

As the current associated with the flow of reactive power is perpendicular (or 90 deg. out of phase) to the current associated with active power and to the voltage on the terminals of the equipment the only energy lost in the process is the resistive losses in lines and components. The losses are proportional to the total current squared. Since the active and reactive currents are perpendicular to each other, the total resulting current is the root of the squared sum of the two currents and the reactive currents hence contribute as much to the system losses as do the active currents. To minimise the losses it is necessary to keep the reactive currents as low as possible and this is accomplished by compensating reactive consumption by installing capacitors at or close to the consuming inductive loads. Furthermore, large reactive currents flowing to inductive loads is one of the major causes of voltage instability in the network due to the associated voltage drops in the transmission lines. Locally installed capacitor banks mitigates this tendency and increases the voltage stability in area.

Many WT are equipped with induction generators. The induction generator is basically an induction motor, and as such a consumer of reactive power, in contrast to the synchronous generator which can produce reactive power. At no load (idling), the consumption of reactive power is in the order of 35-40% of the rated active power increasing to around 60% at rated power. In any given local area with WT, the total reactive power demand will be the sum of the demand of the loads and the demand of WT. To minimise losses and to increase voltage stability, the WT are compensated to a level between their idling reactive demand and their full load demand, depending on the requirements of the local utility or distribution company. Thus the power factor of WT, which is the ratio between active power and apparent power, is in general in the range above 0.96.

For WT with pulse width modulated inverter systems the reactive power can be controlled by the inverter. Thus these WT can have a power factor of 1.00. But these inverter systems also give the possibility to control voltage by controlling the reactive power (generation or consumption of reactive power).

4.6 Protection

The extent and type of electrical protective functions in a WT is governed by two lines of consideration. One is the need to protect the WT, the other to secure safe operation of the network under all circumstances.

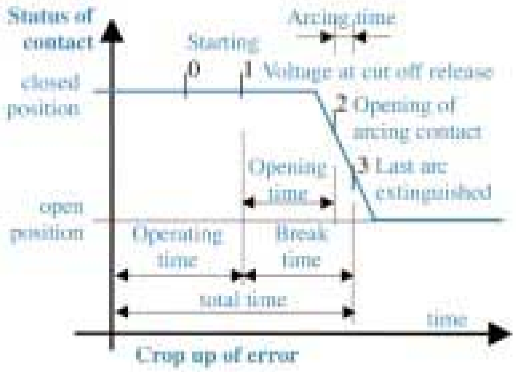

Figure 4.6: Definitions for the cut-off of circuit breakers

- Over fequency (one level delayed, capacitors instantaneously)
- Under frequency (one level delayed)
- Over voltage (one level delayed, one level instantaneously
- Under voltage (one level delayed)
- Loss of mains (instantaneously)
- High overcurrents (short circuit)
- Thermal overload
- Earth fault
- Neutral voltage displacement

Table 4.2: Required functions

The faults associated with first line are short circuits in the WT, overproduction causing thermal overload and faults resulting in high, possibly dangerous, overvoltages, that is earthfaults and neutral voltage displacement.

The second line can be described as the utility view, that is the objective is to disconnect the WT when there is a risk to other consumers or to operating personnel. The faults associated with this line are situations with unacceptable deviations in voltage and/or frequency and loss of one or more phases in the utility supply network. The required functions are given in table 4.2

Depending on the WT design, that is if it can operate as an autonomous unit, a Rate Of Change Of Frequency (ROCOF) relay may be needed to detect a step change in frequency indicating that the WT is operating in an isolated part of the network due for example to tripping of a remote line supplying the area.

In Germany the grid protection device of WT will be tested according [1]. The test shows the capability of the WT, to meet grid protection limiting values set by utilities. During this test the reaction of the WT is checked and recorded for voltage and frequency exceeding upper and lower limits. Responding levels and response times are recorded and depicted in the final data sheet. The functionality of the complete protection system is also verified and certificated.

The present development, where large - hundreds of MW - off shore wind farm will be built and operated in concentrated areas, and the subsequent requirement for stability during grid faults, will put forward new requirements to the protection of WT (see below).

4.7 Network stability

The problem of network stability has been touched upon briefly above. Three issues are central in the discussion and all are largely associated with different types of faults in the network such as tripping of transmission lines (e.g. overload), loss of production capacity (e.g. any fault in boiler or turbine in a power plant) and short circuits.

Permanent tripping of transmissions lines due to overload or component failure disrupts the balance of power (active and reactive) flow to the adjacent areas. Though the capacity of the operating generators is adequate large voltage drops may occur suddenly. The reactive power following new paths in a highly loaded transmission grid may force the voltage operating point of the network in the area beyond the border of stability. A period of low voltage (brownout) possibly followed by complete loss of power is often the result.

Loss of production capacity obviously results in a large power unbalance momentarily and unless the remaining operating power plants have enough so called "spinning reserve", that is generators not loaded to their maximum capacity, to replace the loss within very short time a large frequency and voltage drop will occur followed by complete loss of power. A way of remedy in this situation is to disconnect the supply to an entire area or some large consumers with the purpose of restoring the power balance and limit the number of consumers affected by the fault.

Short circuits take on a variety of forms in a network and are by far the most common. In severity they range from the one phase earth fault caused by trees growing up into an overhead transmission line, over a two phase fault to the three phase short circuit with low impedance in the short circuit itself. Many of these faults are cleared by the relay protection of the transmission system either by disconnection and fast reclosure, or by disconnection of the equipment in question after a few hundred milliseconds. In all the situations the result is a short period with low or no voltage followed by a period where the voltage returns. A large - off shore - wind farm in the vicinity will see this event and disconnect from the grid immediately if only equipped with the protection described above. This is equivalent to the situation "loss of production capacity" and disconnection of the wind farm will further aggravate the situation. Up to now, no utility has put forward requirement to dynamic stability of WT during grid faults. The situation in Denmark today, and the visions for the future, have changed the situation and for wind farms connected to the transmission grid, that is at voltages above 100 kV, this will be required.

4.8 Switching operations and soft starting

Connection and - to a smaller degree - disconnection of electrical equipment in general and induction generators/motors especially, gives rise to so called transients, that is short duration very high inrush currents causing both disturbances to the grid and high torque spikes in the drive train of a WT with a directly connected induction generator.

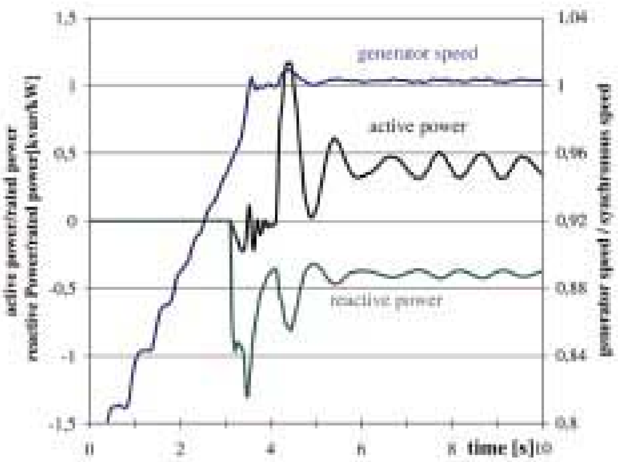

Figure 4.7: Cut-in of a stall regulated WT with direct coupled induction generator

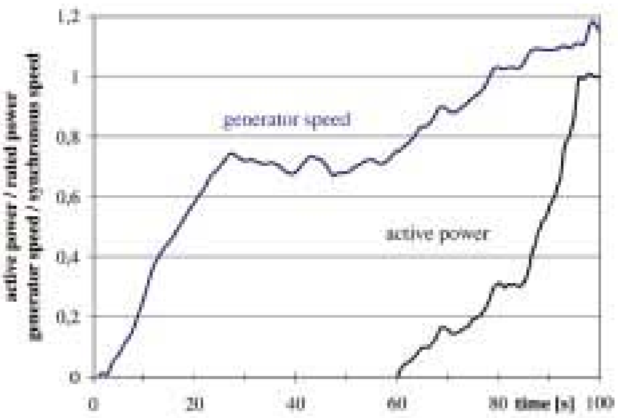

Figure 4.8: Cut-in at rated wind speed of a variable speed WT with power electronics

In this context WT fall into two classes. One featuring power electronics with a rated capacity corresponding to the generator size in the main circuit and one with zero or low rating power electronics in a secondary circuit - typically the rotor circuit of an induction generator.

The power electronics in the first class can control the inrush current continuously from zero to rated current. Its disturbances to the grid during switching operations are minimal and it will not be discussed further here.

Unless special precautions are taken, the other class will allow inrush currents up to 5-7 times the rated current of the generator after the first very short period (below 100ms) where the peak are considerably higher, up to 18 times the normal rated current. A transient like this disturbs the grid and to limit it to an acceptable value all WT of this class are equipped with a current limiter or soft starter based on thyristor technology which typically limits the highest RMS value of the inrush current to a level below two times the rated current of the generator. The soft starter has a limited thermal capacity and is short circuited by a contactor able to carry the full load current when connection to the grid has been completed. In addition to reducing the impact on the grid, the soft starter also effectively dampens the torque peaks in the air gap of the generator associated with the peak currents and hence reduces the loads on the gearbox.

4.9 Costs of Grid Connection

The costs for grid connection can be split up in two. The costs for the local electrical installation and the costs for connecting the wind farm to the electrical grid.

The local electrical installation comprises the medium voltage grid in the wind farm up to a common point and the necessary medium voltage switch gear at that point. Cited total costs for this item ranges from 3 to 10 % of the total costs of the complete wind farm. It depends on local equipment prices, technical requirements, soil conditions, the distance between the turbines, the size of the wind farm and hence the voltage level for the line to the connecting point the existing grid. If the wind farm is large and the distance to the grid long there may be a need for a common transformer stepping up the medium voltage in the wind farm to the local high voltage transmission level.

The costs for connection to the electrical grid ranges from almost 0% for a small farm connected to an adjacent medium voltage line and upwards. For a 150 MW off-shore wind farm a figure of 25% has been given for this item.

Item	**Offshore**		**Onshore**
	Costs in Mill. €	%	%
Foundations	36	16	5.5
Wind turbines	113	51	71.0
Internal electric grid	11	5	6.5
Offshore transformer station	4.5	2	-
Grid connection	40	18	7.5
O&M facilities	4.5	2	-
Engineering and project administration	8.9	4	2.5
Miscellaneous	4.5	2	7
Total:	222	100	100

Table 4.3: Costs of a 150 MW wind farm

Cost of electricity delivered to the grid from offshore wind energy.

Compared to onshore wind farms there is a number of additional costs and uncertainties to take into account when assessing the production costs from large offshore wind farms. The relationship between the different cost items usually specified is quite different from the relationship found for onshore wind farms.

The following Table 4.3 indicates a probable distribution between the different items for a 150 MW offshore wind farm situated approximately 20 km from the shore and with a further 30 km to the nearest high voltage substation where it can be connected to the existing grid. The table further gives the absolute costs in Mill. € (Euro) and - for comparison - shows the distribution between comparable items for a typical onshore wind farm.

The cost of electricity consists of capital costs (interest and repayment) for the investment and costs of operation and maintenance. It is usually expressed as an amount per kWh produced. For typical Danish onshore wind farms situated in places with average wind conditions the equivalent number of full load hours will be in the range 2000 - 2200 hours stretching up to 2500 hours for the best sites. For offshore wind farms in Danish coastal waters, i.e. with wind conditions determined by the same wind climate in the upper atmosphere, figures in the range 3200 - 3500 equivalent full load hours are predicted.

An assessment of costs for operation and maintenance (O&M) for offshore wind farms can be based on known figures for onshore installations. For the 500 - 600 kW generation of WT - where no long term figures are known - recent statistic indicate costs of 0.005 - 0.007 €/kWh for privately owned wind farms and a somewhat lower values for utility owned. In the Danish feasibility studies for offshore wind farms a figure of 0.01 €/kWh has been used. This figure will be used here as well.

The cost of electricity will further depend heavily on the rate of interest for the investment and the depreciation time for the loans.

When the project is built, the cost and financial conditions are known and the uncertainty associated with depreciation time and interest disappears leaving production and O&M costs as the main uncertainties. The wind conditions and prediction techniques over open water are less known than for onshore sites and - though costly - wind speed measurements on site must be strongly recommended. The difference between the above cited figures for equivalent full load hours for on- and offshore installations underscores this need.

O&M cost is a different matter. Experience so far allows no long term precise prediction for offshore wind farms and it is not likely that the costs will remain constant throughout the lifetime (20 years or more) of the installation. If the depreciation time is long - as for some utility owned wind farms - it is likely that a refurbishment will be needed. To take this into account, two approaches are often used:

A fixed amount per kWh produced plus a lump sum for major repair work at a certain point in time. For an onshore wind farm, indicative figures for this approach are 0.007 €/kWh plus 20 % of the initial investment in the WT for major refurbishment during the 11th year of operation. Possible figures for Offshore installations could be 0.01 €/kWh plus 30% of the initial investment.

The second approach is to use a gradual - and linear - increase of the costs throughout the depreciation period. Again, for an onshore wind farm, indicative figures for this approach is 0.007 €/kWh immediately after commissioning increasing to 0.01 €/kWh at the end of the period. Possible figures for an offshore wind farm using this approach could be a start value of 0.01 €/kWh increasing to 0.016 €/kWh.

The future development of production costs from offshore wind farms is closely connected to the technological development of WT and electrical transmission systems (grid connection) as these two items account for a very high proportion of the total cost of offshore installations (70% in the example in table 4.3.).

The tremendous drop in onshore wind energy production prices since the early eighties seem to have levelled off and future price decreases will take place at a slower pace. The main reason for this could be explained by the fact, that the WT have grown into mature technical products with correspondingly smaller marginals for cost decreases.

New technologies for transmission of electrical energy are being developed, in particular the transistor (IGBT - Isolated Gate Bipolar transistor) technology for high voltage direct current (HVDC) transmission. The technology is on the brink of commercial break through and while a potential for price reductions is obviously there, the potential is still unknown - not at least due to lack of competition as there is as yet only few manufacturers of this type of systems. The technology however holds promises as it opens for a number of new design options (see the section on connection to the electricity supply system) that will ease the integration of large amounts of wind energy into the electrical supply system.

All in all: there is a potential for future reductions in production prices from offshore wind farms but they will come slowly and a dramatic change as the one seen for onshore wind power since the early eighties is not likely.

4.10 Safety, Standards and Regulations

Measurement guidelines

The following guidelines give rules and requirements for the measurement of power quality of WT:

- IEC 61400-21-CDV:
  Wind Turbines –
  Part 21: Measurement
  and assessment of power quality
  characteristics of grid connected
  wind turbines.
- MEASNET ”Power quality measurement
  procedure”, November 2000.
- German guideline: Technische
  Richtlinien für Windenergieanlagen,
  Teil 3: Bestimmung
  der Elektrischen Eigenschaften,
  Rev. 13. 01.01.2000. Fördergesellschaft
  Windenergie e.V. FGW, Hamburg.

In addition to the measurement requirements the IEC guideline gives methods for estimating the power quality expected from WT or wind farms when deployed at a specific site.

MEASNET is a network of European measuring institutes with the aim of harmonising measuring procedures and recommendations in order to achieve comparability and mutual recognition of the measurement results of the member institutes.

The German guideline is a national guideline, but is also accepted in other countries. The guideline is different from the IEC-guideline. Thus results from the German guideline and from the IEC guideline are not completely comparable.

Guidelines for grid connection

The following guidelines give requirements and limited values for the grid connection of WT:

- Eigenerzeugungsanlagen am Mittelspannungsnetz. Richtlinie für Anschluß und Parallelbetrieb von Eigenerzeugungsanlagen am Mittelspannungsnetz.
  2. Ausgabe 1998. Vereinigung Deutscher Elektrizitätswerke VDEW e.V. (Frankfurt am Main). Frankfurt am Main: Verlags- und Wirtschaftsgesellschaft der Elektrizitätswerke m.b.H. VWEW.
- Connection of wind turbines to low and medium voltage networks.
  October 1998, Komité rapport 111-E. DEFU, DK-2800 Lyngby.
- Anslutning av mindre produktionsanläggningar till elnätet. Sveriges Elleverantörer, Stockholm 1999.
- Specifications for connecting Wind Farms to the transmission grid.
  Second Edition 2000. Eltra amba, DK.

These three guidelines are national guidelines:
• The German VDEW guideline is based on the results on the German measurement guideline. The Danish and the Swedish guidelines are based on results of the IEC 61400-21 measurement guideline.
• There is no specific international standard, giving limits and recommendations for grid connection of WTGS. However there are IEC guidelines for special items of power quality, but not especially for WTS. The IEC 61000-3-6 gives requirements concerning harmonics and the IEC 61000-3-7 gives requirements concerning flicker:
• IEC 61000-3-6: 1996, EMC. Part 3: Limits - Section 6: Assessment of emission limits for distorting loads in MV and HV power systems - Basic EMC publication. (Technical report)
IEC 61000-3-7: 1996, EMC. Part 3: Limits – Section 7: Assessment of emission limits for fluctuating loads in MV and HV power systems - Basic EMC publication. (Technical report)

4.11 Calculation methods

In the following an example is given for the calculation of the perturbation of the grid by WT. The assessment is performed according to the methods given in the IEC 61400-21 /2/. WT influences the power quality concerning:

- steady-state voltage
- flicker
- harmonics
- switchings (voltage change and flicker)

For each item the emission of the WTGS has to be checked.

Example:

A wind farm, consisting of 3 WT, each of 600kW rated power, shall be connected to a 10kV medium voltage network. From the power quality measurement of the WT, which was performed according to IEC 61400-21, the data, given in table 4.4 are available. The data of the network, which are given by the utility, are also listed in table 4.4. The WT are stall regulated and have fixed speed.

a. Steady-State voltage

The best solution for the determination of the steady-state voltage change by the WT would be a load flow calculation, where all the situations of the network, the loads and the WT could be proved. But in general only extreme values are checked.
4 extreme cases should be the minimum for load flow calculations:

- low loads and low wind power
- low loads and high wind power
- high loads and low wind power
- high loads and high wind power

A more simple method for the calculation of the steady-state voltage change is given by:

$$d = \frac{S_{60}}{S_k} \cdot \left|\cos(\psi + \varphi)\right|$$

only valid for $\cos(\psi+\varphi) > 0.1$
S_k: short circuit power of the grid at the point of common coupling (PCC)
S_{60}: apparent power at the 1-min. active power peak
d: steady state voltage change of the grid at PCC (normalised to nominal voltage)
φ: phase angle between voltage and current
ψ: grid impedance phase angle

The apparent power S_{60} and the phase angle φ can be calculated from the active 1-minute power peak P_{60} and from the belonging reactive power Q_{60}, which are given in the power quality data sheet of the WT. In this case the calculation of S_{60} and of the phase angle φ gives:

S_{60} = 655 kVA, φ = 10 ° (inductive)

With this information the voltage change due to a single WT can be calculated as:

d = 1.11 %

For the whole wind farm (3 WT) the voltage change is as follows:

$d_{\text{wind farm}}$ = 3.32 %

In Germany the maximum permitted steady state voltage change by WT is 2 % of nominal voltage, which is exceeded by the wind farm for the given example. But the more exact load flow calculation could give lower values. In other countries the limited values can be different.

b. Flicker

The flicker distortion for continuous operation of the WT can be calculated by:

$$P_{lt} = c(\psi_k, v_a) \cdot \frac{S_n}{S_k}$$

S_k:	short circuit power of the grid at the point of common coupling (PCC)
ψ_k:	grid impedance angle at PCC
v_a:	annual average wind speed
S_n:	apparent power of the WT at rated power
$c(\psi_k, v_a)$:	flicker coefficient
P_{lt}:	flicker distortion

For the given example the annual average wind speed of the site of the wind farm at hub height of the turbines is 7.2 m/s. Thus the wind speed class of 7.5 m/s is used. The power quality data sheet only gives the flicker coefficients at the grid impedance angles 50° and 70°. But the grid impedance angle of the site is 55°. Thus the flicker coefficient at 55° is interpolated from the values at 50° and 70°. This interpolation gives a flicker coefficient of c(55°,7.5m/s)=5.8.

From this flicker coefficient and the above equation the flicker distortion P_{lt} of a single WT is calculated as P_{lt} = 0.141. Due to smoothing effects the flicker distortion of the whole wind farm is not n-times

Data of the power quality measurement of the WT according to IEC61400/21/2/:

rated power p_n=600 kW
rated apparent power: S_n=607 kVA
rated voltage: U_n=690 V
rated current In=508 A
max. power P_{60}=645 kW
max. Reactive power Q_{60}=114 kvar

Flicker:

Grid impendance angle ψ_k:	30°	50°	70°	85°
Annual av. wind speed v_a (m/s):	Flicker coefficient, $c(\psi_k, v_a)$:			
6.0 m/s	7.1	5.9	5.1	6.4
7.5 m/s	7.4	6.0	5.2	6.6
8.5 m/s	7.8	6.5	5.6	7.2
10.0 m/s	7.9	6.6	5.7	7.3

Switching operations:

Case of switching operation:	cut-in at cut in wind speed			
Max. number of switchings N_{10}:	3			
Max. number of switchings N_{120}:	30			
Grid impendance angle, ψ_k:	30°	50°	70°	85°
Flicker step factor k_f (ψ_k):	0.35	0.34	0.38	0.43
Voltage change factor k_u (ψ_k):	0.7	0.7	0.8	0.9

Case of switching operation:	cut-in at rated wind speed			
Max. number of switchings N_{10}:	1			
Max. number of switchings N_{120}:	8			
Grid impendance angle, ψ_k:	30°	50°	70°	85°
Flicker step factor k_f (ψ_k):	0.35	0.34	0.38	0.43
Voltage change factor k_u (ψ_k):	1.30	0.85	1.05	1.60

Data of the site:

annual average wind speed: v_a=7.2 m/s
nominal voltage of the grid: 10 kV
Short circuit power of the grid: S_k=25 MVA
grid impendance angle: ψ_k=55°
Number of wind turbines: N=3
Type of wind turbine: stall, direct
grid coupled induction generator

Table 4.4: Data of the WT and of the site

higher (n: number of turbines of the wind farm) than the flicker distortion of a single WT. Instead it is the square root of the number of turbines. In this example it is:

$$P_{lt\ windfarm} = \sqrt{n} \cdot P_{lt\ single\ wind\ turbine} = \sqrt{3} \cdot 0.141 = 0.244$$

IEC61000-3-7 gives a maximum permitted flicker level for medium voltage grids of P_{lt}=0.25. Thus the flicker during continuous operation is within the limits.

c. Harmonics

A WT with an induction generator directly connected to the electrical system is not expected to cause any significant harmonic distortions during normal operation. Only WT with power electronics have to be checked concerning harmonics.

The harmonic current emission of such WT with power electronics are given in the power quality data sheet. Limits for harmonic emissions are often given only for harmonic voltages, not for harmonic currents. Thus harmonic voltages must be calculated from the harmonic current emission of the WT. But the grid impedances vary with frequency, where the utilities often can not give the frequency dependency of the grid impedances, which makes calculations difficult. In Germany also limits for harmonic currents are given. Thus it has only to be checked, if the harmonic current emission is within the limits.

For the given example harmonics have not be checked, because the WT have directly grid connected induction generators without power electronics.

d. Switching operations

For switching operations two criterions must be checked: the voltage change due to the inrush current of a switching and the flicker effect of the switching.

On the assumption that a control of a wind farm ensures, that two or more WT of a wind farm are not switched on simultaneously, only one WT has to be taken into account for the calculation of the voltage change:

$$d = k_u(\psi_k) \cdot \frac{S_n}{S_k}$$

S_n: apparent power of the WT at rated power
S_k: short circuit power of the grid at the point of common coupling (PCC).
$k_u(\psi_k)$: voltage change factor
d: relative voltage change

For the example the worth case of switchings concerning the voltage change is the cut-in of the WT at rated wind speed. For this switching the voltage change factor is $k_u(55°) = 0.9$ (interpolation of the voltage change factors at 50 ° and at 70 °. From this the voltage change due to the switching of a single WT is d = 2,19%.

The flicker emission due to switching operations of a single WT can be estimated by:

$$P_{lt} = 8 \cdot N_{120}^{0.31} \cdot k_f(\psi_k) \cdot \frac{S_n}{S_k}$$

S_n: apparent power of the WT at rated power
S_k: short circuit power of the grid at the point of common coupling (PCC).
$k_f(\psi_k)$: flicker step factor
N_{120}: Number of switchings within a 2 hours period.
P_{lt}: flicker distortion

The flicker effect has to be calculated for both types of switching: for the cut-in at cut-in wind speed and for the cut-in at rated wind speed. For both types of switchings the power quality data sheet gives the essential data: The flicker step factor at 55° must be interpolated from the values at 50° and 70°, the number of switchings within a 2-hours period are given. But for the wind farm these numbers must be multiplied by the number of WT. Thus it can be calculated:

cut-in at cut-in wind speed:
number of switchings: $N*N_{120}=3*30$
flicker step factor: $k_f(55°)=0,35$
thus the flicker distortion by cut-in switchings at cut-in wind speed is calculated as: P_{lt}=0.27.

cut-in at rated wind speed:
number of switchings: $N*N_{120}=3*8$
flicker step factor: $k_f(55°)=0,62$
thus the flicker distortion by cut-in switchings at rated wind speed is calculated as: P_{lt}=0.32.

The flicker distortions of both types of switchings exceeds the flicker level of 0.25. Thus improvements should be made. The improvement could be made by strengthen the grid or by improve the power quality behaviour of the WT, may be by limiting the number of switchings within a 2-hours period or by decreasing the flicker emission during switchings.

5 Integration into the National Grid

5.1 Emission Savings

Numerous utility studies have shown that a unit of wind energy saves a unit of energy generated from coal, gas or oil - depending on the utility's plant [3]. Each unit of electricity generated by wind energy saves emissions of greenhouse gases, pollutants and waste products.

Emission savings depend on the mix of plant operated by the utility. WT and wind farms usually run whenever they can do so and when they come on-line they displace the so-called "load following" plant. These are the generating sets, which are loaded and unloaded to follow fluctuations in demand. In many parts of Europe (with the exception of Sweden and Finland, which have a high proportion of hydro plant) they are coal-fired, a situation likely to continue for some years. In island systems, however, wind may displace oil-fired generation and in the future wind may displace gas-fired generation.

The emissions saved by displacing coal plant are in the range 850-1450g/kWh of carbon dioxide, plus oxides of sulphur and nitrogen. The exact savings in a particular system depend on the efficiency of the generating plant and the type of fuel displaced. Table 5.1 shows data for five EU states, drawn from the studies cited in reference [3]. The reports quoted emission savings for a 5% (energy) penetration level. The displaced fuel was generally coal, although in Ireland and Germany a mixture of fuels was saved. Levels of sulphur dioxide savings, also shown, depend on whether or not flue gas desulphurisation equipment is fitted. Columns 6-9 are specific estimates for several fuels [4]; although the study was carried out in the UK, levels elsewhere are very similar. Using wind energy also saves waste ash, typically around 34g/kWh of electricity generated[5].

Column	1	2	3	4	5	6	7	8	9
States	DE	GB	IR	NL	P				
Fuels						Coal	Coal + FGD	Oil	CCGT
Carbon dioxide	642	870	690	1,440	983	935	973	741	421
Nitrogen oxides	0.5	2.4	2.1	1.22	3	4.5	2.8	1.9	0.007
Sulphur dioxide	0.5	1.2	4.5	0.5	0.2	nq	nq	nq	nq
Carbon monoxide	nq	nq	nq	nq	nq	0.13	0.13	0.14	0.41

nq= not quoted

Table 5.1: Emissions saved by wind energy, in g/k Wh of electricity generated

5.2 Energy Credit

Fuel savings are the major economic benefit from wind energy plant. The savings result from the reduced need to run other generating plant. This, in turn, results in lower fuel and related variable costs, including maintenance and staff costs. In the European Union, wind energy will usually replace coal plant, (except in Sweden and Finland - where hydro may be displaced and France - where nuclear may be displaced) as this is the plant which is used for load following.

Fuel	Price, €/GJ	Thermal efficiency	Energy credit, €/kWh
Coal	2	35 %	0.0205
Gas	3.3	55 %	0.0215

Table 5.2: Reference values of energy credits

Calculation methods for the energy cost savings arising from the introduction of wind energy on a network vary. There are three factors to be taken into account:

- Fuel savings
- Operation and maintenance cost savings
- Penalties arising from the enforced operation of additional thermal plant at part load

As coal and gas prices are now reasonably uniform across the European Union, it is possible to estimate reference prices for these fuels. These are summarised in the table 5.2. These values do not, of course, apply when the Hydro or nuclear plant are replaced by wind energy. Values in these cases tend to be specific to the particular location.

The variable component of operation and maintenance costs for coal plant is around € 0.003/kW. Additional savings from the installation of wind energy plant may accrue due to reductions in the energy losses in transmission and distribution systems. As these losses may account for around 10% of the overall energy in an electricity network, their value may be significant. Levels are site-specific and in some instances, when the addition of the wind plant adds to system losses, the value will be negative.

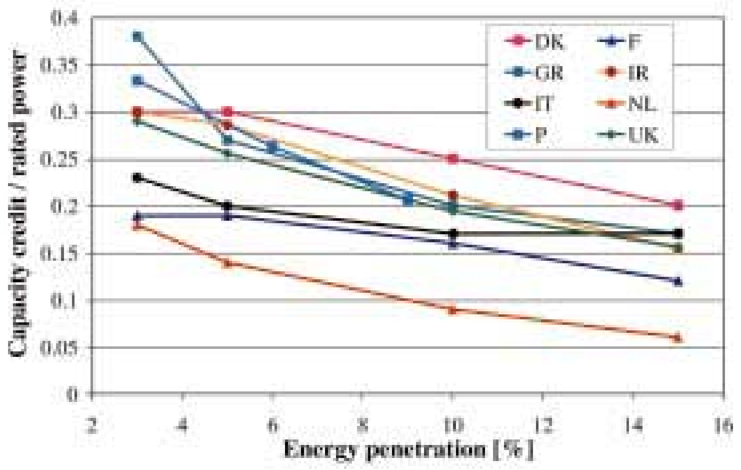

Figure 5.1: Capacity Credits–EU

The operational penalties arising from the installation of wind energy on an electricity network are extremely small until the amount of wind energy rises to around 10% of the total. One study [6] suggested that this level of penetration would incur a penalty around € 0.0016/kWh, but recent data suggests that the variations in wind output may be less than expected and so this estimate may be pessimistic.

5.3 Capacity Credit

There is no universally-agreed definition of capacity credit but the following would be generally acceptable [7]: „The amount of conventional generating capacity which can be omitted from a utility's planned requirements if a wind power plant is planned".

A utility's need for capacity is dictated by the magnitude of the peak demands on its system. A key issue, therefore, is the ability of wind plant to contribute to this demand. As wind power is intermittent, it is sometimes argued that it has no capacity credit. However, conventional thermal plant is not 100% reliable and power system operations depend on assessments of risk. No system is risk-free, and plant needs are framed to keep the risks within defined limits. Risk is a statistical concept, which relies on time-averaged estimates of plant output, so the average expectation of a 1000 MW nuclear plant being ready to provide full output at peak times is, say, 90%. Similarly the average expectation of wind plant being able to provide full output is, say, 30%, to first order.

A simple mathematical analysis can be used to prove this point and show that the contribution of any item of power plant to firm capacity is equal to the average power it can generate [8].

Several studies have addressed the issue in more detail and their conclusions are succinctly summarised in one of the utility studies [9]: „At low (energy) penetration the firm power that can be assigned to wind energy will vary in direct proportion with the expected output at time of system risk". In practice, this statement is true for any energy source whether it is renewable or not. It may be noted at this point that „firm power" is not the same as „capacity credit"; capacity credits are usually related to the conventional plant that is displaced by wind. 100 MW of wind might have a "firm power" equivalent of 30 MW, say (its load factor), but the capacity credit would be 33.3 MW, assuming the winter peak availability of thermal plant was 90%.

In northern Europe, where peak demands on most electricity systems occur around 1800 hours during the winter months[10], the output, and hence the capacity credit, of wind plant in Europe is generally around 10-25 % higher than the average power, as wind strengths are higher in winter [11].

As the amount of wind in a system rises, its intermittent nature does mean that the capacity credit declines. Figure 5.1 shows data from 9 studies carried out by EU states, showing how the credit changes up to energy penetrations of around 15%. The exact levels differ, as they depend on wind speeds and the characteristics of the utility systems.

6 Case Studies

6.1 Tunø Knob Wind farm, DK

Tunø Knob is the second of two off-shore wind farms built by the Danish utilities as part of the agreement between the Danish Government and the utilities to build and operate wind farms as part of the country's electricity supply system. The farm consists of 10 pitch controlled 500 kW WT of type V39 made by Vestas Wind Systems A/S. The turbines have induction generators with a slip of 1.8 %. Builder and owner of the wind farm is I/S Midtkraft – one of the 6 local production companies making up the utility group ELSAM. The wind farm was put into operation in early October 1995. The operating experience up to now has been good showing monthly availabilities of above 95% except for short periods where the turbines have been stopped in connection with birdlife studies on the site and exchange of one of the transformers (see below). The production in each of the three full years (1996- 1998) of operation until now has been 12.623, 13.021 and 15.126GWh respectively. The original estimated average wind speed was 7.5 m/s at hub height (43 m above average water level including foundation) but the achieved production figures (corrected for the missing production during stops as outlined above) indicate a wind energy resource about 20 % above the original estimate.


Figure 6.1: Tunø Knob offshore wind farm

Tunø Knob wind farm is situated in the shallow water between the east coast of Jutland and the small island of Tunø and just north of the reef Tunø Knob. The water depth varies between 3.1 and 4.7 m. The distance to Jutland is about 6 km and there are 3 km to the island Tunø. The roughness class is consequently very close to 0.

The ten turbines are placed in two rows facing north-south and with 400 m between the rows and 200 m between the turbines. Each WTGS is equipped with a dry-type cast resin insulated transformer stepping the voltage up from 0.7 kV (the generator voltage) to 10 kV. The transformers have a rated power of 510 kVA, no-load losses of 1.445 kW, total load losses of 5.6 kW and are placed in the bottoms of the towers. The turbines are connected in a ring by a 3 x 150 mm^2 Cu-PEX submarine cable with sea armour. The wind farm is connected to the nearest 60/10 kV transformer station by a combined sea and landcable. The landcable is a 3 x 240 mm^2 Al-PEX with an approximate length of 2.5 km. The cable is, together with radials to other consumers, connected to the 10 kV bus of the station through a circuit breaker. The short circuit power level of the 10 kV busbar is 55 MVA corresponding to a short circuit ratio of approximately 11. All submarine cables are washed 1 m down into the bottom to prevent damage from anchoring ships.

The total cost of the project was 10.4 M€, about 11 % below the budget. The total cost of electrical works were 2.6 M€ excluding transformers and ring main units which were supplied together with the WT. The costs of grid connection, i.e. the cable connecting the wind farm to the on-shore station and circuit breaker, was approximately 1.8 M€.


Figure 6.2: Tunø Knob offshore wind farm

There have not been reported any problems with the power quality in the point of common coupling to other consumers (the 10 kV busbar in the 60/10 kV transformer station). In September 1998 one of the transformers in the WTGS developed a fault and had to be replaced. The lead time for the delivery of the replacement was 2.5 month and the turbine was back in operation in December the same year.

6.2 Rejsby Hede Wind Farm, DK

Rejsby Hede wind farm in the extreme south-western corner of Denmark is the largest wind farm

Figure 6.3: Wind farm Rejsby Hede

built in Denmark as one project. The wind farm consists of forty Micon M1500 - 600/150 kW turbines with a total installed capacity of 24 MW. The turbines have induction generators with a nominal speed of 1500 RPM and 0.4 % slip. The wind farm is build as part of the agreement between the Danish Government and the utilities to build and operate wind farms as part of the country's electricity supply system. Builder and owner of the wind farm is Sønderjyllands Højspændingsværk An/S – one of the 6 local production companies making up the utility group ELSAM. The wind farm was put into operation on August 1, 1995 and operating experience has been good showing annual availabilities in the above 97% range. The production in each of the three full years (1996-1998) of operation until now has been 48.7, 52.3 and 61.7GWh respectively.

Rejsby Hede wind farm is, as already mentioned, situated in Jutland, in the most south-westerly corner of Denmark 1.5 to 3 km from the coastline behind the dike facing the wadden-sea just south-east of the village Rejsby. The surrounding terrain is flat pastoral with hedges and fields. The average wind speed is calculated to 6.1 m/s. The turbines are placed in 9 rows facing east-west with from 4 to 6 turbines in each row and with 260 m between WT and rows. In the north-south direction there is a small shift between the WT.

The wind farm is connected to a 60 kV overhead line passing immediately beside the site through a 3-winding 60/15 kV transformer in order to keep the short circuit power level down on each of the 15 kV busses. The transformer has a rating of 31.5 MVA (2 x 15.75 MVA) and a nominal e_{sc} of 10 %. The load losses are 73 kW per winding and the no load losses are 16.5 kW. The short circuit power level on each of the 15 kV busses are 120 MVA. There are 2 respectively 3 outgoing radials from the two 15kV busbars with a total of 18 and 22 WT respectively. The cables are connected through circuit breakers to the busses. From the station each of the 5 radials expands into a tree structure in order to reduce the number of ring main units and thus reduce the costs. Cabling between the turbines and between the turbines and the station is done with different cross-section underground Al-PEX cables. Four different types with cross-sections from 25 to 150 mm^2 are used depending on the loading. The lengths of the cables vary from 273 to 924 m and the total amount of cables used is:

150 mm^2 Al-PEX.	5126 m
95 mm^2 Al-PEX.	4252 m
50 mm^2 Al-PEX.	6478 m
25 mm^2 Al-PEX.	2939 m

The generator voltage of the WT are 0.7 kV and there is a step-up transformer to 15 kV placed immediately beside each turbine. The transformers are oil-filled distribution transformers with a rated power of 800 kVA, nominal e_{sc}= 6 %, no-load losses 1.09 kW and total load losses of 8.19 kW.

The total cost of electrical works in the wind farm and the transformer station amounts to 2.2 M€. The cost of grid connection was and reinforcement were zero as the 60 kV line passes directly by. The cost of the 60/15 kV station was 0.88 M€ and the remaining electrical works in the wind farm i.e. 15 kV cables, transformers and 0.7 kV cables 1.3 M€.

There have not been reported any problems with the power quality in the point of common coupling with other consumers, i.e. the 60 kV terminals of the 60/165 kV substation, and there have not been any problems associated with electrical components or issues.

The needs and ways of compensating the reactive power demand of induction generators and the reactive loads they supply with active power have been discussed at length during the last 20 years. Modern power electronics provides the means for continuous and fast adjustment of the reactive compensation level and at the same time contribute to improve the power quality of the wind farm. Although no problems were reported or expected, Rejsby Hede Wind farm was found to be a suitable place to test this new technology and a 2 x 4 Mvar Static Var Compensator (SVC) was installed as part of the R&D efforts directed towards developing this new technology for practical use in power systems. The project was supported by the European Commission within the "Joule-Thermie" Programme.

6.3 Delabole wind farm, UK

The first wind farm built in the UK was completed in December 1991 and comprises 10 400 kW WT. The turbines are of the constant speed type with induction generators. As the wind farm was the first in the UK it has been extensively monitored and detailed insights into the wind characteristics, machine performance and electrical aspects have been obtained.

The machines generate at 690 volts and step-up transformers are positioned at the base of each WT to raise the voltage to 11 kV, which is used for interconnections within the farm.

The wind farm output is brought together at a central sub station, where an 11/33 kV transformer raises the voltage for connection into the local distribution network.

Figure 6.4: Delabole wind farm, UK

Shortly after the wind farm was commissioned measurements were carried out to establish the effect of the wind farm on the local distribution network. In addition it was necessary to determine whether faults on the local distribution network would affect the wind farm. It was not certain, for example, whether or not switching operations and trips would cause the WT generators to trip.

Current surges when the WT are first connected are limited by „soft-start" thyristor equipment. This is common practice and limits the current at starting to the level corresponding to maximum output. During the test programme the voltage dip on the network was measured at start-up and it was found that the most severe dip occurred when the first turbine was started. The voltage dip increased as the fault level was reduced. The recommended limit of a 1% dip was exceeded when the fault level fell below 40 MVA, 100 times the power rating of an individual WT.

Measurements of current fluctuations during erratic wind conditions to showed that large step changes in output did not occur and even under severe gusting conditions the wind farm took two to three minutes to reach maximum output. Conversely, when the local circuit breaker was tripped and produced an 8 % voltage dip, the wind farm continued to operate.

As the wind farm is situated in a lightly populated rural area, there were times when it's output provided the entire local load supplied by an 11 kV sub station. Surplus power flowed „backwards" into the 33 kV system and no voltage problems were experienced.

Minor problems encountered included measurable voltage fluctuations at blade passing frequency and some generation of harmonics but neither was detectable by consumers in the area.

6.4 Cold Northcott Wind Farm, UK

The Cold Northcott Wind farm in Cornwall, UK, originally comprised 21 300 kW WT, generating at 415 volts and connected to individual generation step-up transformers.

The possibility of employing either underground interconnections or pole mounted overhead lines was examined. Important factors which influenced the choice were environmental factors and cost.

The site was expected to offer a harsh environment to overhead lines in terms of wind loading, ice loading and lightning. These do not pose problems in the case of underground cables. In any case, it would be necessary to use short runs of cable close to the turbines to clear the turbine blades. On the other hand, cable trenching for about 18 inches in depth was not be seen as a problem with an automatic trench cutter. Cabling was seen as providing an aesthetic arrangement, with more appeal to the public.

Rough estimates showed that the underground cables would cost some 7 ECU (1988 levels) per metre extra compared with overhead line costs. With an estimated route length of 10km, the additional cost of cabling would therefore be in the order of 70,000 ECU, small compared with the overall cost. Furthermore this would be offset by the possible difference in line repair costs over a 30-year period.

Two alternative transformer configurations were assessed:

- 500 kVA, the nominal reactance between windings was 4.75 percent, which results in a relatively low voltage drop for 326kVA loading of about 3.0 percent.
- 315 kVA rating, with an interwinding voltage drop of 4.9 percent.

The price difference per transformer was in the order of 1400 ECU per transformer or 30,800 ECU for the 22 machines.

An assessment was made of the energy losses associated with the annual operating characteristics expected for the Cold Northcott site. The results were:

- 6,297 kWh for the 500kVA transformer
- 12,72 kWh for the 315kVA transformer

(Photo by Helge Pommer, IfE Ingenieurges. für Energieprojekte mbH & Co. KG)

Figure 6.6: Installation of a wind turbine at Wybelsumer Polder

This gave a difference of 6423kWh, which is additional energy lost by the small transformer each year. Based on the energy revenue of 11pence per kWh, the loss amounts to 9600 ECU over a 10-year period. The wind farm would contain 22 transformers and hence would lose 240,000 ECU per annum over a 10-year period. Based on a net return of 8 percent per annum, this would capitalise to a value of 520,000 ECU over the period. Based on the assumed operating conditions, the 500kVA unit was judged to be the best choice technically and economically. Although wind energy prices have fallen substantially since the time the appraisal was made, the use of the larger transformer would still be the most economic option

6.5 Wybelsumer Polder, D

The wind farm Wybelsumer Polder is located in the north-west part of Germany near to the shore, where the region is very flat. The wind farm consists of 41 WT of E66 manufactured by Enercon, Germany. The rated power of each turbine is 1.5 MW, that means an installed power of the wind farm of 61.5

(Photo by Helge Pommer, IfE Ingenieurges. für Energieprojekte mbH & Co. KG)

Figure 6.5: Part of the wind farm Wybelsumer Polder

Figure 6.8: Single WT at Belvedere, Germany

MW. The hub heights of the wind turbines are 68 m. From June 1997 until end of 1999 7 WT were erected. In 2000 27 WT will be installed. The rest, 7 WT, will be installed in 2001.

With the annual wind speed of 8.0 m/s at hub height the energy production of the first WT, installed in 1997, was 4.500MWh per year and per WT.
The wind farm is split into two parts. One part, consisting of 16 WT belongs to the local utility. These WT are connected to an existing substation from 20 kV to 110 kV. Within the wind farm the WT are connected by a ringed network by cables of Al 240 mm^2.

The second part of the wind farm consists of 25 turbines. Owner is a consortium of private people. For the grid connection of these WT a separate substation (20 kV to 110 kV) was installed. Within this part of the wind farm the turbines are connected by a radial network, where cables of Al 150 mm^2 and Al 240 mm^2 were used. The total length of the cabling is 28 km. The costs for the grid connection of this second part of the wind farm can be split into costs of the substation (2.3 Mill.€), costs of the cabling within the wind farm (0.28 Mill.€) and costs for the reinforcement of the grid (4.6 Mill.€).

A separate 110 kV line of some km length will be installed to connect the wind farm to the high voltage system. This line will also take in the energy production of additional smaller wind farms in the region Krummhörn, a region with a higher than-average penetration of wind power.

6.6 Belvedere, D

Belvedere is a single WT project located in the north-west of Germany. It is a typical project for wind energy utilisation in single units in Northern Germany. The turbine is located directly at a agricultural farm, the main cultivation is for dairy farming and growing of cereals. In the beginning of wind energy development in Germany this type of utilisation was the most important one; mainly farmers started to develop a new, additional economic basis by operating a single WT on their farm. Generally the additional income improved the situation for the involved farmers reasonably. With the growing wind energy development in Germany, stimulated by a new building law, the single turbine installation scheme was replaced by the development of wind farms. Nowadays areas for wind energy utilisation are legally established in many German communities, so that today prevailingly wind farms are installed instead of single units.

The WT at the Belvedere site is a Vestas V42 with 600kW rated power, 42m rotor diameter and a hub height of 53m. The turbine was installed in October 1995 and is operating since with good technical availability. The average annual energy production amounts to 1.400MWh/a.

The turbine generates power at a voltage level of 690V, which is transformed to 20MV. The transformer is located in a separate building together with the medium voltage switch gear and the utility energy counters. The distance between transformer and turbine is about 30m. The transformer

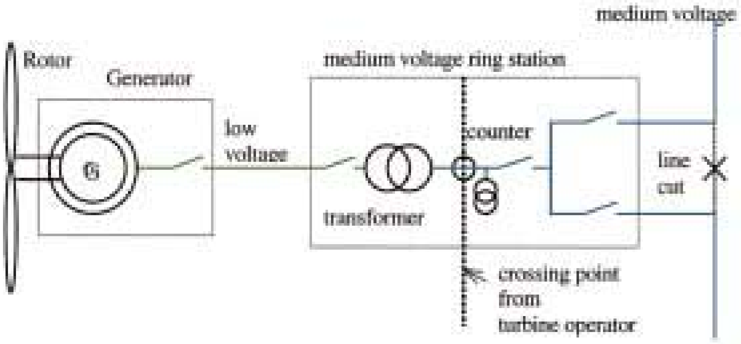

Figure 6.7: Grid connection sheme of the single wind turbine

is connected to the medium voltage line by a cable of approximately 10km length. All low and medium voltage cables are laid underground according to the standard of the local utility. The costs for grid connection cost were extremely high; due to the large number of installed WT the grid reinforced to be paid to the utility amounted to approximately 150 €/kW. The total cost for grid reinforcement and grid connection amounted to nearly 20 % of the total investment costs, including transformer and switch gear the amount was nearly 28 %.

7 Glossary

Distribution network, distribution grid:
used to connect consumers to the transmission network.

Electrical network:
particular installations, lines and cables for the transmission and distribution of electricity.

Flicker:
voltage fluctuations cause changes of the luminance of lamps which can create the visual phenomenon called flicker.

Induction generator (asynchronous generator):
used to convert mechanical power to electric power.

Inverter system:
in this context the inverter system converts alternating current into alternating current, but at different frequency.

Point of common coupling (PPC):
the point on an electrical network, electrically nearest to a particular installation, and at which other installations are, or may be, connected. An installation may in this context supply or consume electricity.

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NOTICE TO THE READER

Extensive information on the European Union is available through the EUROPA service at internet website address http://europa.eu.int

The overall objective of the European Union's energy policy is to help ensure a sustainable energy system for Europe's citizens and businesses, by supporting and promoting secure energy supplies of high service quality at competitive prices and in an environmentally compatible way. European Commission DG for Energy and Transport initiates, coordinates and manages energy policy actions at, transnational level in the fields of solid fuels, oil & gas, electricity, nuclear energy, renewable energy sources and the efficient use of energy. The most important actions concern maintaining and enhancing security of energy supply and international cooperation, strengthening the integrity of energy markets and promoting sustainable development in the energy field.

A central policy instrument is its support and promotion of energy research, technological development and demonstration (RTD), principally through the ENERGIE sub-programme (jointly managed with DG Research) within the theme 'Energy, Environment & Sustainable Development' under the European Union's Fifth Framework Programme for RTD. This contributes to sustainable development by focusing on key activities crucial for social well-being and economic competitiveness in Europe.

Other programmes managed by DG Energy and Transport such as SAVE, ALTENER and SYNERGY focus on accelerating the market uptake of cleaner and more efficient energy systems through legal, administrative, promotional and structural change measures on a trans-regional basis. As part of the wider Energy Framework Programme, they logically complement and reinforce the impacts of ENERGIE.

The internet website address for the Fifth Framework Programme is
http://www.cordis.lu/fp5/home.html

Further information on DG for Energy and Transport activities is available
at the internet website address
http://europa.eu.int/comm/dgs/energy_transport/index_fr.html

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