WIND POWER - A POWER SOURCE NOW ENABLED BY POWER ELECTRONICS

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***Abstract* – The global electrical energy consumption is still rising and there is a steady demand to increase the power capacity. It is expected that it has to be doubled within 20 years. The production, distribution and use of the energy should be as technological efficient as possible and incentives to save energy at the end-user should be set up. Deregulation of energy has lowered the investment in larger power plants, which means the need for new electrical power sources may be increased in the near future. Two major technologies will play important roles to solve the future problems. One is to change the electrical power production sources from the conventional, fossil (and short term) based energy sources to renewable energy resources. Another is to use high efficient power electronics in power generation, power transmission/distribution and end-user application. This paper discuss the most emerging renewable energy sources, wind energy, which by means of power electronics are changing from being minor energy sources to be acting as important power sources in the energy system.**

***Keywords* – Grid Codes, Power Electronics, Wind Farms, Wind Turbines, Wind Power.**

I. 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 [1]-[2] 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 many places. E.g. Denmark has a high power capacity penetration (> 20%) of wind energy in major areas of the country and today 18% of the whole electrical energy consumption is covered by wind energy. The main advantages of using renewable energy sources are the elimination of harmful emissions and inexhaustible resources of the primary energy. However, the main disadvantage, apart from the higher costs, e.g. photovoltaic, is the uncontrollability. 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.

Among the renewable sources, wind energy has been noted as the most rapidly growing technology; it attracts interest as one of the most cost-effective ways to generate electricity from renewable sources [3]-[11].

The wind turbine technology started in the 1980'es with a few tens of kW production power and being today a mature technology with multi-MW size wind turbines installed [1]-[66]. The wind turbine design objectives have also changed over these years from being convention-driven to being optimized-driven within the operating regime and market environment [12]. As well as becoming larger, wind turbine designs were progressing from fixed-speed, stall-controlled and with drive trains with gearboxes, to become pitch controlled, variable speed with or without gearboxes [12]-[20], [40]. The control objectives as well as the interconnection requirements have also changed during the years. The traditional fixed speed wind turbines were directly grid connected and the power pulsations in the wind were almost directly transferred to the electrical grid. Moreover, the grid connection requirements were minimal [12], [15], [57] and [58]. As the power range of the turbines increases the power delivered to the grid must be controlled and the power quality issues become more important [37], [57]-[64]. Today, there are very hard grid connection requirements [12], [57]-[59], which require MW-size wind turbines concentrated in large wind farms to support the grid actively and to remain grid-connected during grid problems (i.e. voltage dip), otherwise it could cause a grid blackout [60]-[64]. The main role for such technical demands of the grid operators is played today by the power electronics as an interface between the wind turbine and the grid and wind farms [7]-[15]. Thus, the power electronics is changing the basic characteristic of the wind turbine/farm from being just an energy source to become an active power source. The electrical technology used in wind turbine is not new. It has been discussed for several years [7]-[56] but now the price pr. produced kWh is so low, that solutions with power electronics are very attractive [7]-[11].

This paper will first discuss the basic development in power electronics and power electronic conversion. Then different wind turbine configurations will be explained both aerodynamically and electrically. Also different control methods will be shown for a wind turbine. They are now also installed in remote areas with good wind conditions (off-shore, on-shore) and different configurations for wind farms are shown and compared. Then, an overview of the most relevant grid connection requirements from different national grid codes is given. Finally, the actual status on the market as well as some future trends in wind turbine development is presented.

II. MODERN POWER ELECTRONICS AND SYSTEMS

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 load/source and a control unit is shown in Fig. 1.

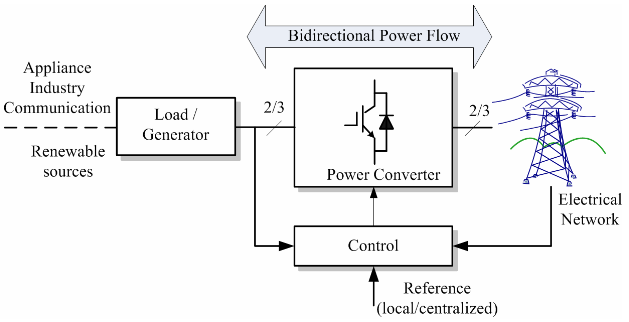

Fig. 1. Power electronic system with the grid, load/source, power converter and control.

The power converter is the interface between the load/generator and the grid. The power may flow in both directions, of course, dependent on topology and applications.

Three important issues are of concern using such a system. The first one is reliability; the second is efficiency and the third one is cost. For the moment 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 based on [5].

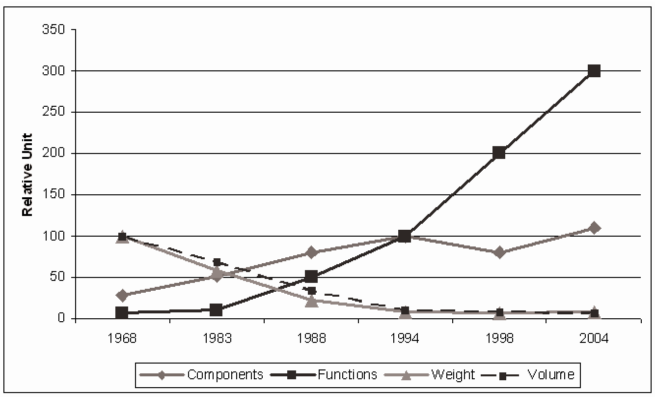

Fig. 2. Development of standard adjustable speed drives for the last four decades [5].

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.

The key driver of this development is that the power electronic device technology is still undergoing important progress.

Fig. 3 shows different power devices and the areas where the development is still going on [6].

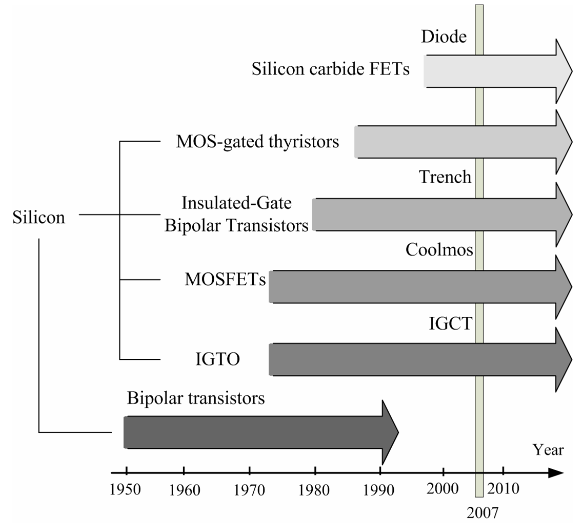

Fig. 3. Development of power semiconductor devices in the past and in the future [6].

The only power device which is not under development any more 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.

III. 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 normally three. As the blade tip-speed typically 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 will be 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.

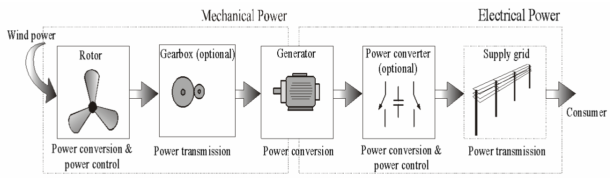

Fig. 4. Converting wind power to electrical power in a wind turbine [7], [8].

The gear-box is optional as multi-pole generator systems are possible solutions. Between the grid and the generator a power converter can be inserted.

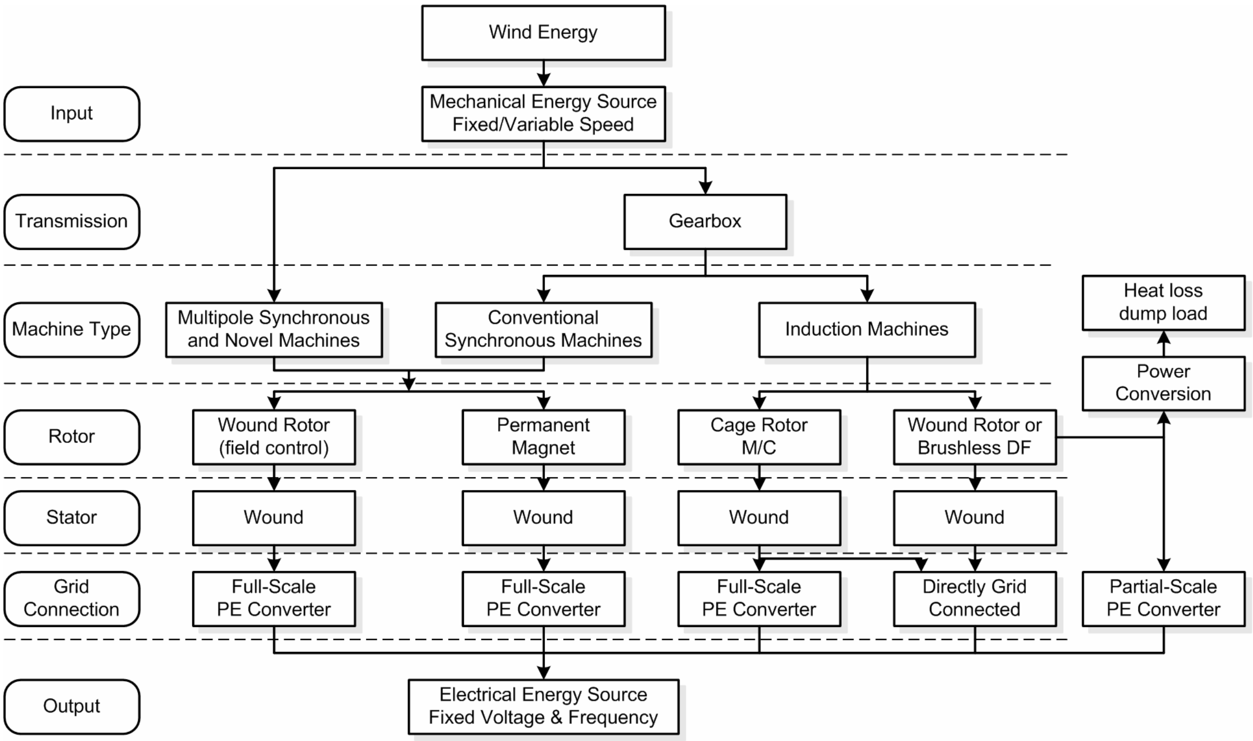

Fig. 5. Technological roadmap for wind turbine's technology [13], [24].

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.

IV. CONTROL METHODS FOR WIND TURBINES

The most commonly applied wind turbine concepts can be classified by both their ability of speed control and their type of power control [2], [12]-[20]. In the following the attention is mainly drawn to the standard wind turbine configurations existing in the industry, with their particular advantages and disadvantages. The other alternative wind turbine designs, with slightly differences are not discussed.

A. Power Controllability

All wind turbines are designed with some type of power control. In order to avoid damages on the wind turbine in the case of very strong winds there are different ways to control aerodynamic forces on the turbine rotor and thus to limit the power. The ability of controlling the power (blade) classifies the wind turbine concepts in three main categories discussed in the following sections [2], [8], [12] and [15]-[20].

1) Stall control (passive control)

It is the simplest, most robust and cheapest control method. The blades are bolted onto the hub at a fixed angle. The design of rotor aerodynamic causes the rotor to stall when the wind speed exceeds a certain level. Thus the aerodynamic power produced by the blades is 'automatically' limited in the rated power region. As wind speed increases, stall conditions occur gradually, starting at the blade root. Such slow aerodynamic power regulation causes less power fluctuations than a fast pitch power regulation. Some drawbacks of this design are: lower efficiency at low wind speeds, no assisted start-up and potential variations in the maximum steady state power due to variation in the air density and grid frequencies.

2) Pitch control (active control)

In this case the blades can be turned away from or into the wind as the power output becomes too high or too low, respectively. Below rated wind speed the blades are pitched for optimum power extraction, while above rated wind speeds the blades are pitched to small angle of attack for limiting the power.

Generally, the advantages of this type of control are good power control performance, assisted start-up and emergency-stop power reduction (the blades are forced rapidly out of the wind). From an electrical point of view, good power control means that, at large wind speeds, the mean value of the power output is kept close to the rated power of the generator. The instantaneous power fluctuates around the rated mean value of the power, due to gusts and the limited response time of the pitch mechanism. Some disadvantages of these concepts are: extra complexity due to the pitch mechanism and inherent large power fluctuations that appear from the turbulence at large wind speeds.

3) Active stall control (active control)

As the name indicates, the stall of the blade is actively controlled by pitching the blades to larger angle of attack. At wind speeds less than for rated power, the blades are pitched for optimum power extraction, as with a pitch controlled wind turbine, so achieving the maximum efficiency. However, at wind speeds greater than for rated power, the blades go into a deeper stall by being pitched to larger angle of attack (i.e. in the opposite direction to a pitch-controlled turbine in the same conditions). Active stall wind turbine achieves a smooth limitation of power, without the large inherent power fluctuations of pitch controlled wind turbines. This control concept has the advantage of being able to compensate for variations in air density. The combination with the pitch mechanism facilitates both emergency stop and assisted start-up of the wind turbine.

The basic output characteristics of these three methods of controlling the power are summarized in Fig. 6.

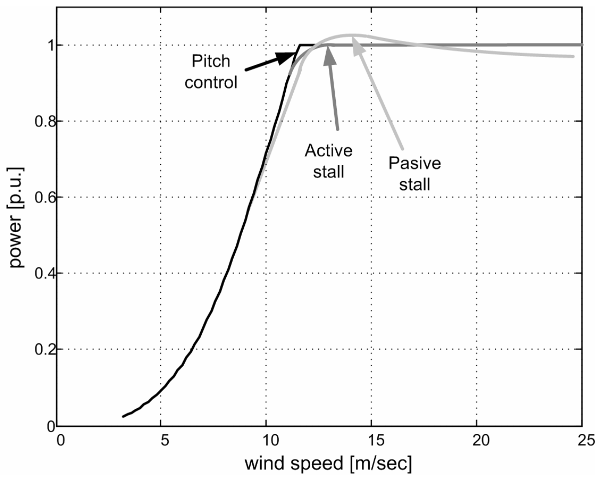

Fig. 6. Power characteristics of different fixed speed wind turbine systems [8].

B. Speed Controllability

Another control variable in wind turbine system is the speed. Based on this criterion the wind turbines are classified into two main categories [12], [15]:

1) Fixed speed wind turbines:

In the early 1990s, most installed wind turbines had standard induction generators that operated at almost fixed speed. Neglecting the generator slip as having a very small aerodynamic effect, this implies that regardless of the wind speed, the wind turbine's rotor speed is fixed and determined by the frequency of the supply grid, the gear ratio and the generator layout. Characteristic for the fixed speed wind turbines is that they are equipped with an induction generator (squirrel cage induction generator SCIG or wound rotor induction generator WRIG) connected directly to the grid, a soft-starter and a capacitor bank for reduction of the reactive power consumption. They are designed to obtain maximum efficiency at one wind speed. In order to increase the power production, some of the fixed speed wind turbines are equipped with two sets of windings in the generator: one is used for low wind speeds (typically 8 pole-pairs) and one is used for medium and high wind speeds (typically 4-6 pole-pairs). A fixed speed wind turbine has the advantages of being simple, robust and reliable, well proven and with low cost of the electrical parts. Its direct drawbacks are the uncontrollable reactive power consumption, mechanical stress and limited power quality control. Due to its fixed speed operation, wind speed fluctuations are converted to mechanical torque fluctuations, beneficially reduced slightly by small changes in generator slip, and transmitted as fluctuations into electrical power to the grid. The power fluctuations can also yield large voltage fluctuations in the case of a weak grid and thus, significant line losses [22].

2) Variable speed wind turbines:

The variable speed wind turbines are designed to achieve maximum aerodynamic efficiency over a wide range of wind speeds. 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 *v*, in such a way that tip speed ratio is kept constant to a predefined value corresponding to the maximum power coefficient [12] - [20]. Contrary to a fixed speed system, a variable speed system keeps the generator torque nearly constant, the variations in wind being absorbed by the generator speed changes. The introduction of variable speed wind turbine concept increases the number of applicable generator types and further introduces several degrees of freedom in the combination of generator type and power converter type [12]-[14]. The electrical system of a variable speed wind turbine is thus more complicated than for a fixed speed wind turbine. It is typically equipped with an induction or synchronous generator and connected to the grid through a power converter. The power converter controls the generator speed in such a way that the power fluctuations caused by wind variations are more or less absorbed by changing the generator speed and implicitly the wind turbine rotor speed. The presence of the power converter makes the variable speed operation itself possible. The variable speed wind turbines can therefore be designed to achieve maximum power coefficient over a wide range of wind speeds. The power converter controls the generator speed in such a way that the fast power fluctuations caused by wind variations are more or less absorbed by changing the generator speed and implicitly the wind turbine rotor speed [12]-[20].

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 [12]-[20]:

- *reduced mechanical stress on the mechanical components such as shaft and gearbox* – the high inertia of the wind turbine is used as a flywheel during gusts, i.e. the power fluctuations are absorbed in the mechanical inertia of the wind turbine.
- *increased power capture* – due to the variable speed feature, 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 the power coefficient is kept at its maximum value.
- *reduced acoustical noise* – low speed operation is possible at low power conditions (low wind speeds).

Additionally, the presence of power converters in wind turbines provides also high potential control capabilities for both large modern wind turbines and wind farms to fulfil the high technical demands imposed by the grid operators [12], [15] and [57]-[64]and such as:

- controllable active and reactive power (frequency and voltage control);
- quick response under transient and dynamic power system situations

- influence on network stability
- improved power quality (reduced flicker level, low order harmonics filtered out and limited in-rush and short circuit currents)

The main disadvantages of variable speed turbines are:

- additional losses due to power electronics,
- more components, thereby reliability issues,
- increased capital cost due to the power electronics.

V. WIND TURBINE CONCEPTS

The most commonly applied wind turbine designs can be categorized into four wind turbine concepts [8], [12], [15] and [23]. The main differences between these concepts are 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 in detail in the following paragraphs.

A. Fixed Speed Wind Turbines (WT Type A)

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.

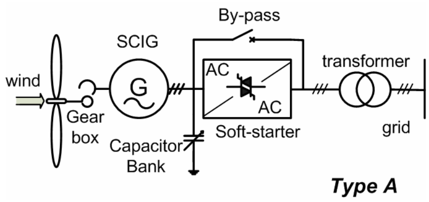

Fig. 7. Fixed speed wind turbine with directly grid connected squirrel-cage induction generator [15].

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.

Thus, the main drawbacks of this concept are: 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.

B. Partial Variable Speed Wind Turbine with Variable Rotor Resistance (WT Type B)

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

It uses a wound rotor induction generator (WRIG) and it has been used by the Danish manufacturer Vestas Wind Systems since the mid 1990's.

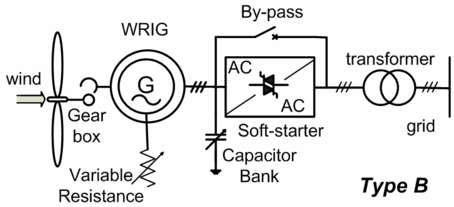

Fig. 8. Partial variable speed wind turbine with variable rotor resistance [15].

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; 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. In [24] an alternative concept using passive component instead of a power electronic converter is described. This concept achieves 10% slip, but it does not support controllable slip.

C. Variable Speed WT with partial-scale frequency converter (WT Type C)

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 frequency converter (rated to approx. 30% of nominal generator power) on the rotor circuit as shown in Fig. 9.

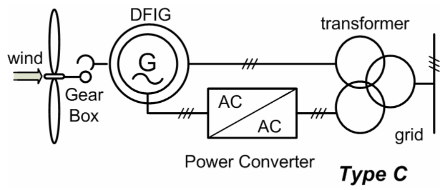

Fig. 9. Variable speed wind turbine with partial scale power converter [15].

The stator is directly connected to the grid, while a partial-scale power converter controls the rotor frequency and thus the rotor speed. 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 protection schemes in the case of grid faults.

D. Variable Speed Wind Turbine with Full-scale Power Converter (WT Type D)

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

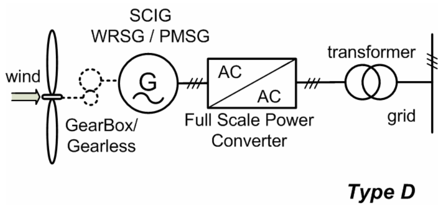

Fig. 10. Variable speed wind turbine with full-scale power converter [15].

The frequency converter performs the reactive power compensation and a smooth grid connection for the entire speed range [12]-[20]. 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.

Some full variable speed wind turbines systems are gearless – see dotted gearbox in Fig. 10. In these cases, a bulky direct driven multi-pole generator is used.

E. System comparison of wind turbines

Comparing the different wind turbine topologies in respect to their performances will reveal a contradiction between cost and the performance to the grid [8], [15]. A technical comparison of the main wind turbine concepts, where issues on grid control, cost, maintenance, internal turbine performance is given in Table I [15].

Table I System comparison of wind turbine configurations [15].

System	Type A	Type B	Type C	Type D
Variable speed	No	No	Yes	Yes
Control active power	Limited	Limited	Yes	Yes
Control reactive power	No	No	Yes	Yes
Short circuit (fault-active)	No	No	No/Yes	Yes
Short circuit power	contribute	contribute	contribute	limit
Control bandwidth	1-10 s	100 ms	1 ms	0.5-1 ms
Standby function	No	No	Yes +	Yes ++
Flicker (sensitive)	Yes	Yes	No	No
Softstarter needed	Yes	Yes	No	No
Rolling capacity on grid	Yes, partly	Yes, partly	Yes	Yes
Reactive compensator (C)	Yes	Yes	No	No
Island operation	No	No	Yes/No	Yes
Investment	++	++	+	0
Maintenance	++	++	0	+

VI. POWER CONVERTER TOPOLOGIES FOR WIND TURBINES

Basically two power converter topologies with full controllability of the generated voltage on the grid side are used currently in the wind turbine systems. These power converters are related with Type C and Type D wind turbine concepts.

A. Bidirectional back-to-back two-level power converter

This topology is state-of-the-art especially in large DFIG based wind turbines [25]-[35]. The back-to-back PWM-VSI is a bi-directional power converter consisting of two conventional PWM-VSCs. The topology is shown in Fig. 11.

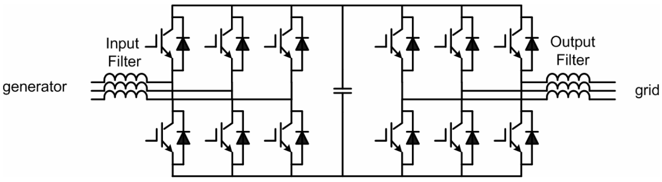

Fig. 11. Structure of the back-to-back Voltage Source Converter.

To achieve full control of the grid current, the DC-link voltage must be boosted to a level higher than the amplitude of the grid line-line voltage. The power flow of the grid side converter is controlled in order to keep the DC-link voltage constant, while the control of the generator side is set to suit the magnetization demand and the reference speed. The control of the back-to-back PWM-VSC in the doubly-fed induction generator based wind turbine is described in many articles e.g. [25]-[35].

Some wind turbine manufacturers e.g. Siemens Wind Power have this topology for full-scale power converter wind turbines with squirrel-cage induction generator.

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 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). Due to this, 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-VSI are reported in literature [7], [8] and [13]-[15]. 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 [8] ,the voltage gradient may have to be limited by applying an output filter.

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 as shown in Fig. 12 [15].

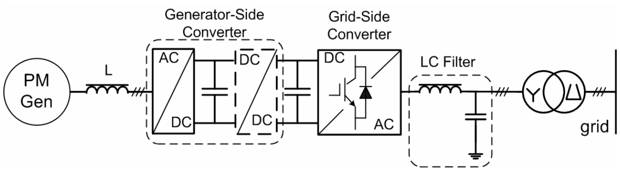

Fig. 12. Permanent magnet synchronous generator based wind turbine with bidirectional power converter [15].

B. Unidirectional power converter

A wound rotor synchronous generator requires only a simple diode bridge rectifier for the generator side converter as shown in Fig. 13.

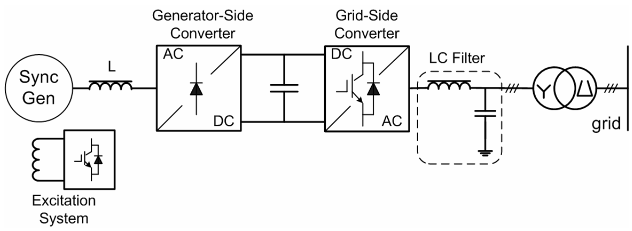

Fig. 13. Variable speed wind turbine with synchronous generator and full-scale power converter (WT Type D) [15].

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-bus. 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 [40]. The same topology with an extra DC-DC conversion stage can be used for permanent magnet synchronous generators.

C. Multilevel Power Converter

Currently there is an increasing interest in multilevel power converters especially for medium to high-power, high-voltage wind turbine applications [42]-[43].

Since the development of the neutral-point clamped three-level converter [44], 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 [13], [14], [42] and [51]: a) multilevel configurations with diode clamps, b) multilevel configurations with bi-directional switch interconnection, c) Multilevel configurations with flying capacitors, d) multilevel configurations with multiple three-phase inverters, e) multilevel configurations with cascaded single phase H-bridge inverters. These topologies are shown in Fig. 14 [13].

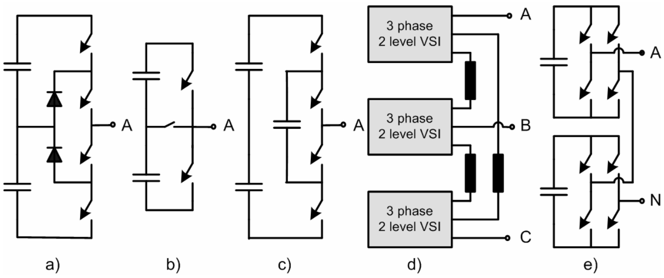

Fig. 14. Multilevel topologies: a) one leg of a three-level diode clamped converter; b) one leg of a three-level converter with bidirectional switch interconnection; c) one leg of a three-level flying capacitor converter; d) three-level converter using three two-level converters and e) one leg of a three-level H-bridge cascaded converter [13].

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 [13]. The switching losses of the multilevel converter are another feature, which is often accentuated in literature. In [45], 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 conducting 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 [13]. 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 [13], [14] and [42]-[50]. 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. However, 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 [13], [14] and [47]. By a proper modulation control of the switches, the imbalance problem can be solved [48]. In [47] the voltage balancing problem is solved by hardware, while [49] and [50] 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. 14a) and the three-level flying capacitor multilevel converter (Fig. 14c) 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 [46]. 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. 14b [13].

It is evident for all presented topologies in Fig. 14 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 [14].

D. Modular Power Converters

At low wind speeds and hence low level of the produced power, the full scale 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. 15.

The power converter in this case can be one of the structures presented above.

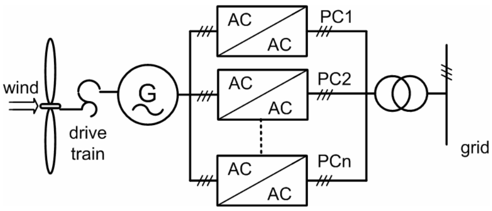

Fig. 15. Full-scale power converter with n-paralleled power converters.

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. 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 [8]-[15]; 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.

VII. CONTROL OF WIND TURBINES

Controlling a wind turbine involves both fast and slow control dynamics. Overall the power has to be controlled by means of the aerodynamic system and has to react based on a set-point given by a dispatched center or locally with the goal to maximize the power production based on the available wind power. The power controller should also be able to limit the power. An example of an overall control scheme of a wind turbine with a doubly-fed generator system is shown in Fig. 16 [8], [53].

Below maximum power production the wind turbine will typically vary the speed proportional with the wind speed and keep the pitch angle θ fixed.

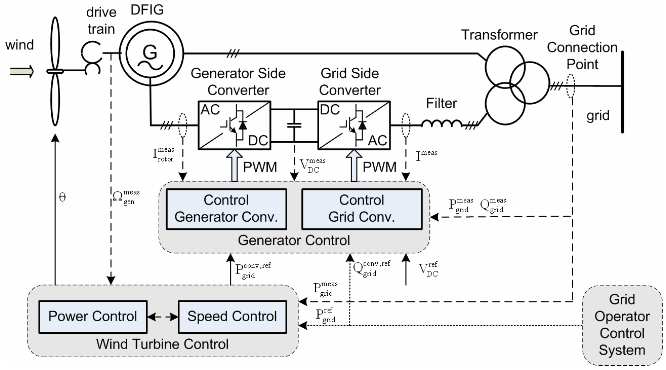

Fig. 16. Control of a wind turbine with doubly-fed induction generator (WT Type C).

At very low wind the speed of the turbine will be fixed at the maximum allowable slip in order not to have over voltage. A pitch angle controller limits the power when the turbine reaches nominal power. The generated electrical power is done by controlling the doubly-fed generator through the rotor-side converter. The control of the grid-side converter is simply just keeping the dc-link voltage fixed. Internal current loops in both converters are used which typically are linear PI-controllers, as it is illustrated in Fig. 16. The power converters to the grid-side and the rotor-side are voltage source converters.

Another solution for the electrical power control is to use the multi-pole synchronous generator. A passive rectifier and a boost converter are used in order to boost the voltage at low speed. The system is industrially used today and it is shown in Fig. 17.

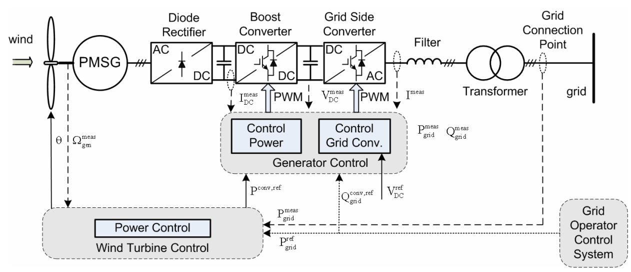

Fig. 17. Control of active and reactive power in a wind turbine with multi-pole synchronous generator (WT Type D)

A grid-side inverter is interfacing the dc-link to the grid. Common for both systems are they are able to control active and reactive power to the grid with fast control performance.

VIII. MARKET PENETRATION

The wind turbine market was dominated in the last years by ten major companies [15] and [66]. At the end of 2005 the wind turbine market share by manufacturer was as shown in Fig. 18.

The Danish company VESTAS Wind Systems A/S is still on the top position among the largest manufacturers of wind turbines in the world, followed by GE Wind, as the second largest in the world. German manufacturers ENERCON, Gamesa and Suzlon are in third, fourth and fifth positions, respectively. Notice that, the first four largest suppliers (Vestas, Gamesa, Enercon, GE Wind) had much larger markets with the first leading positions, compared to the others).

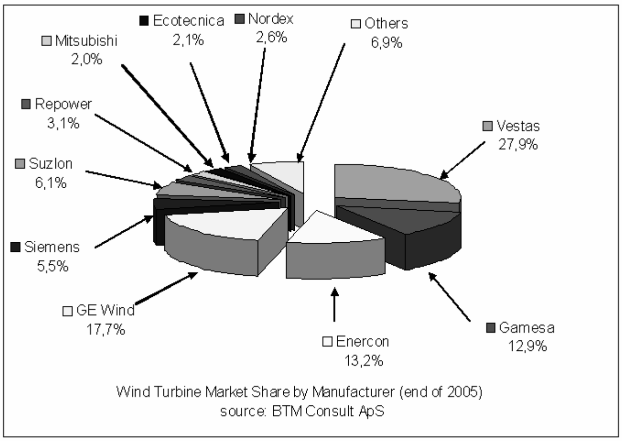

Fig. 18. Wind turbine market share by manufacturer (end of 2005).

A summary of the large wind turbine concepts available on the market in 2005 is presented in Table II [15].

Table II. Current status regarding the available wind turbine concepts in MW range on the market for the top five manufacturers

Manufacturer	WT rated power	Concept	Control	Generator
Vestas	V120–4.5 MW off-shore	Type C	Variable speed variable pitch gearbox	DFIG (WRIG) 4.5 MW/6 kV
	V90-3 MW	Type C	Variable speed variable pitch gearbox	DFIG (WRIG) 3 MW/1 kV
	V100–2.75 MW low wind sites	Type C	Variable speed variable pitch gearbox	DFIG (WRIG) 2.75 MW/1 kV
Gamesa	G90-2MW	Type C	Variable speed variable pitch gearbox	DFIG (WRIG) 2 MW/0.69 kV
Enercon	E112-4.5MW	Type D	Variable speed variable pitch Direct driven	Multipole WRSG 4.5MW/440V(?)
GE Wind	3.6 MW	Type C	Variable speed variable pitch gearbox	DFIG 3.6 MW/(?)
	2.x MW	Type D	Variable speed variable pitch gearbox	WRSG with full scale power converter
Siemens Power Generation	SWT 3.6-107	Type D	Variable speed variable pitch	SCIG with full scale power converter 3.6 MW/690V
	SWT 2.3-82 VS	Type D	Variable speed variable pitch	SCIG with full scale power converter 2.3 MW/690V
	SWT 2.3-82/93	Type A	Active stall	SCIG 2.3 MW/690V

As illustrated in Table II, all major manufacturers, at the end of 2006, had commercial turbines available in the 2-MW to 4.5-MW size range

Nowadays, the most attractive concept seemed to be the variable speed wind turbine with pitch control. Out of the Top Five-suppliers, only Siemens Wind Power (ex Bonus) used the 'traditional' active stall fixed speed concept, while the other manufacturers had at least one of their two largest wind turbines with the variable speed concept. However, recently Siemens Wind Power has released the multi-megawatt class variable speed full-scale power converter wind turbine based on the squirrel-cage induction generator. The most used generator type was the induction generator (WRIG and SCIG). Only ENERCON and GE wind used the synchronous generator (WRSG). One manufacturer, ENERCON, offered a gearless variable speed wind turbine. All wind turbines manufacturers are using a step-up transformer for connection of the generator to the grid.

A trend towards the configuration using a doubly-fed induction generator concept (Type C) with variable speed and variable pitch control, can be identified. In order to illustrate this trend, a dedicated investigation of the market penetration for the different wind turbine concepts is presented in [12]. The analysis cover approximately 75% of the accumulated world power installed at the end of 2004 as shown in Fig. 19.

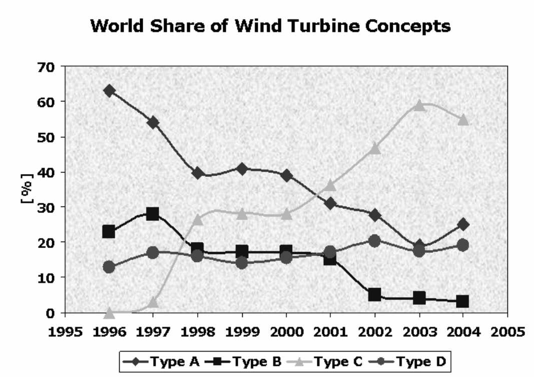

Fig. 19. Wind World share of yearly installed power for the considered wind turbine concepts [12].

Full-scale power converter based wind turbines have a relative constant market share over the years, while the interest for the variable-rotor resistance wind turbines (Type B) have fall down in the considered period.

IX. WIND FARM CONFIGURATIONS

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 [15] and [57]-[64].

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 [57]-[64]. 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 [8]-[15].

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 as well as reduce the mechanical stress and noise. This solution is shown in Fig.

20 and it is in operation in Denmark as a 160 MW off-shore wind power station.

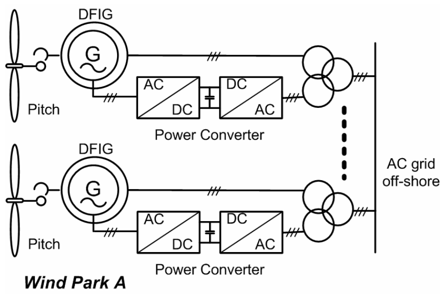

Fig. 20. Doubly Fed Induction Generator based wind farm with an AC grid connection [15].

The active stall wind farms based on wind turbine Type A (see Fig. 7) are directly connected to the grid. A reactive power compensation unit is used in the connection point as shown in Fig. 21.

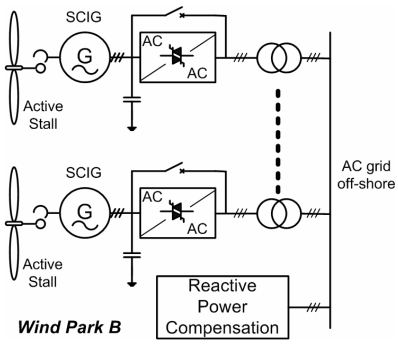

Fig. 21. Active stall wind farm with an AC grid connection [15].

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. 22. The topology may even be able to vary the speed on the wind turbines in the complete wind farm [54], [56].

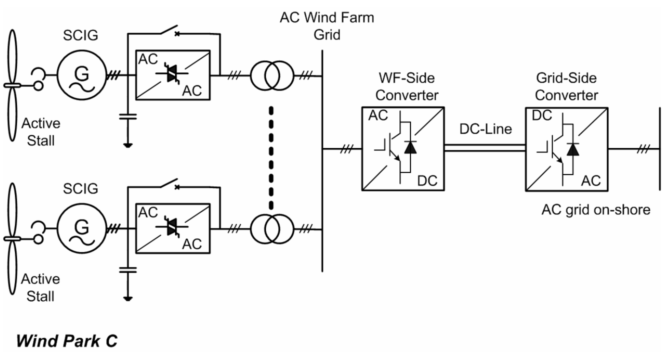

Fig. 22. Active stall wind farm with a DC-link grid connection [15].

Another possible DC transmission system configuration is shown in Fig. 23, 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 full scale power converter is used for the on-shore grid connection.

A comparison of these possible wind farm topologies is shown in Table III.

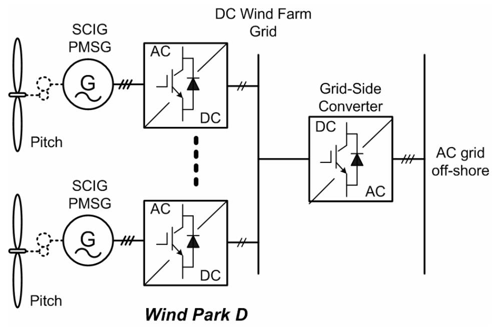

Fig. 23. Wind farm with common DC grid based on variable speed wind turbines with full scale power converter [15].

Table III. Comparison of wind farm topologies [15].

	Wind Park A	Wind Park B	Wind Park C	Wind Park D
Individual speed control	Yes	No	Yes	No
Control active power electronically	Yes	No	Yes	Yes
Control reactive power	Yes	Centralized	Yes	Yes
Short circuit (active)	Partly	Partly	Yes	Yes
Short circuit power	Contribute	Contribute	No	No
Control bandwidth	10-100 ms	200ms - 2s	10 -100 ms	10 ms – 10 s
Stand by-function	Yes	No	Yes	Yes
Soft-starter needed	No	Yes	No	No
Rolling capacity on grid	Yes	Partly	Yes	Yes
Redundancy	Yes	Yes	No	No
Investment	+	++	+	+
Maintenance	+	++	+	+

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.

X. GRID CONNECTION REQUIREMENTS

Some European countries have at this moment dedicated grid codes addressed to interconnection requirements of RES and in most of the cases these requirements reflects the penetration of renewable sources into the electrical network or a future development is prepared with these demands. Among all kinds of renewable sources only wind power and PV installations have specific requirements.

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 [12] and [57]-[59] in some of the cases these requirements are very difficult to fulfil.

A. 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 range. The active power is typically controlled based on the system frequency e.g. Denmark, Ireland, Germany [67]-[73] so that the power delivered to the grid is decreased when the grid frequency rises above 50 Hz.

A typical characteristic for the frequency control in the Danish grid code is shown in Fig. 24

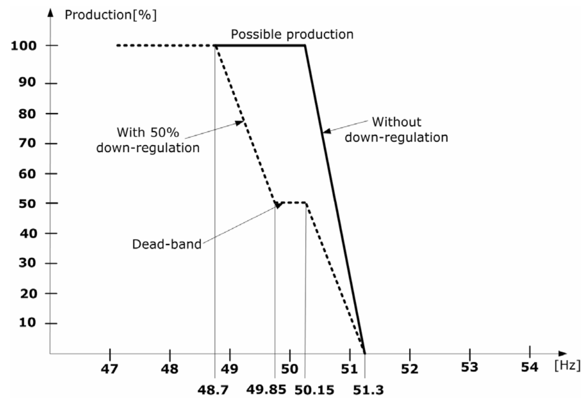

Fig. 24. Frequency control characteristic for the wind turbines connected to the Danish grid [67], [68].

On the other hand other grid codes, e.g. Great Britain [74] 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 the 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 [68]. Seven regulation functions are required in the wind farm control. Among these control functions, each one prioritized, the following must be mentioned: delta control, balance control, absolute production and system protection as shown in Fig. 25.

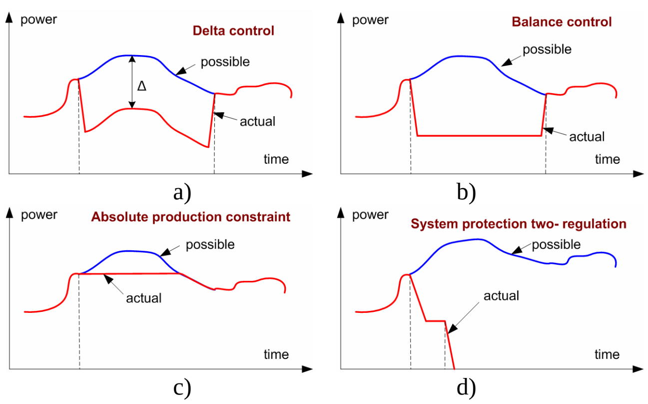

Fig. 25. Regulation function for active power implemented in the wind farm controller required by the Danish grid code: a) delta control, b) balance control, c) absolute production constraint and d) system protection [68].

B. 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 Denmark's grid code gives a band for controlling the reactive power based on the active power output as shown in Fig. 26.

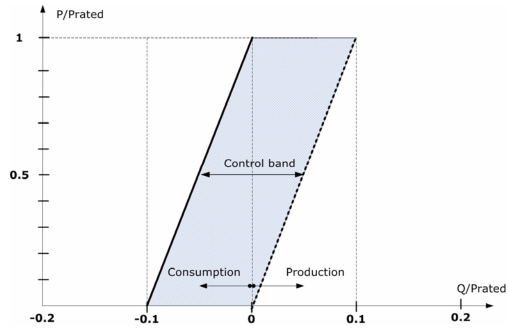

Fig. 26. Danish grid code demands for the reactive power exchange in the PCC [67] and [68].

The Irish grid code specifies e.g. the reactive power capability in terms of power factor as shown in Fig. 27.

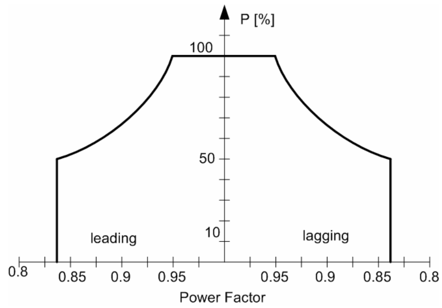

Fig. 27. Requirements for reactive power control in the Irish grid code for wind turbines [69] and [70].

The German transmission grid code for wind power specifies that these units must provide reactive power provision in the connection point without limiting the active power output the range of as shown in Fig. 28.

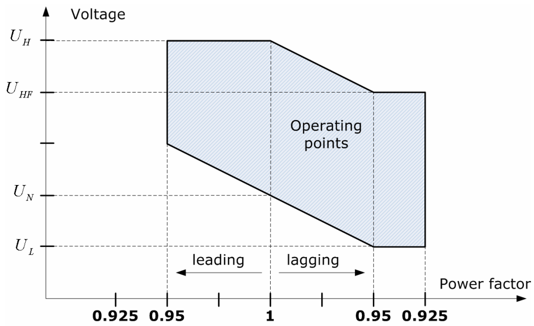

Fig. 28. Requirements for reactive power provision of generating units without limiting the active power output in the German transmission grid code [71] and [72].

C. Power Quality

Power quality issues are addressed especially for wind turbines connected to the medium voltage networks. However, some grid codes, e.g. in Denmark and Ireland have also requirements at the transmission level.

Mainly two standards are used for defining the power quality parameters namely: IEC 61000-x-x and EN 50160. Specific values are given for fast variations in voltage, short term flicker severity, long term flicker severity and the total harmonic distortion. A schedule of individual harmonics distortion limits for voltage are also given based on standards or in some cases e.g. Denmark custom harmonic compatibility levels are defined [67]. Interharmonics may also be considered.

D. Ride through capability

All considered grid codes require fault ride-through capabilities for wind turbines [67]-[80]. 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. 29 [15].

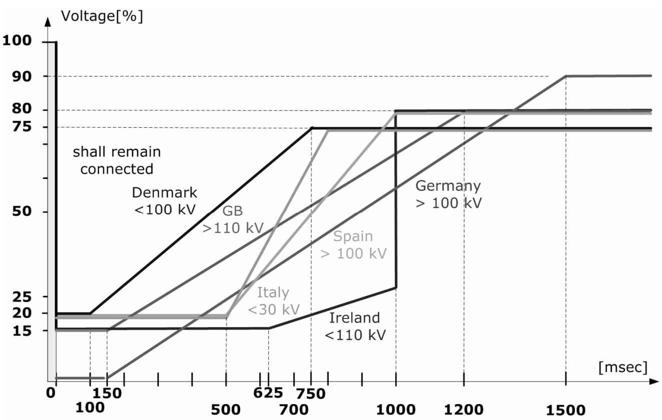

Fig. 29. Voltage profile for fault ride-through capability for European countries [15].

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 [67], [68].

On the other hand Germany and Spain requires grid support during faults by reactive current injection up to 100% from the rated current [71], [72], [76] as shown in Fig. 30.

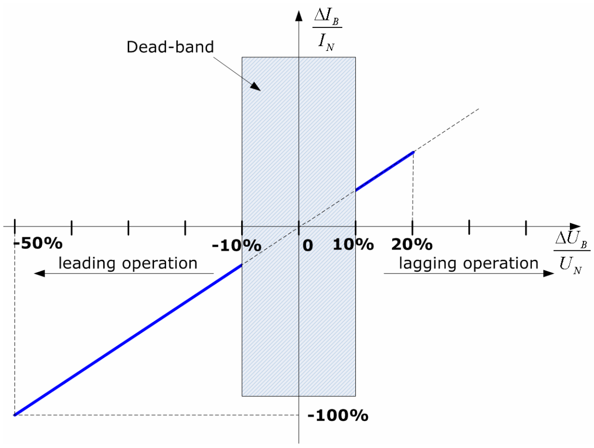

Fig. 30. Reactive current support during faults as specified in the German grid code [71].

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 (WT Type A). A very detailed analysis of the fault ride-through requirements for Europe, US and Canada is given in [65].

A summary regarding the interconnection requirements for wind power in Europe is given in detail in Appendix I [15] and [65].

XI. TRENDS AND CONCLUSIONS

It is obvious that currently there is an increasing trend both to remove dispersed single wind turbines in the favour of concentrated wind turbines in large wind farms and to move to the MW-size wind turbines, in order to reduce the cost. The percentage of wind power within the total grid capacity continues therefore to increase drastically, from year to year in the wind power contributor countries. The connection of such large wind turbines and wind farms to the grid has a large impact on grid stability and therefore, one major research challenge, in the present and in the next years, is directed towards connecting and optimised integration of large wind farms within the electrical power grid. It is therefore clear that the survival of different wind turbine concepts is strongly conditioned by their ability to support the grid, to handle faults on the grid and to comply with the stringent requirements of the utility companies.

Consequently, there is much worldwide research investigating the suitability of different wind turbine concepts to comply with the grid utilities requirements [8]-[12], [57]-[64].

Back in 80's and in the beginning of 90's, typical installations were dispersed single small fixed-speed wind turbines. These were popular due to their robustness, simplicity and low cost. The power electronics was expensive and grid connection requirements were minimal.

Since then, the developments in high-voltage high-current semiconductor devices and the microprocessor technology as well as the reduction in size, weight and an increased number of functions at low price have made possible the utilization of power converters in the wind turbine technology.

On the other hand the wind turbine's size was in a continuous growth in the last 25 years and today prototype turbines of 4-5 MW are seen around the world being tested. The development of wind turbines is illustrated in Fig. 31. It is expected 10 MW wind turbines will be present in 2010.

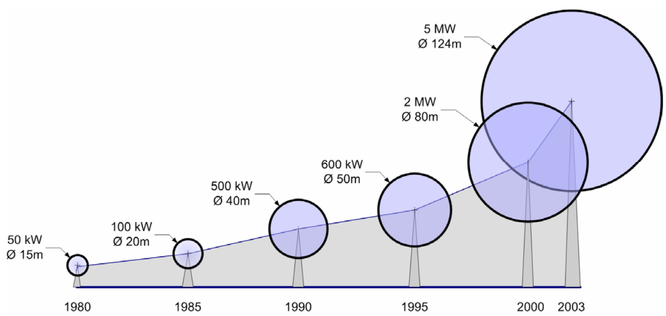

Fig. 31. Development of wind turbines during the last 25 years.

The penetration of wind turbines in the power system was back in 80's, not as significant as today, so the turbines could be switched off without detrimental effect, e.g. in the case of a major grid problem. Such a solution is not applicable today, when the electrical power system depends on the increased and concentrated penetration of wind energy. Therefore the power system is more vulnerable and dependent on the wind energy production.

Today, there are very hard grid connection requirements [12], [57]-[59], [67]-[80] which require MW-size wind turbines concentrated in large wind farms to support the grid actively and to remain connected during grid events (i.e. voltage sags), otherwise it could cause a grid blackout. The main role for such technical demands of the grid operators is played today by the power electronics within the wind turbines and wind farms. The presence of power electronics gives increased interest in variable speed concepts. Moreover, power electronic can also support common variable speed operation for wind farms consisting of fixed speed wind turbines (Type A), as it is the case of High Voltage Direct Current (HVDC) wind turbine configuration. Consequently, variable speed operation is attractive for wind turbines within wind farms for a number of reasons, including reduced mechanical stress, increased power capture, reduced acoustical noise and, not least, its controllability, which is a prime concern for the grid integration of large wind farms. It is therefore clear that variable speed operation will continue to be the norm and not the exception. It has been shown that the market interest for the fixed speed wind turbine concept (Type A) has decreased slightly in favour of variable speed wind turbine concepts. However, the market interest for fixed speed turbines may increase if it is demonstrated that HVDC-based wind farms of Type A with squirrel-cage induction generators are robust to grid faults, as technically they should be.

Today, variable speed wind turbine concepts (Type C and Type D) have already a substantial increasing share of the wind power market. In the future, it seems that they still may dominate and be very promising wind technologies for large wind farms. The doubly-fed induction generator wind turbine concept has developed into a semi-industry standard for gear-driven wind turbines, being increasingly adopted by a wide range of international suppliers. At the same time, there is presently an intensive research activity in gearless drives and other types of synchronous generators, which makes the Type D concept potentially attractive in the future too. The Type C and Type D wind turbine concepts will continue to compete in the market, each with weaker and stronger features. Presently, the main advantage of the doubly-fed induction concept, Type C, is that the percentage of power generated in the generator passing through a frequency converter is only 30%, as compared with 100% for a full-scale power converter wind turbine (WT Type D). Even with low priced power electronics, doubly-fed technology has a substantial cost advantage as compared to the conversion of full power. On the other hand, compared with full power converters, the doubly-fed induction concept shows, at the moment, a more technically difficult grid behaviour, because, during failure situations, large peak currents are introduced into the system [5]. This requires advanced protection systems. Moreover, grid support by means of 100% reactive current injection into the grid might not be supported by this concept. In contrast, full power converters are very attractive because they can provide complete grid support during network events. The Type D wind turbine concept is slightly more efficient, less complicated from an electrical engineering point, easier to construct but more expensive. Looking to the future, further developments of Type C and Type D are expected, focusing on more optimised turbines and, thus, towards more cost-effective machines. Different and improved versions of these concepts may be developed. For example, the brushless doubly-fed induction generator concept and other types of generators may be exploited.

As with all technologies, the future is difficult to predict. Concepts borrowed from other fields or other applications could have profound effects on future designs. However, one thing is sure - power electronics will continue to play a vital role in the integration of large future wind turbine/farms. The very fast development of power electronics offers both enlarged capabilities and lower price per kW capacity. In this context, more new wind turbine generator concepts may be developed. Such new concepts will be specifically designed for the application and will require demonstrated performance to survive market expectations.

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Appendix I. Review of connection requirements for wind power in European grid codes [15].

		Denmark		Ireland	Germany	Great Britain	Spain	Italy (draft)
Voltage Level		DS	TS	DS(TS)	TS(DS)	TS(DS)	TS	> 35 kV
Power Level		all	all	≥5MW	all	all	all	> 10 MW
Tolerance over frequency range		yes	yes	yes	yes	yes	-	yes
Frequency	**Frequency control**	all	all	all	all	all	-	> 25 MW
	MW Curtailment	20-100% P_r	20-100% P_r	yes	yes	-	-	-
	Maximum Ramp Rates	10-100% P_r/min	10-100% P_r/min	1-30 MW/min	yes	-	-	<20% P_r/min
Voltage	**Voltage Control**	no	no	yes	no	no	-	no
	Reactive Power Control	yes	yes	yes	yes	yes	-	yes
Voltage quality	**Fast voltage variations**	≤ 3%	≤ 3%	-	≤ 2%	≤ 3%-	-	EN 50160
	Short Term Flicker Severity	-	≤ 0.3	≤ 0.35	-	≤0.8	-	EN 50160
	Long Term Flicker Severity	≤ 0.35	≤ 0.2	≤ 0.35	≤ 0.46	≤0.6	-	EN 50160
	Harmonic Compatibility Levels	Specific levels	-	Specific Levels[1)]	EN 50160	IEC 61000-3-2	-	EN 50160
	THD	-	≤ 1.5%	≤ 1.5%	≤ 8%	N/A	-	EN 50160
Fault ride-through	**Fault duration**	100 msec	100 msec	625 msec	150 msec	140 msec	500 msec	500 msec
	Min voltage	25%U_r	25%U_r	15%U_r	0%U_r	15%U_r	20%U_r	20% U_r
	Recovery time	1 sec	1 sec	3 sec	1.5 sec	1.2 sec	1 sec	0.3 sec
	Voltage profile	2, 3-ph	1, 2, 3- ph	1, 2, 3- ph	generic	generic	generic	generic
	Reactive current injection	no	no	no	Up to 100%	no	Up to 100%	no
Island operation		not required	not required	not required	not required	not required	not required	not required
Black start capability		not required	not required	may	if required	not required	not required	not required
Signals, Communication and Control	**Availability**	yes	yes	yes	yes	yes	-	yes
	Active power output	yes	yes	yes	yes	yes	-	yes
	Reactive power output	yes	yes	yes	yes	yes	-	yes
	MW Curtailment	yes	yes	yes	yes	yes	-	-
	Frequency control	yes	yes	yes	yes	yes	-	-
	Circuit breaker status	yes	yes	yes	yes	yes	-	yes
	Meteorological data: Wind speed, wind direction, air pressure and temperature	yes	yes	yes	-	-	-	yes

1) Harmonic compatibility levels are given in general for loads and installations. DSO shall provide a schedule of individual limits where appropriate.