# Power Electronics Control of Wind Energy in Distributed Power Systems

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## 1. Introduction

In classical power systems, large power generation plants located at adequate geographical places produce most of the power, which is then transferred towards large consumption centres over long distance transmission lines. The system control centres monitor and regulate the power system continuously to ensure the quality of the power, namely frequency and voltage. However, now the overall power system is changing, a large number of dispersed generation (DG) units, including both renewable and non-renewable sources such as wind turbines, wave generators, photovoltaic (PV) generators, small hydro, fuel cells and gas/steam powered Combined Heat and Power (CHP) stations, are being developed (Heier, 1998), (Bossany, 2000) and installed. A wide-spread use of renewable energy sources in distribution networks and a high penetration level will be seen in the near future in many places. For instance Denmark has a high power capacity penetration (> 20%) of wind energy in major areas of the country and today around 20% of the whole electrical energy consumption is covered by the wind energy. The main advantages of using renewable energy sources are the elimination of harmful emissions and inexhaustible resources of the primary energy. The availability of renewable energy sources has strong daily and seasonal patterns and the power demand by the consumers could have a very different characteristic. Therefore, it is difficult to operate a power system installed with only renewable generation units due to the characteristic differences and the high uncertainty in the availability of the renewable energy sources. This is further strengthened as no real large energy storage systems exist.
The wind turbine technology is one of the most emerging renewable energy technologies. It started in the 1980'es with a few tens of kW power capacity to today with multi-MW size wind turbines that are being installed. It also means that wind power production in the beginning did not have any impact on the power system control but now due to their size they have to play an active role in the grid. The technology used in wind turbines was in the beginning based on a squirrel-cage induction generator connected directly to the grid. By that power pulsations in the wind are almost directly transferred to the electrical grid. Furthermore, there is no control of the active and reactive power, which typically are important control parameters to regulate the frequency and the voltage. As the power range of the turbines increases these control parameters become more important and it is

necessary to introduce power electronics (Hansen et al., 2002) as an interface between the wind turbine and the grid. The power electronics is changing the basic characteristic of the wind turbine from being an energy source to be an active power source. The electrical technology used in wind turbines is not new. It has been discussed for several years e.g. (Hansen et al. 2004); (Gertmar, 2003); (Blaabjerg et al., 2004); (Iov & Blaabjerg, 2007) etc. but now the price pr. produced kWh is so low, that solutions with power electronics are very attractive.
Firstly, the basic development in power electronics and power electronic conversion will be discussed. Then, different wind turbine configurations will be explained both aerodynamically and electrically. A short overview of the interconnection requirements will be given. Also, different control methods for power converters within a wind turbine system will be presented. Finally, a general technology status of the wind power is presented demonstrating still more efficient and attractive power source for the future.

## 2. Modern power electronics

Power electronics has changed rapidly during the last thirty years and the number of applications has been increasing, mainly due to the developments of the semiconductor devices and the microprocessor technology. For both cases higher performance is steadily given for the same area of silicon, and at the same time they are continuously reducing in price. A typical power electronic system, consisting of a power converter, a renewable energy source and a control unit, is shown in Fig. 1.

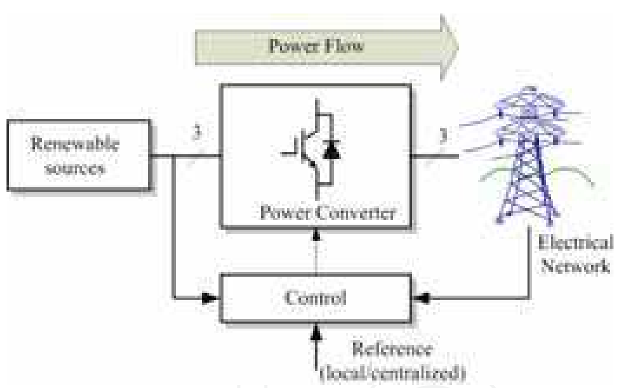


Fig. 1. Power electronic system with the grid, renewable source, power converter and control.

The power converter is the interface between the generator and the grid. Typically, the power flow is uni-directional from the generator to the electrical network. Three important issues are of concern using such a system namely the reliability, the efficiency and last but not least the cost. Currently, the cost of power semiconductor devices is decreasing 1÷5 % every year for the same output performance and the price pr. kW for a power electronic system is also decreasing. An example of a mass-produced and high competitive power electronic system is an adjustable speed drive (ASD). The trend of weight, size, number of components and functions in a standard Danfoss Drives A/S frequency converter can be seen in Fig. 2. It clearly shows that power electronic conversion is shrinking in volume and weight. It also shows that more integration is an important key to be competitive as well as more functions become available in such a product.

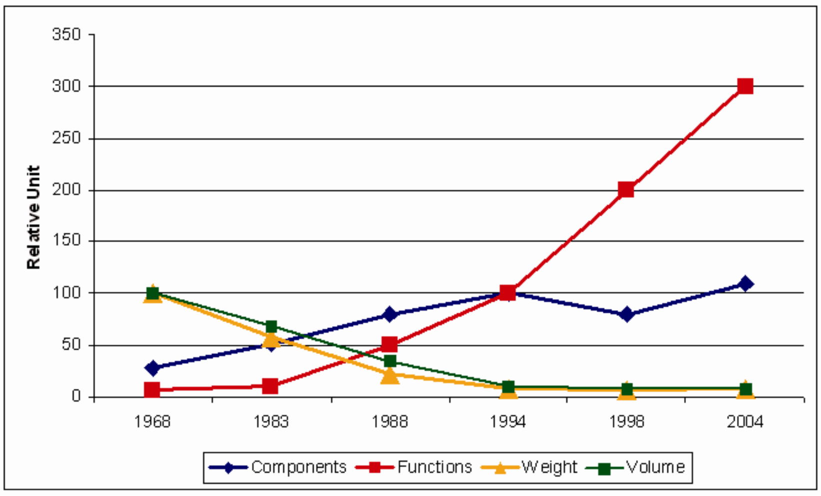

Fig. 2. Development of standard adjustable speed drives for the last four decades.

The key driver of this development is that the power electronic device technology is still undergoing important progress. An overview of different power devices and the areas where the development is still going on is presented in Fig. 3.

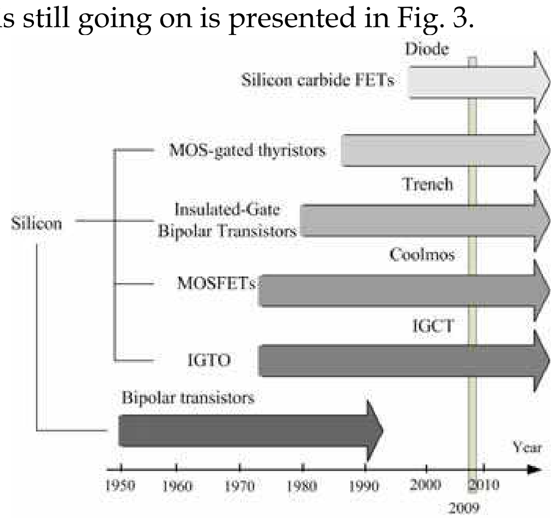

Fig. 3. Development of power semiconductor devices in the past and in the future (based on (Baliga, 1995)).

The only power device which is not under development anymore is the silicon-based power bipolar transistor because MOS-gated devices are preferable in the sense of easy control. The breakdown voltage and/or current carrying capability of the components are also continuously increasing. Important research is going on to change the material from silicon to silicon carbide, which may dramatically increase the power density of power converters as well as their voltage capability. Using such devices a direct connection on the medium voltage networks of the power converters without a step-up transformer may be possible.

## 3. Wind energy conversion

Wind turbines capture power from the wind by means of aerodynamically designed blades and convert it to rotating mechanical power. The number of blades is three in a modern wind turbine. As the blade tip-speed should be lower than half the speed of sound the rotational speed will decrease as the radius of the blade increases. For multi-MW wind turbines the rotational speed is typically 10-15 rpm. The most weight efficient way to convert the low-speed, high-torque power to electrical power is to use a gear-box and a standard fixed speed generator as illustrated in Fig. 4.

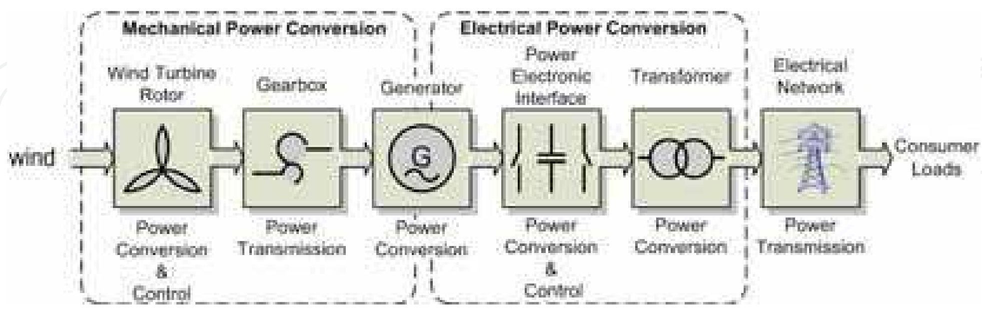


Fig. 4. Converting wind power to electrical power in a wind turbine (based on Kazmierkowski et al., 2002)).

The gear-box is optional as multi-pole generator systems are also possible solutions. Between the grid and the generator a power converter can be inserted. The possible technical solutions are many and a technological roadmap starting with wind energy/power and converting the mechanical power into electrical power is shown in Fig. 5. The electrical output can either be AC or DC. In the last case a power converter will be used as interface to the grid.

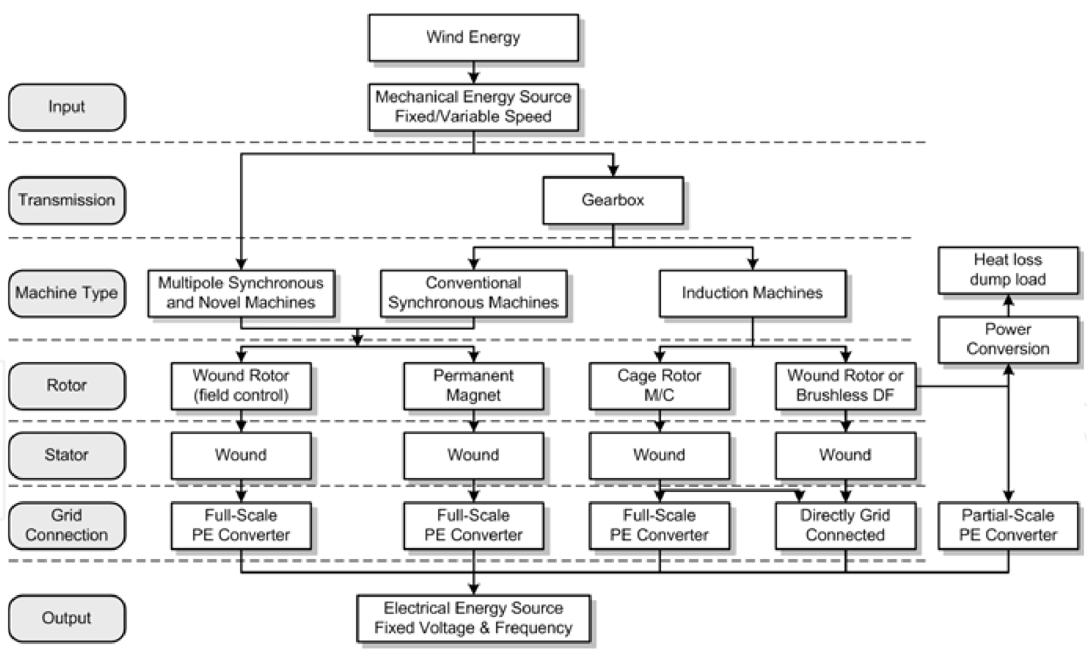


Fig. 5. Technological roadmap for wind turbine's technology (based on (Hansen et al., 2001)).

The development in wind turbine systems has been steady for the last 25 years and four to five generations of wind turbines exist and it is now proven technology. It is important to be able to control and limit the converted mechanical power at higher wind speed, as the power in the wind is a cube of the wind speed. The power limitation may be done either by stall control (the blade position is fixed but stall of the wind appears along the blade at higher wind speed), active stall (the blade angle is adjusted in order to create stall along the blades) or pitch control (the blades are turned out of the wind at higher wind speed) (Hansen et al., 2004), (Iov & Blaabjerg, 2007). The basic output characteristics of these three methods of controlling the power are summarized in Fig. 6. The modern wind turbines use only active stall and pitch control.

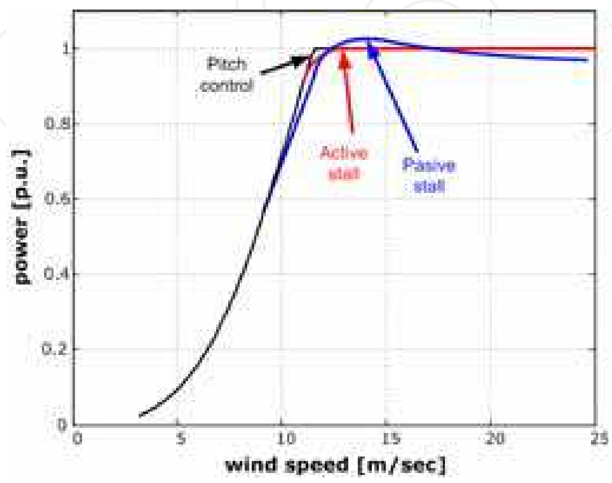


Fig. 6. Power characteristics of different wind turbine systems.

Another control variable in a wind turbine system is the speed. Based on this criterion the wind turbines are classified into two main categories (Hansen et al., 2004), (Iov & Blaabjerg, 2007); namely fixed speed and variable speed wind turbines respectively.
Additionally, the presence of power converters in wind turbines also provides high potential control capabilities for both large modern wind turbines and wind farms to fulfil the high technical demands imposed by the grid operators (Sørensen et al., 2000); (Hansen et al., 2004); (Milborrow, 2005) and (Iov & Blaabjerg, 2007), such as: controllable active and reactive power (frequency and voltage control); quick response under transient and dynamic power system situations, influence on network stability and improved power quality.

## 4. Wind Turbine Concepts

The most commonly applied wind turbine designs can be categorized into four wind turbine concepts. The main differences between these concepts concern the generating system and the way in which the aerodynamic efficiency of the rotor is limited during above the rated value in order to prevent overloading. These concepts are presented briefly in the following paragraphs.

### 4.1 Fixed Speed Wind Turbines

This configuration corresponds to the so called Danish concept that was very popular in 80's. This wind turbine is fixed speed controlled machine, with asynchronous squirrel cage induction generator (SCIG) directly connected to the grid via a transformer as shown in Fig. 7. This concept needs a reactive power compensator to reduce (almost eliminate) the reactive power demand from the turbine generators to the grid. It is usually done by continuously switching capacitor banks following the production variation (5-25 steps) Smoother grid connection occurs by incorporating a soft-starter. Regardless the power control principle in a fixed speed wind turbine, the wind fluctuations are converted into mechanical fluctuations and further into electrical power fluctuations. These can yield to voltage fluctuations at the point of connection in the case of a weak grid. Because of these voltage fluctuations, the fixed speed wind turbine draws varying amounts of reactive power from the utility grid (in the case of no capacitor bank), which increases both the voltage fluctuations and the line losses.

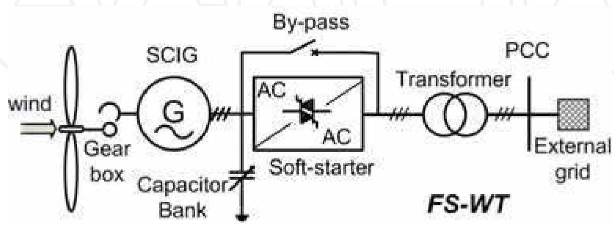


Fig. 7. Fixed speed wind turbine with directly grid connected squirrel-cage induction generator.

Thus, this concept does not support any speed control, requires a stiff grid and its mechanical construction must be able to support high mechanical stress caused by wind gusts.

### 4.2 Partial Variable Speed Wind Turbine with Variable Rotor Resistance

This configuration corresponds to the limited variable speed controlled wind turbine with variable rotor resistance, known as OptiSlip (VestasTM) as presented in Fig. 8.

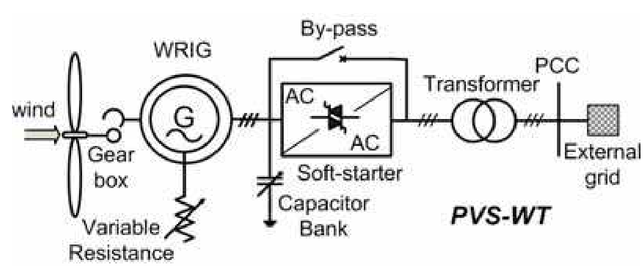


Fig. 8. Partial variable speed wind turbine with variable rotor resistance.

The generator is directly connected to the grid. The rotor winding of the generator is connected in series with a controlled resistance, whose size defines the range of the variable speed (typically 0-10% above synchronous speed). A capacitor bank performs the reactive power compensation and smooth grid connection occurs by means of a soft-starter. An extra resistance is added in the rotor circuit, which can be controlled by power electronics. Thus, the total rotor resistance is controllable and the slip and thus the power output in the system are controlled. The dynamic speed control range depends on the size of the variable rotor resistance. Typically the speed range is 0-10% above synchronous speed. The energy coming from the external power conversion unit is dumped as heat loss.

### 4.3 Variable Speed WT with partial-scale power converter

This configuration, known as the doubly-fed induction generator (DFIG) concept, corresponds to the variable speed controlled wind turbine with a wound rotor induction generator (WRIG) and partial-scale power converter (rated to approx. 30% of nominal generator power) on the rotor circuit as shown in Fig. 9. The stator is directly connected to the grid, while a partial-scale power converter controls the rotor frequency and thus the rotor speed.

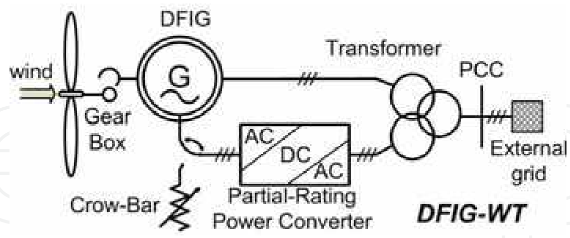


Fig. 9. Variable speed wind turbine with partial scale power converter.

The power rating of this partial-scale frequency converter defines the speed range (typically ±30% around synchronous speed). Moreover, this converter performs the reactive power compensation and a smooth grid connection. The control range of the rotor speed is wide compared to that of OptiSlip. Moreover, it captures the energy, which in the OptiSlip concept is burned off in the controllable rotor resistance. The smaller frequency converter makes this concept attractive from an economical point of view. Moreover, the power electronics is enabling the wind turbine to act as a more dynamic power source to the grid. However, its main drawbacks are the use of slip-rings and the complicated protection schemes in the case of grid faults.

### 4.4 Variable speed wind turbine with full-rating power converter

This configuration corresponds to the variable speed controlled wind turbine, with the generator connected to the grid through a full-rating power converter as shown in Fig. 10.

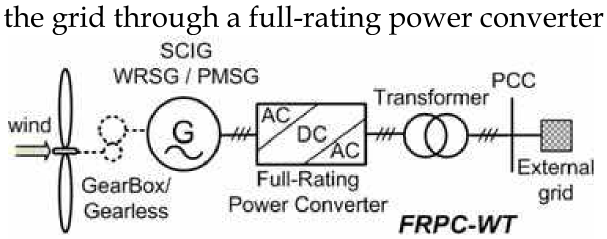


Fig. 10. Variable speed wind turbine with full-rating power converter.

The power converter performs the reactive power compensation and a smooth grid connection for the entire speed range. The generator can be electrically excited (wound rotor synchronous generator WRSG) or permanent magnet excited type (permanent magnet synchronous generator PMSG). The stator windings are connected to the grid through a full-scale power converter. Recently, due to the advancement in the power electronics the squirrel-cage induction generator has also started to be used for this concept.

Some variable speed wind turbines systems are gearless – see dotted gearbox in Fig. 10. In these cases, a direct driven multi-pole generator is used. The wind turbine companies Enercon, Siemens Wind Power, Made and Lagerwey are examples of manufacturers using this configuration.

The variable speed wind turbines are designed to achieve maximum aerodynamic efficiency over a wide range of wind speed. By introducing the variable speed operation, it is possible to continuously adapt (accelerate or decelerate) the rotational speed of the wind turbine to the wind speed, in such a way that tip speed ratio is kept constant to a predefined value

corresponding to the maximum power coefficient. Contrary to a fixed speed system, a variable speed system keeps the generator torque nearly constant. Thus, the variations in wind are absorbed by the generator speed changes.
Seen from the wind turbine point of view, the most important advantages of the variable speed operation compared to the conventional fixed speed operation are: reduced mechanical stress on the mechanical components such as shaft and gearbox, increased power capture and reduced acoustical noise.

## 5. Grid connection requirements for wind power

Some European countries have at this moment dedicated grid codes for wind power. These requirements reflect, in most of the cases, the penetration of wind power into the electrical network or that a future development is prepared.
The requirements for wind power cover a wide range of voltage levels from medium voltage to very high voltage. The grid codes for wind power address issues that make the wind farms to act as a conventional power plant into the electrical network. These requirements have focus on power controllability, power quality, fault ride-through capability and grid support during network disturbances. According to several references e.g. (Hansen et al., 2004) and (Milborrow, 2005) in some of the cases these requirements are very stringent. An overview of the most important requirements of the European grid codes is given in the following based on (Iov & Blaabjerg, 2007).

### 5.1 Active power control

According to this demand the wind turbines must be able to control the active in the Point-of-Common-Coupling (PCC) in a given power range. The active power is typically controlled based on the system frequency e.g. Denmark, Ireland, Germany so that the power delivered to the grid is decreased when the grid frequency rise above 50 Hz. A typical characteristic for the frequency control in the Danish grid code is shown in Fig. 11.

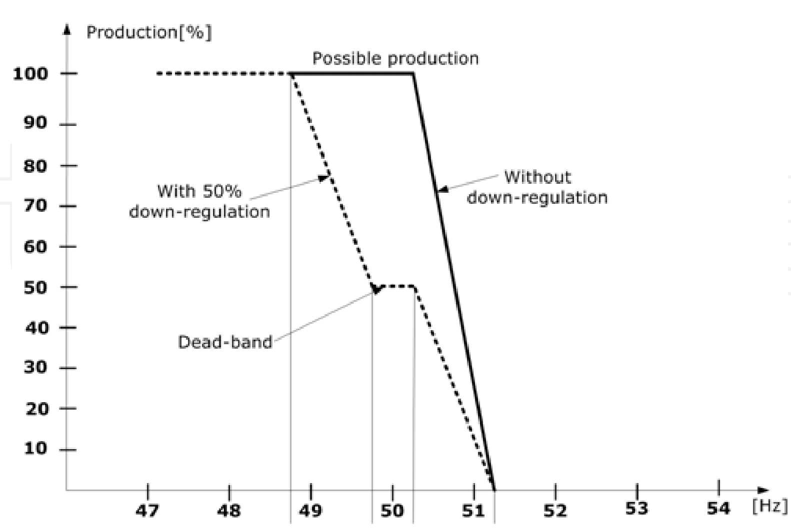


Fig. 11. Frequency control characteristic for the wind turbines connected to the Danish grid.

On the contrary other grid codes, e.g. Great Britain specifies that the active power output must be kept constant for the frequency range 49.5 to 50.5 Hz, and a drop of maximum 5% in the delivered power is allowed when frequency drops to 47 Hz.
Curtailment of produced power based on system operator demands is required in Denmark, Ireland, Germany and Great Britain. Currently, Denmark has the most demanding requirements regarding the controllability of the produced power. Wind farms connected at the transmission level shall act as a conventional power plant providing a wide range of controlling the output power based on Transmission System Operator's (TSO) demands and also participation in primary and secondary control. Seven power regulation functions, each of them prioritized, are required in the wind farm control as shown in Fig. 12.

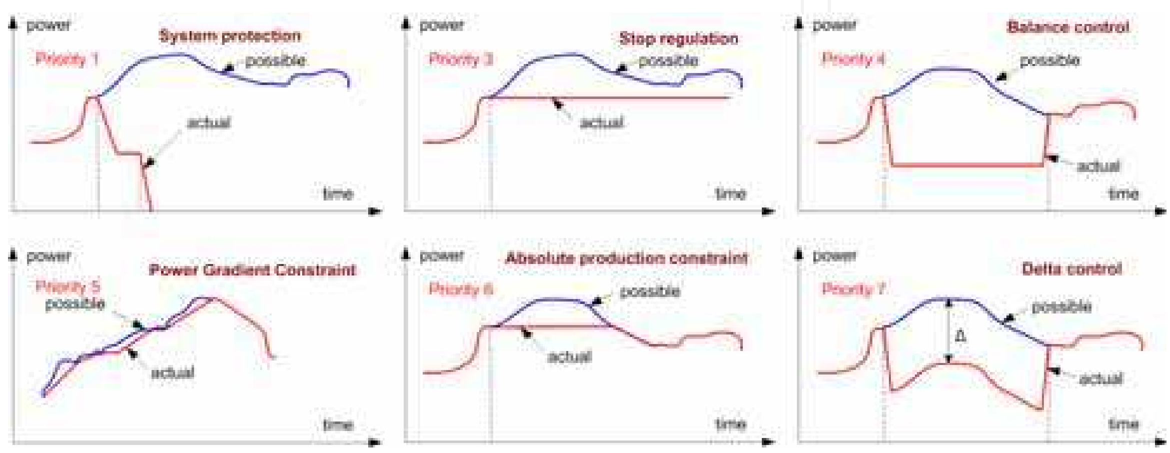

Fig. 12. Regulation functions for active power required by the Danish grid codes in the wind farm controller.

It must be noticed that the frequency control characteristic presented in Fig 11 has the second priority. Using all these power regulation functions a wind farm can be operated as a conventional power plant.

### 5.2 Reactive power control and voltage stability

Reactive power is typically controlled in a given range. The grid codes specify in different ways this control capability. The Danish grid code gives a band for controlling the reactive power based on the active power output as shown in Fig. 13.

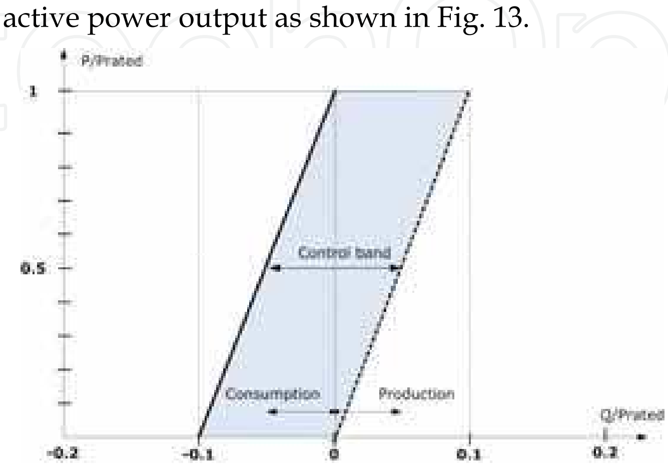

Fig. 13. Danish grid code demands for the reactive power exchange in the PCC.

The Irish grid code specifies e.g. the reactive power capability in terms of power factor and reactive power as shown in Fig. 14 while the German transmission grid code for wind power specifies that the wind power units must provide a reactive power provision in the connection point without limiting the active power output as shown in Fig. 15.

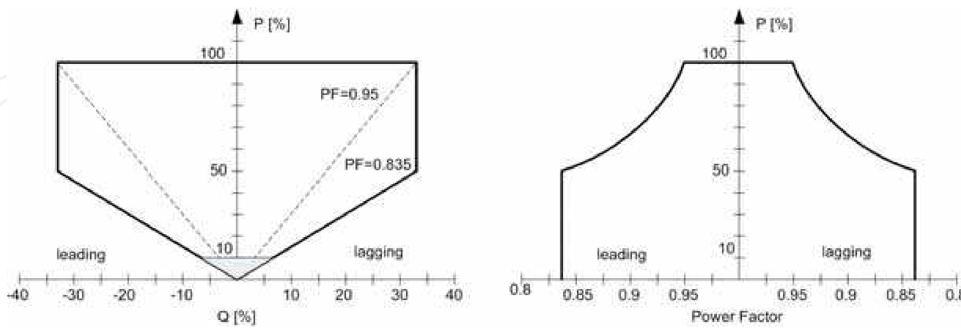


Fig. 14. Requirements for reactive power control in the Irish grid code for wind turbines.

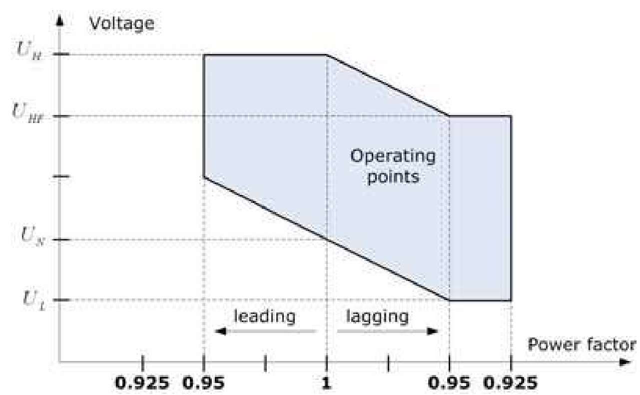


Fig. 15. Requirements for reactive power provision of generating units without limiting the active power output in the German transmission grid code.

### 5.3. Low-voltage ride-through capability

All considered grid codes requires fault ride-through capabilities for wind turbines. Voltage profiles are given specifying the depth of the voltage dip and the clearance time as well. One of the problems is that the calculation of the voltage during all types of unsymmetrical faults is not very well defined in some grid codes. The voltage profile for ride-through capability can be summarized as shown in Fig. 16.

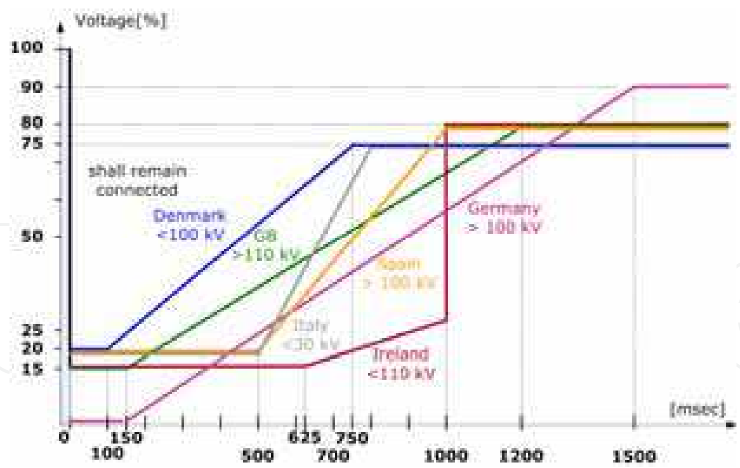


Fig. 16. Voltage profile for fault ride-through capability for wind power in European grid codes.

Ireland's grid code is very demanding in respect with the fault duration while Denmark has the lowest short circuit time duration with only 100 msec. However, Denmark's grid code requires that the wind turbine shall remain connected to the electrical network during successive faults which is a technical challenge. On the other hand Germany and Spain requires grid support during faults by reactive current injection up to 100% from the rated current as shown in Fig. 17. This demand is relative difficult to meet by some of the wind turbine concepts e.g. active stall wind turbine with directly grid connected squirrel cage induction generator.

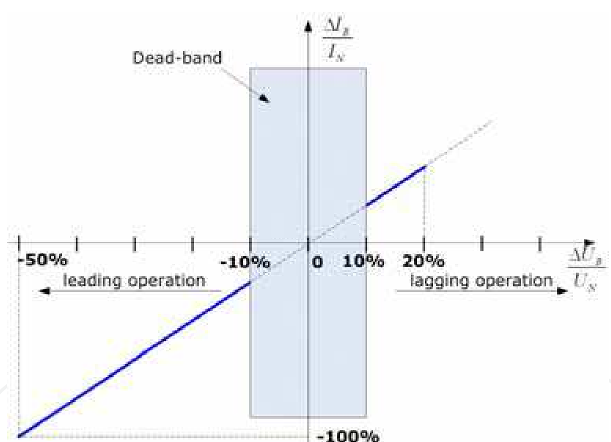


Fig. 17. Reactive current support during faults as specified in the German grid code.

Since more European countries are planning to increase the installed wind power capacity a change in their grid code requirements is expected in the near future. Also, in order to accommodate more wind power into the electrical networks, these connection requirements will be more demanding.

## 6. Power converter topologies for wind turbines

Basically two power converter topologies with full controllability of the generated voltage are currently used in the commercial wind turbine systems. These power converters are related to the partial-rating power converter wind turbine and the full-rating one. However, other topologies have been proposed in the last years.

### 6.1 Bi-directional back-to-back two-level power converter

The back-to-back Pulse Width Modulation-Voltage Source Converter is a bi-directional power converter consisting of two conventional PWM-VSCs. The topology is shown in Fig. 18.

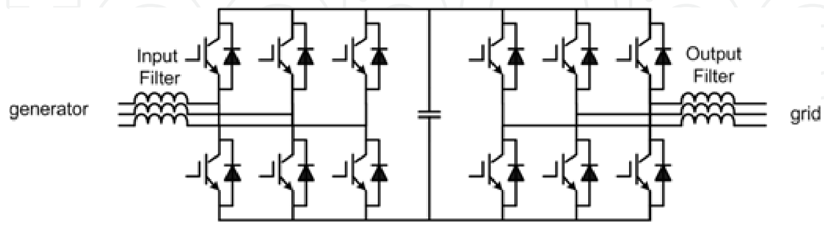


Fig. 18. Structure of the back-to-back voltage source converter.

The PWM-VSC is the most frequently used three-phase frequency converter. As a consequence of this, the knowledge available in the field is extensive and very well established. Furthermore, many manufacturers produce components especially designed for use in this type of converter (e.g., a transistor-pack comprising six bridge coupled transistors and anti-paralleled diodes). Therefore, the component costs can be low compared to converters requiring components designed for a niche production. A technical advantage of the PWM-VSC is the capacitor decoupling between the grid inverter and the generator inverter. Besides affording some protection, this decoupling offers separate control of the two inverters, allowing compensation of asymmetry both on the generator side and on the grid side, independently. The inclusion of a boost inductance in the DC-link circuit increases the component count, but a positive effect is that the boost inductance reduces the demands on the performance of the grid side harmonic filter, and offers some protection of the converter against abnormal conditions on the grid.

However, some disadvantages of the back-to-back PWM-VSC are reported in literature (Hansen et al., 2002) and (Kazmierkowski et al., 2002). In several papers concerning adjustable speed drives, the presence of the DC-link capacitor is mentioned as a drawback, since: it is bulky and heavy; - it increases the costs and maybe of most importance; - it reduces the overall lifetime of the system.

Another important drawback of the back-to-back PWM-VSI is the switching losses. Every commutation in both the grid inverter and the generator inverter between the upper and lower DC-link branch is associated with a hard switching and a natural commutation. Since the back-to-back PWM-VSI consists of two inverters, the switching losses might be even more pronounced. The high switching speed to the grid may also require extra EMI-filters. To prevent high stresses on the generator insulation and to avoid bearing current problems the voltage gradient may have to be limited by applying an output filter.

This topology is state-of-the-art especially in large DFIG based wind turbines e.g. (Carlson et al., 1996); (Bhowmik et al., 1999); (Ekanayake et al., 2003); (Gertmar, 2003) and (Carrasco et al., 2006). However, recently some wind turbine manufacturers use this topology for full-rating power converter wind turbines with squirrel-cage induction generator (e.g. Siemens Wind Power). The topology can also be used for permanent magnet synchronous generators.

**6.2 Unidirectional power converter**

A wound rotor synchronous generator requires only a simple diode bridge rectifier for the generator side converter as shown in Fig. 19.

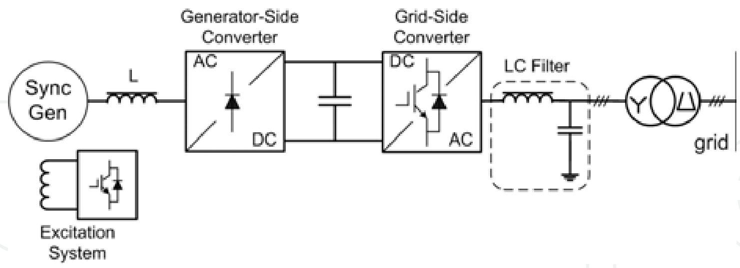


Fig. 19. Variable speed wind turbine with synchronous generator and full-rating power converter.

The diode rectifier is the most common used topology in power electronic applications. For a three-phase system it consists of six diodes. The diode rectifier can only be used in one quadrant, it is simple and it is not possible to control it. It could be used in some applications with a DC-link. The variable speed operation of the wind turbine is achieved by using an extra power converter which feed the excitation winding. The grid side converter will offer a decoupled control of the active and reactive power delivered to the grid and also all the grid support features. These wind turbines can have a gearbox or they can be direct-driven (Dubois et al., 2000). In order to achieve variable speed operation the wind turbines equipped with a permanent magnet synchronous generator (PMSG) will require a boost DC-DC converter inserted in the DC-link.

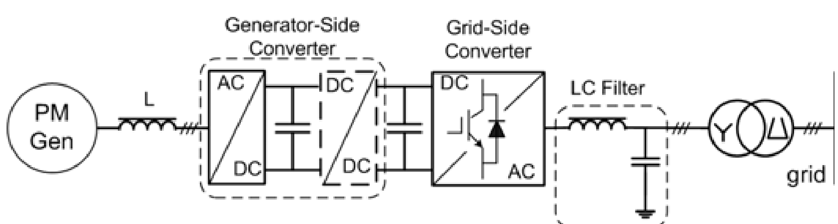


Fig. 20. Full rating power converter wind turbine with permanent magnet generator.

**6.3 Multilevel power converter**

Currently, there is an increasing interest in multilevel power converters especially for medium to high-power, high-voltage wind turbine applications (Carrasco et al., 2006) and (Portillo et al., 2006).

Since the development of the neutral-point clamped three-level converter (Nabae et al., 1981), several alternative multilevel converter topologies have been reported in the literature. The general idea behind the multilevel converter technology is to create a sinusoidal voltage from several levels of voltages, typically obtained from capacitor voltage sources. The different proposed multilevel converter topologies can be classified in the following five categories (Hansen et al., 2002); (Carrasco et al., 2006) and (Wu, 2006): multilevel configurations with diode clamps, multilevel configurations with bi-directional switch interconnection, multilevel configurations with flying capacitors, multilevel configurations with multiple three-phase inverters and multilevel configurations with cascaded single phase H-bridge inverters. These topologies are shown in Fig. 21 (Hansen et al., 2002).

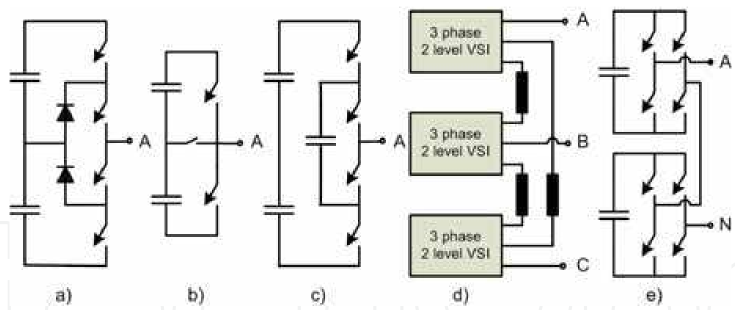


Fig. 21. Multilevel topologies: a) one leg of a three-level diode clamped converter; b) one leg of a three-level converter with bidirectional switch interconnection; c) one leg of a three-level flying capacitor converter; d) three-level converter using three two-level converters and e) one leg of a three-level H-bridge cascaded converter (Hansen et al., 2002).

Initially, the main purpose of the multilevel converter was to achieve a higher voltage capability of the converters. As the ratings of the components increases and the switching- and conducting properties improve, the secondary effects of applying multilevel converters become more and more advantageous. The reduced content of harmonics in the input and output voltage as well as a reduced EMI is reported (Hansen et al., 2002). The switching losses of the multilevel converter are another feature, which is often accentuated in literature. In (Marchesoni & Mazzucchelli, 1993), it is stated, that for the same harmonic performance the switching frequency can be reduced to 25% of the switching frequency of a two-level converter. Even though the conduction losses are higher for the multilevel converter, the overall efficiency for the diode clamped multilevel converter is higher than the efficiency for a comparable two-level converter (Hansen et al., 2002). Of course, the truth in this assertion depends on the ratio between the switching losses and the conduction losses.

However, some disadvantages exist and are reported in literature e.g. (Hansen et al., 2002); (Carrasco et al., 2006); (Portillio et al., 2006) and (Lai & Peng, 1995). The most commonly reported disadvantage of the three level converters with split DC-link is the voltage imbalance between the upper and the lower DC-link capacitor. Nevertheless, for a three-level converter this problem is not very serious, and the problem in the three-level converter is mainly caused by differences in the real capacitance of each capacitor, inaccuracies in the dead-time implementation or an unbalanced load (Shen & Butterworth, 1997) and (Hansen et al., 2001). By a proper modulation control of the switches, the imbalance problem can be solved (Sun-Kyoung Lim et al., 1999). In (Shen & Butterworth, 1997) the voltage balancing problem is solved by hardware, while (Newton & Sumner, 1997) and (Peng et al., 1995) proposed solutions based on modulation control. However, whether the voltage balancing problem is solved by hardware or software, it is necessary to measure the voltage across the capacitors in the DC-link.

The three-level diode clamped multilevel converter (Fig. 21a) and the three-level flying capacitor multilevel converter (Fig. 21c) exhibits an unequal current stress on the semiconductors. It appears that the upper and lower switches in an inverter branch might be de-rated compared to the switches in the middle. For an appropriate design of the converter, different devices are required (Lai & Peng, 1995). The unequal current stress and the unequal voltage stress might constitute a design problem for the multilevel converter with bidirectional switch interconnection presented in Fig. 21b (Hansen et al., 2002).

It is evident for all presented topologies in Fig. 21 that the number of semiconductors in the conducting path is higher than for e.g. a two-level converter. Thus, the conduction losses of the converter might increase. On the other hand, each of the semiconductors need only to block half the total DC-link voltage and for lower voltage ratings, the on-state losses per switch decreases, which to a certain extent might justify the higher number of semiconductors in the conducting path (Hansen et al., 2002).

### 6.4 Modular power converters

At low wind speeds and hence low level of the produced power, the full-rating power converter concept exhibits low utilization of the power switches and thus increased power losses. Therefore, a concept in which several power converters are running in parallel is used as shown in Fig. 22. The power converter in this case can be one of the structures presented above. This configuration can also be used for standard generators.
By introducing power electronics many of the wind turbine systems get similar performances with the conventional power plants. Modern wind turbines have a fast response in respect with the grid operator demands. However the produced real power depends on the available wind speed. The reactive power can in some solutions, e.g. full scale power converter based wind turbines, be delivered without having any wind producing active power.

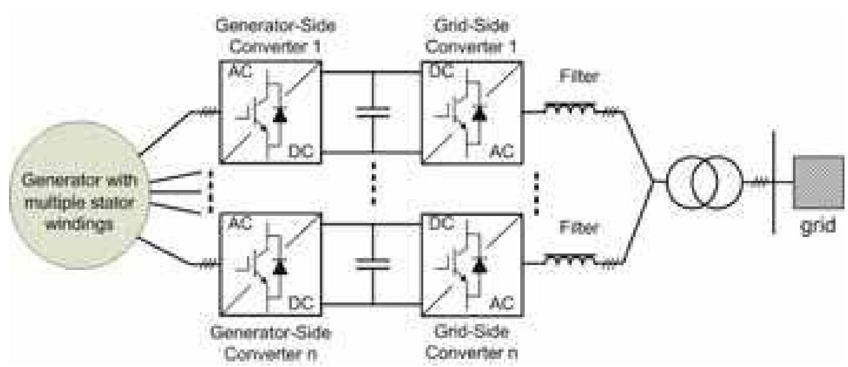


Fig. 22. Full-rating power converter based wind turbine with n-paralleled power converters.

These wind turbines can also be active when a fault appears on the grid and where it is necessary to build the grid voltage up again (Hansen et al., 2004) and (Iov & Blaabjerg, 2007); having the possibility to lower the power production even though more power is available in the wind and thereby act as a rolling capacity for the power system. Finally, some systems are able to work in island operation in the case of a grid collapse.

## 7. Control of generator-side converter

The control of the generator side-converter is basically determined by the generator type. However, since the wind turbine concepts available on the market are based on AC machines some basic control configurations can be identified. It must be noticed that these control schemes have their origins in the motor drives applications and they have been adapted to generator mode of operation. The general structure of a generator fed by an IGBT based power converter is shown in Fig. 23.

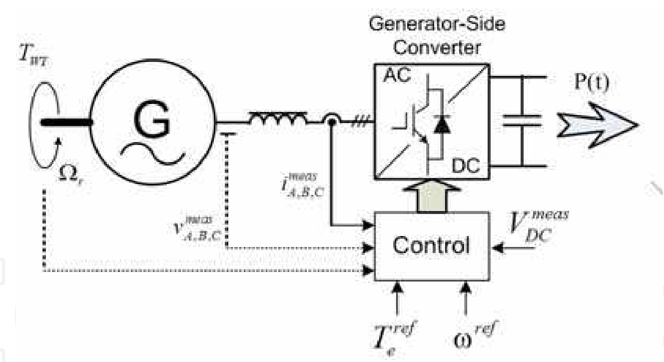


Fig. 23. General layout of a VSC-fed based three-phase AC generator.

### 7.1 Field oriented control

Field oriented control is one of the most used control methods of modern AC drives systems (Vas, 1998) and (Godoy Simoes & Farrat, 2004). The basic idea behind this control method is to transform the three-phase quantities in the AC machine in an orthogonal dq system aligned to one of the fluxes in the machine. Thus, a decoupling in controlling the flux and electromagnetic torque of the machine is achieved. Two methods of field oriented control for induction machines are used namely: indirect and direct vector control. Each of these methods has advantages and drawbacks. The indirect vector control can operate in four-quadrant down to standstill and it is widely used in both motor drives and generator applications. Typically the orthogonal synchronous reference frame is aligned on the rotor flux. However, this control is highly dependent on machine parameters. The direct vector control oriented along the stator flux does not need information about the rotor speed and is less sensitive to the machine parameters. However, it presents low performances for low speeds near to standstill. A general control structure for field oriented control in synchronous reference frame for induction machines is shown in Fig. 24.

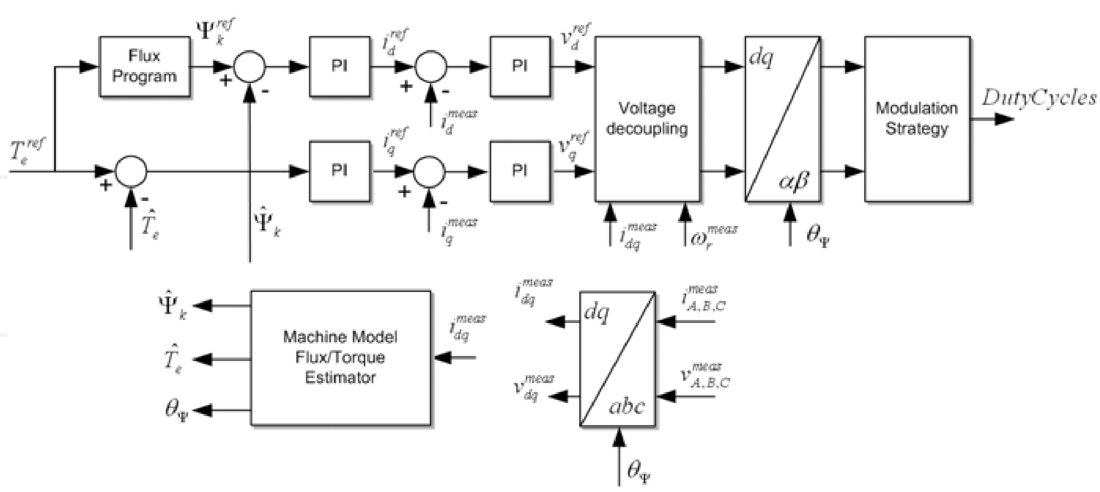


Fig. 24. General structure of a field oriented control in synchronous reference frame for an induction machine.

The electromagnetic torque is controlled in q-axis while the d-axis controls the flux of the machine. The actual flux and torque as well as the flux angle are determined based on the machine equations using the currents.

Similar control structure is used for the DFIG systems. Typically, the outer control loops are used to regulate the active and reactive power on the stator side of the machine.

### 7.2 Direct torque control

The Direct Torque Control proposed by Depenbrock eliminates the inner current loops and the needs of transformations between different references frames (Godoy Simoes & Farrat, 2004). It controls directly the magnitude of the stator flux and the electromagnetic torque of the machine by using hysteresis comparators as shown in Fig. 25.
The outputs of the hysteresis comparators as well as the flux angle are used directly to determine the switching states of the converter.
The performances of all the control schemes used for the generator-side converter must be evaluated in terms of current and hence torque ripple. High torque ripple can cause damages into the gearbox, while important low frequency harmonics can induce resonances with the mechanical structure of the wind turbine.

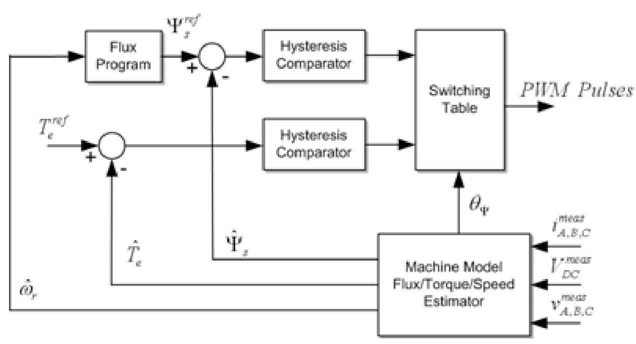


Fig. 25. General structure of the direct torque control for AC machines.

## 8. Control of grid-side converter

Independently of the generator type and the power converter configuration, the grid side converter is responsible for the quality of the generated power and the grid code compliance. A typical configuration of the grid side converter in wind turbine applications is given in Fig. 26.

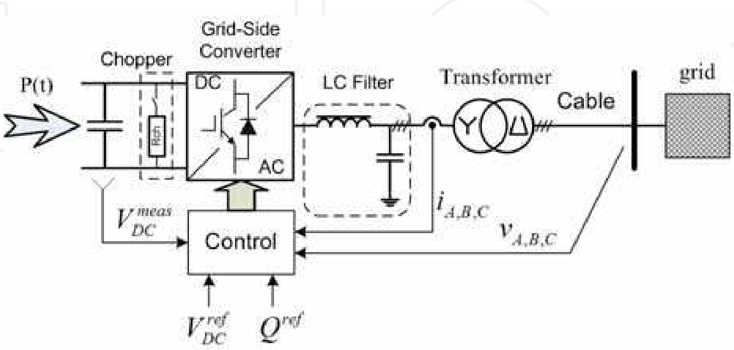


Fig. 26. Structure of the grid-side converter in wind turbine applications.

The system consist of a DC-link circuit, an IGBT based Voltage Source Converter, an LC filter, a Dyn11 transformer and a cable to the Point of Common Coupling. The LC filter is used to minimize the ripple of the output current due to the switching of the power devices

### 8.1 Grid synchronization

Initially, the synchronization of the delivered current with the utility network voltage was a basic requirement for interconnecting distributed power generators with the power system. In case of wind turbines, reactive power control at the point of common coupling is requested. Consequently, the wind turbine control should accommodate an algorithm capable of detecting the phase angle of grid voltage in order to synchronize the delivered current. Moreover, the phase angle plays an important role in control, being used to transform the feedback variables to a suitable reference frame in which the control structure is implemented. Hence, phase angle detection has a significant role in control of the grid side converter in a wind turbine. Numerous research papers report several algorithms capable of detecting the grid voltage phase angle, i.e. zero crossing detection, the use of *atan* function or Phase-Locked Loop (PLL) technique.

An overview of the grid synchronization and monitoring methods is presented in the following, based on (Iov & Blaabjerg, 2007) and (Iov et al., 2008).

#### 8.1.1 Zero crossing method

A simple method of obtaining the phase and frequency information is to detect the zero-crossing point of the grid voltage (Mur et al., 1998); (Choi et al., 2006). This method has two major drawbacks as described in the following.

Since the zero crossing point can be detected only at every half cycle of the utility frequency, the phase tracking action is impossible between the detecting points and thus the fast dynamic performance can not be obtained (Chung, 2000). Some work has been done in order to alleviate this problem using multiple level crossing detection as presented in (Nguyen & Srinivasan, 1984).

Significant line voltage distortion due to notches caused by power device switching and/or low frequency harmonic content can easily corrupt the output of a conventional zero-crossing detector (McGrath et al., 2005). Therefore, the zero-crossing detection of the grid voltage needs to obtain its fundamental component at the line frequency. This task is usually made by a digital filter. In order to avoid the delay introduced by this filter numerous techniques are used in the technical literature. Methods based on advanced filtering techniques are presented in (Vainio et al., 1995); (Valiviita et al., 1997); (Vainio et al., 2003); (Wall, 2003) and (McGrath et al., 2005). Other methods use Neural Networks for detection of the true zero-crossing of the grid voltage waveform (Valiviita, 1998); (Valiviita, 1999) and (Das et al., 2004). An improved accuracy in the integrity of the zero-crossing can also be obtained by reconstructing a voltage representing the grid voltage (Weidenbrug et al., 1993); (Baker and Agelidis, 1998); (Nedeljkovic et al, 1998) and (Nedeljkovic et al, 1999).

However, starting from its simplicity, when the two major drawbacks are alleviated by using advanced techniques, the zero-crossing method proves to be rather complex and unsuitable for applications which require accurate and fast tracking of the grid voltage.

#### 8.1.2 Arctangent method

Another solution for detecting the phase angle of grid voltage is the use of *arctangent* function applied to voltages transformed into a Cartesian coordinate system such as synchronous or stationary reference frames as shown in Fig. 27a and Fig. 27b respectively.

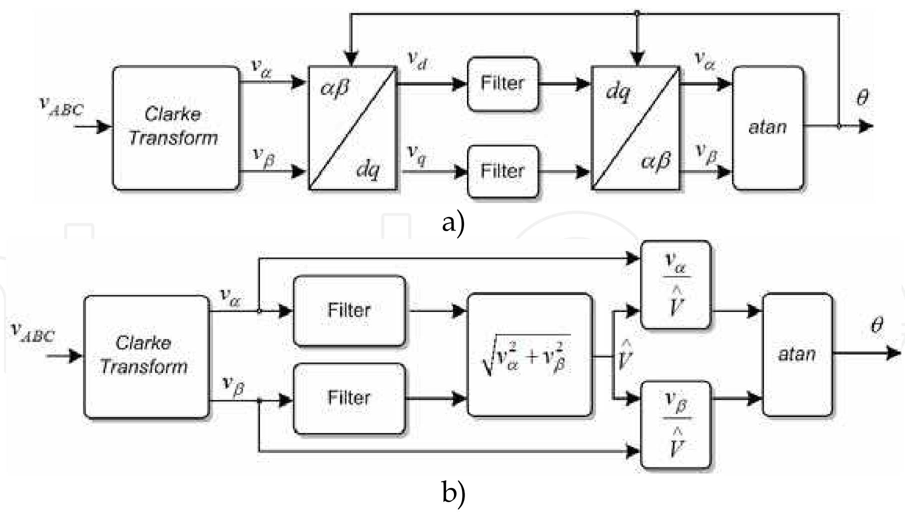


Fig. 27. Synchronization method using (a) filtering on the dq synchronous rotating reference frame and (b) filtering on stationary frame.

This method has been used in drives applications (Kazmierkowski et al., 2002), for transforming feedback variables to a reference frame suitable for control purposes. However, this method has the drawback that requires additional filtering in order to obtain an accurate detection of the phase angle and frequency in the case of a distorted grid voltage. Therefore, this technique is not suitable for grid-connected converter applications.

### 8.1.3 PLL technique

Phase-Locked Loop (PLL) is a phase tracking algorithm widely applied in communication technology (Gardner, 1979), being able to provide an output signal synchronized with its reference input in both frequency and phase.

Nowadays, the PLL technique is the state of the art method to extract the phase angle of the grid voltages (Nguyen & Srinivasan, 1984); (Kaura & Blasko, 1997); (Chung, 2000a) and (Chung, 2000b). The PLL is implemented in dq synchronous reference frame and its schematic is illustrated in Fig. 28. As it can be noticed, this structure needs the coordinate transformation form abc to dq and the lock is realized by setting the reference to zero. A controller, usually PI, is used to control this variable. This structure can provides both the grid frequency as well as the grid voltage angle.

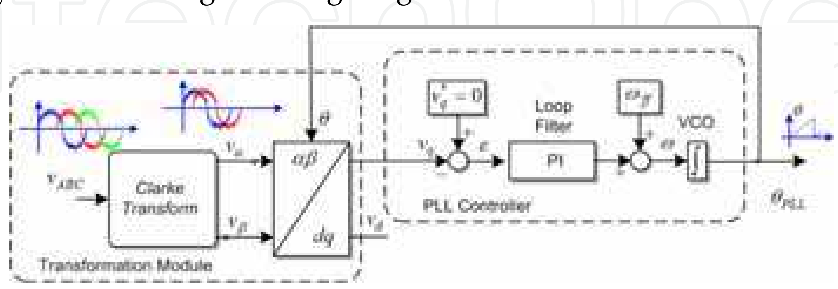


Fig. 28. Basic structure of a PLL system for grid synchronization.

After the integration of the grid frequency, the utility voltage angle is obtained, which is fed back into the Park Transform module in order to transform into the synchronous rotating reference frame.

This algorithm has a better rejection of grid harmonics, notches and any other kind of disturbances but additional improvements have to be done in order to overcome grid unbalance (Lee et al., 1999); (Song et al., 1999); (Karimi-Ghartemani & Iravani, 2004); (Rodriguez et al., 2005) and (Benhabib & Saadate, 2005);. In the case of unsymmetrical voltage faults, the second harmonics produced by the negative sequence will propagate through the PLL system and will be reflected in the extracted phase angle. In order to overcome this, different filtering techniques are necessary such that the negative sequence is filtered out. As a consequence, during unbalance conditions, the three phase dq PLL structure can estimate the phase angle of the positive sequence of the grid voltages.

### 8.1.4 Grid Monitoring

Grid requirements applying to utility connected power generation units impose the operation conditions in respect to voltage and frequency values. The demands are country specific. A graphical representation of allowed operation area in respect to the grid voltage amplitude and grid frequency as specified in the Danish Grid code for wind turbines connected to the distribution system (Iov & Blaabjerg, 2007) is illustrated in Fig. 29.

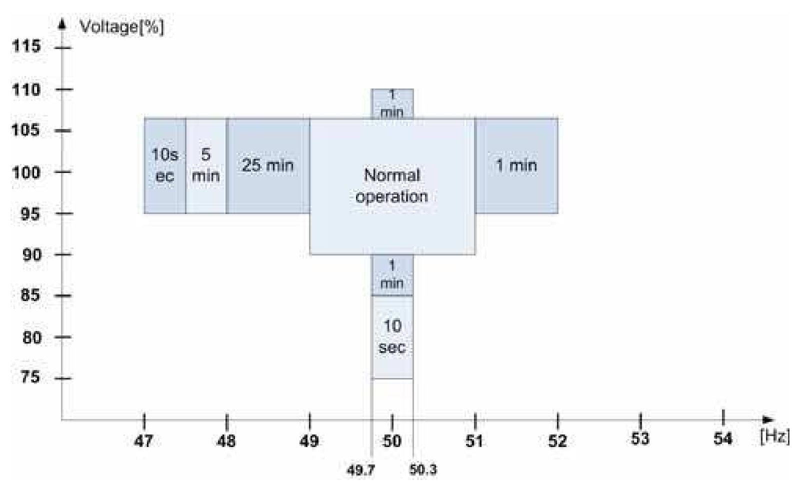


Fig. 29. Voltage and frequency operational ranges for wind turbines connected to the Danish distribution system.

A normal operation area between 95 and 105% of the nominal grid voltage and ±1 Hz around the nominal frequency is defined. Either frequency or voltage exceeds the predefined limits, the wind turbine should disconnect within the specified time interval. Therefore, in order to be able to disconnect in time, the wind turbine should accommodate a fast and reliable grid monitoring unit.

The PLL structures are used in the grid monitoring techniques. In a three-phase system, the grid voltage information can easily be obtained through the Clarke Transform as shown in Fig. 30.

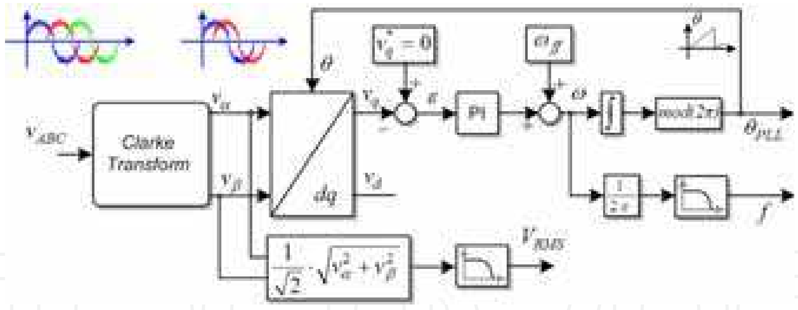


Fig. 30. General structure of a grid monitoring system based on three-phase PLL.

### 8.2 Converter control

Different control strategies can be used for the power converter such as synchronous Voltage Oriented Control (VOC) with PI controllers, stationary VOC with Proportional Resonant controllers, Synchronous Virtual Flux Oriented Control (VFOC) with PI controller, Adaptive Band Hysteresis (ABH) Current Control, Direct Power Control (DPC) with Space Vector Modulation (SVM), Virtual Flux DPC with SVM (Kazmierkowski et al., 2002), (Iov et al., 2006), (Teodorescu et al., 2006). However, in industrial applications few of these control strategies are used.

The synchronous Voltage Oriented Control with PI controllers is widely used in grid applications. This control strategy is based on the coordinate transformation between the stationary αβ and the synchronous dq reference frames. It assures fast transient response and high static performance due to the internal current control loops (Kazmierkowski et al., 2002) and (Iov et al., 2006). The decomposition of the AC currents in two axes provides a decoupled control for the active and reactive power.

A block diagram of the VOC control with PI controllers is shown in Fig. 31

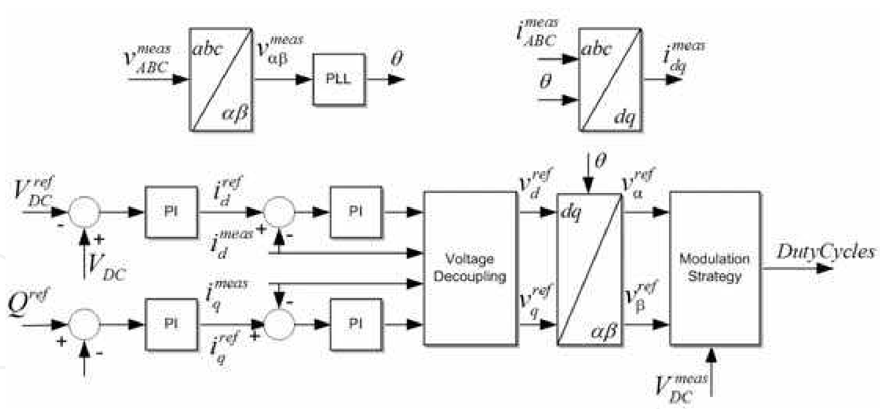


Fig. 31. Block diagram of the VOC in the synchronous reference frame.

A Phase Locked Loop (PLL) is used for the coordinate transformation. The control scheme comprises the DC-link voltage controller and the current controller in the d-axis, while the reactive power and the reactive component of the current are controlled in the q-axis.

In order to achieve a high accuracy current tracking the control algorithm accounts for the output filter inductance. Therefore, the output of the current controllers is compensated with the voltage drop on the output filter. Then the reference voltages are translated to the stationary reference frame and applied to a Space Vector Modulator (SVM).

It should be noticed that the performances of this control strategy relies on the accuracy of the PLL system for the voltage grid angle estimation.
Another control strategy used by some wind turbine manufacturers is the adaptive hysteresis-band current control that provides a very fast-response current-loop (Iov et al., 2006). This control strategy is also based on the synchronous reference frame; therefore a PLL is used for the reference frame transformation of the currents.

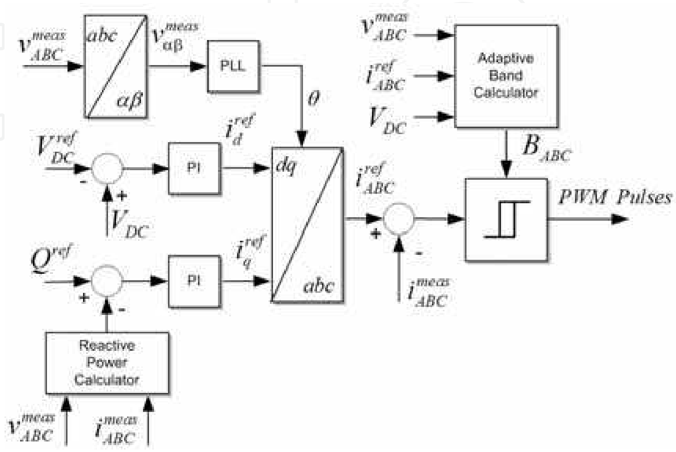

Fig. 32. Block diagram of the Adaptive Band Hysteresis Current Control.

A PI controller provides the control of the DC-link voltage in the d-axis while the reactive power is controlled in the q-axis. The current control is performed by the hysteresis comparators for each phase independently after the transformation of the reference dq currents (Iov et al., 2006) and (Teodorescu et al., 2006).
Both control algorithms require the estimation of the reactive power based on measured voltages and currents. Also, both control algorithms can meet the requirements for harmonic current injection in the PCC (Iov et al., 2006). However, the VOC algorithm is more sensitive to voltage unbalances and asymmetries than the ABH current control due to the double transformation of axes.
A typical control scheme for a cascaded H-bridge multilevel converter is presented in Fig. 33 (Ciobotaru et al., 2008).

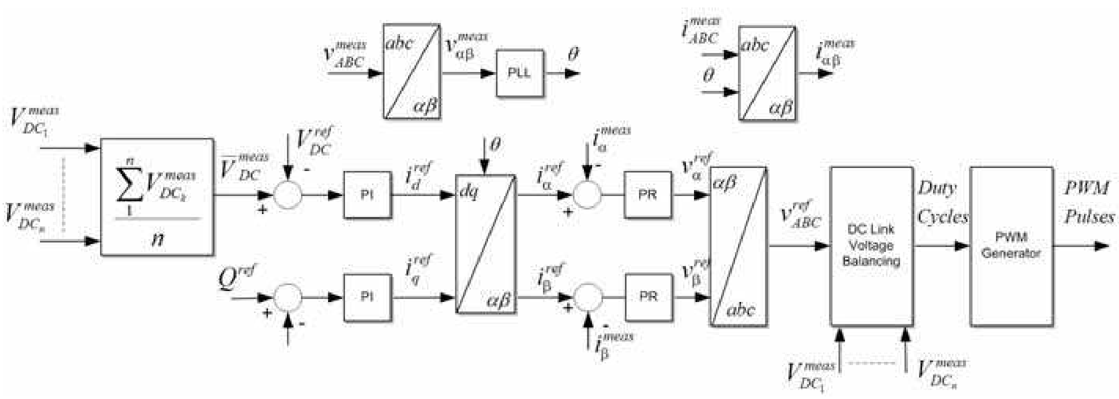

Fig. 33. Control structure in synchronous reference frame for a seven level cascaded H-bridge multilevel converter.

The overall structure of this control is shown in Fig. 4.6 and it is based on PR current controllers. The PR controller has been chosen due to the fact that it gives better performances compare to the classical PI. The two well known drawbacks of the PI controller (steady-state errors and poor harmonics rejection capability) can be easily overcome by the PR controller. The PR controller is able to remove the steady-state error without using voltage feed-forward, which makes it more reliable compared with the "classical" synchronous reference frame control. However, a three-phase PLL (Phase-Locked Loop) system is used to obtain the necessary information about the grid voltage magnitude and its angle.

In order to support the bidirectional power flow through the system, the current reference in d-axis is obtained based on the active power set-point and the average voltage (provided by PLL) and a correction given by the DC-link voltage control loop. This controller controls the average value of the DC link voltages. The reactive power is controlled using a PI controller which provides the current reference in the q-axis. One of the drawbacks of this control is the transformation of the control variables from synchronous reference frame to the stationery one. Based on the grid voltage angle the current references in synchronous reference frame are transformed into the stationary frame and then applied to the PR current controllers. It is also worth to notice that this control does not require a neutral connection.

It is obviously that all these control strategies need information about the grid voltage angle in order to operate properly. The number of transformations between reference frames (*abc* to *dq* and back) makes them more or less sensitive to changes into the grid behaviour. Thus, their capability to handle events into the network such as voltage asymmetries/unbalances, frequency excursions and phase jumps as well as grid faults is very important for fulfilling the grid connection requirements. Bottom-line, the harmonic content injected into the grid as well as their capability of selective harmonic elimination will be a factor key in choosing a particular control structure for the grid-side converter.

## 9. Wind Farm Connection

In many countries energy planning is going on with a high penetration of wind energy, which will be covered by large offshore wind farms. These wind farms may in the future present a significant power contribution to the national grid, and therefore, play an important role on the power quality and the control of complex power systems. Consequently, very high technical demands are expected to be met by these generation units, such as to perform frequency and voltage control, regulation of active and reactive power, quick responses under power system transient and dynamic situations, for example, to reduce the power from the nominal power to 20 % power within 2 seconds. The power electronic technology is again an important part in both the system configurations and the control of the offshore wind farms in order to fulfil the future demands.

One off-shore wind farm equipped with power electronic converters can perform both active and reactive power control and also operate the wind turbines in variable speed to maximize the energy captured and reduce the mechanical stress and acoustical noise. This solution is shown in Fig. 34 and it is in operation in Denmark as a 160 MW off-shore wind power station.

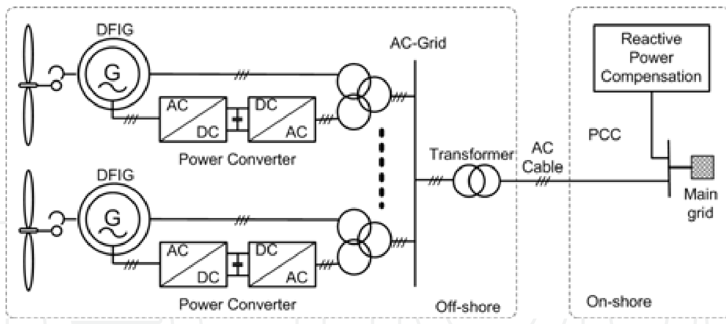

Fig. 34. DFIG based wind farm with an AC grid connection.

For long distance power transmission from off-shore wind farm, HVDC may be an interesting option. In an HVDC transmission system, the low or medium AC voltage at the wind farm is converted into a high dc voltage on the transmission side and the dc power is transferred to the on-shore system where the DC voltage is converted back into AC voltage as shown in Fig. 28.

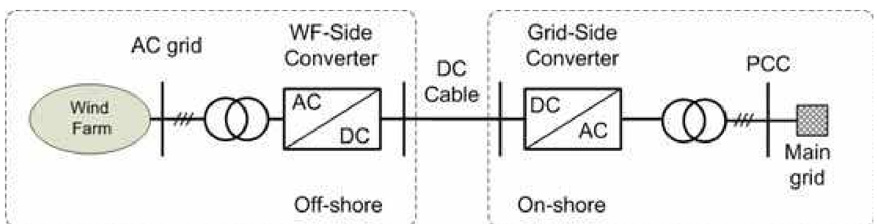

Fig. 35. HVDC system based on voltage source converters for wind farm connection.

This connection type is considered for Borkum wind farm in the Baltic Sea and it will be commissioned in 2009.
Another possible DC transmission system configuration is shown in Fig. 36, where each wind turbine has its own power electronic converter, so it is possible to operate each wind turbine at an individual optimal speed. A common DC grid is present on the wind farm while a power converter terminal realizes the on-shore grid connection. In this case any of the wind turbine configurations based on full-rating power converter can be used.

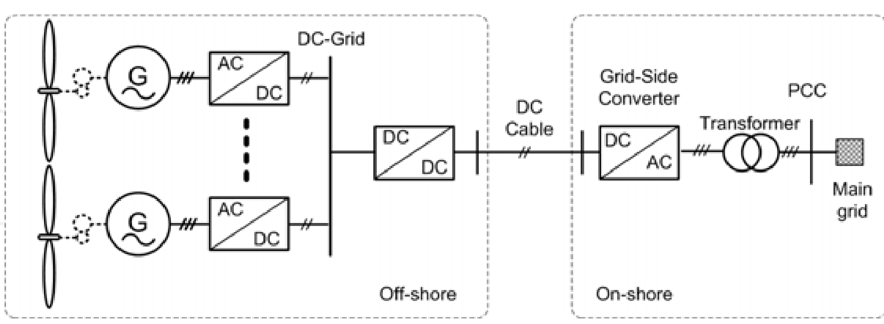

Fig. 36. Wind farm with common DC grid based on variable speed wind turbines with full rating power converter.

This topology can be extended by adding the input of more wind farms in the DC grid and then multiple DC cables and converters for connection to other AC power grids. In this case a multi-terminal DC connection will result.
As it can be seen the wind farms have interesting features in order to act as a power source to the grid. Some have better abilities than others. Bottom-line will always be a total cost

scenario including production, investment, maintenance and reliability. This may be different depending on the planned site.

## 10. Developments and trends in wind energy systems

Wind turbine's size was in a continuous growth in the last 25 years as shown in Fig. 37 and today prototype turbines of 5-6 MW are seen around the world being tested.

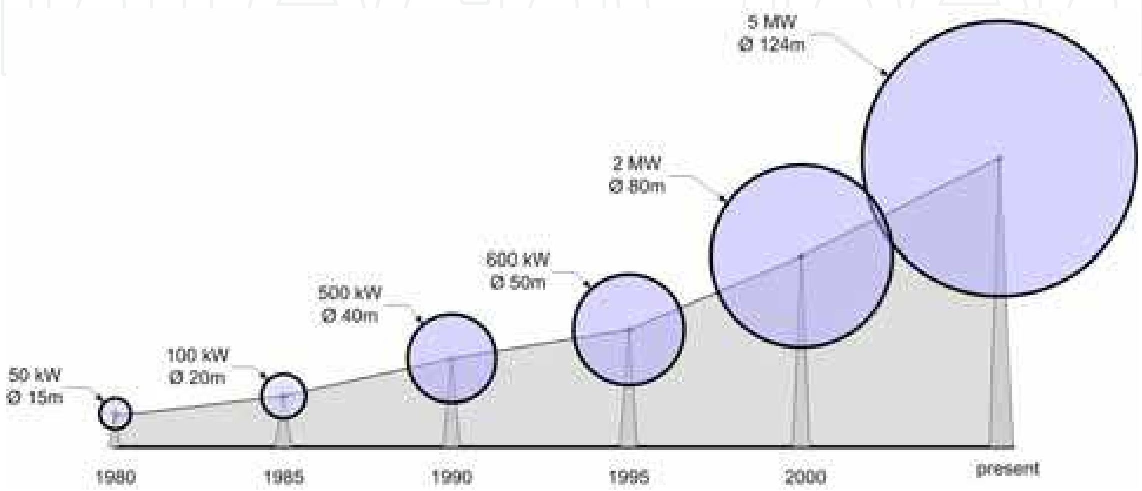


Fig. 37. Development of wind turbines during the last 25 years.

Currently, dispersed single wind turbines are replaced with MW-size wind turbines concentrated in wind power plants. Also, the grid penetration of wind power is increasing dramatically especially in the European countries like Denmark, Germany and Spain. It is expected that more countries worldwide will follow this trend. Due to the unpredictable nature of the wind, the grid connection of these modern MW-size wind turbines and wind power plants has a large impact on grid stability and security of supply. Thus, in order to accommodate more wind power into the grid, one of the major challenges in the future is directed towards the integration of wind power within the existing electrical network.

Today, the grid connection requirements, in countries with a relatively high penetration of wind power, require MW-size wind turbines and wind farms to support the grid actively and to remain connected during grid events. These requirements are mainly fulfilled by using power electronics within the wind turbines and wind farms. The power electronics make also possible the variable speed operation of wind turbines and further improve the performances of the wind turbines by reducing the mechanical stress and acoustical noise, and by increasing the wind power capture. Also, the power electronics increase the controllability of the wind turbines, which is a major concern for their grid integration. All these features are provided at low price share of power electronics compared to other components from a modern MW-size wind turbine as shown in Fig. 38.

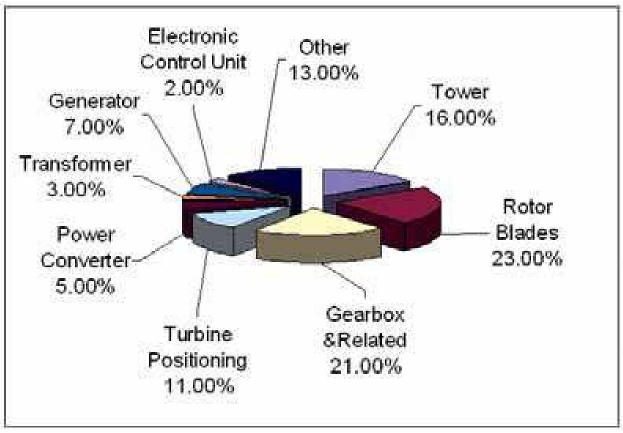


Fig. 38. Cost share of main components in a typical 2 MW variable speed wind turbine [Bernstein Research, 2007].

Currently, the variable speed wind turbines dominate the market. The doubly-fed induction generator based wind turbine has developed into a semi-industry standard for gear-driven wind turbines. On the other hand, more manufacturers are coming with wind turbine prototypes based on the full-rating power converter using different generator types. The main advantage of the doubly-fed wind turbine of using a partial scale power converter may be overcame by its behaviour during grid events. Moreover, the grid support during faults by means of 100% reactive current injection into the grid required by some grid operators cannot be provided by this concept. On the contrary, the full-rating power converters based wind turbines are very attractive because they can provide complete grid support during network events. Thus, further developments of both wind turbine concepts are expected, focusing on more optimised turbines and, thus, towards more cost-effective machines.

Moving to large wind power plants installations these wind turbine concepts may be modified for a better integration into the electrical grid. The HVDC solution for connecting wind farms might create a new class of wind turbines that will deliver only DC power into a common DC-grid. Thus, the present layout of a full-rating power converter based wind turbine can be simplified by removing some of the conversion stages, e.g. DC to AC including the step-up transformer. The receiving-end station of such a system will be responsible with fulfilling the grid connection requirements, while the wind turbine itself will just maximize the wind power conversion.

The future is difficult to predict. Technologically, improvements of the current designs are expected. Concepts borrowed from other fields or other applications might change the future design of the wind turbines. Economically, the cheapest and the most reliable solution will be preferred. Looking at the wind power plants the overall costs against performances will definitely be the main driver. Thus, in order to minimize de costs at high control capabilities required by the system operators, an integrated design of wind power plants will be required. However, power electronics including control will be the key technology for the large scale grid integration of wind power.

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Renewable Energy is energy generated from natural resources-such as sunlight, wind, rain, tides and geothermal heat-which are naturally replenished. In 2008, about 18% of global final energy consumption came from renewables, with 13% coming from traditional biomass, such as wood burning. Hydroelectricity was the next largest renewable source, providing 3% (15% of global electricity generation), followed by solar hot water/heating, which contributed with 1.3%. Modern technologies, such as geothermal energy, wind power, solar power, and ocean energy together provided some 0.8% of final energy consumption. The book provides a forum for dissemination and exchange of up-to-date scientific information on theoretical, generic and applied areas of knowledge. The topics deal with new devices and circuits for energy systems, photovoltaic and solar thermal, wind energy systems, tidal and wave energy, fuel cell systems, bio energy and geo-energy, sustainable energy resources and systems, energy storage systems, energy market management and economics, off-grid isolated energy systems, energy in transportation systems, energy resources for portable electronics, intelligent energy power transmission, distribution and inter-connectors, energy efficient utilization, environmental issues, energy harvesting, nanotechnology in energy, policy issues on renewable energy, building design, power electronics in energy conversion, new materials for energy resources, and RF and magnetic field energy devices.