Power Electronics in Wind Turbine Systems

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***Abstract* – The global electrical energy consumption is still rising and there is a steady demand to increase the power capacity. The production, distribution and the use of the energy should be as technological efficient as possible and incentives to save energy at the end-user should be set up. The deregulation of energy has lowered the investment in larger power plants, which means the need for new electrical power sources may be very high 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. The other is to use high efficient power electronics in power systems, power production and end-user application. This paper discuss the most emerging renewable energy source, wind energy, which by means of power electronics is changing from being a minor energy source to be acting as an important power source in the energy system. By that wind power is also getting an added value in the power system operation.**

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 centers over long distance transmission lines. The system control centers monitor and control the power system continuously to ensure the quality of the power, namely the frequency and the 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 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 the 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.

The wind turbine technology is one of the most emerging renewable technologies. It started in the 1980'es with a few tens of kW production power to today with Multi-MW range wind turbines that are being installed. This 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 part 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 those control parameters become more important and it is necessary to introduce power electronics [3] 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 turbine is not new. It has been discussed for several years [6]-[46] but now the price pr. produced kWh is so low, that solutions with power electronics are very attractive.

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 explained for a turbine. Wind turbines are now more often installed in remote areas with good wind conditions (off-shore, on-shore) and different possible configurations are shown and compared. Finally, a general technology status of the wind power is presented demonstrating a still more efficient and attractive power source.

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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 the price. Fig. 1 shows a typical power electronic system consisting of a power converter, a load/source and a control unit.

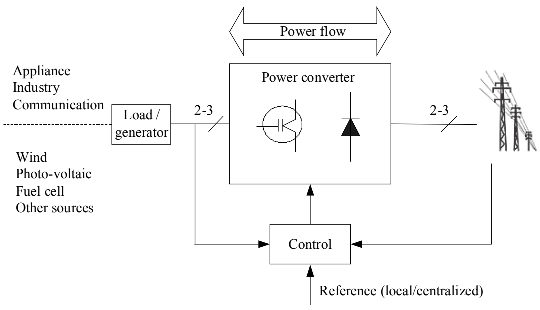
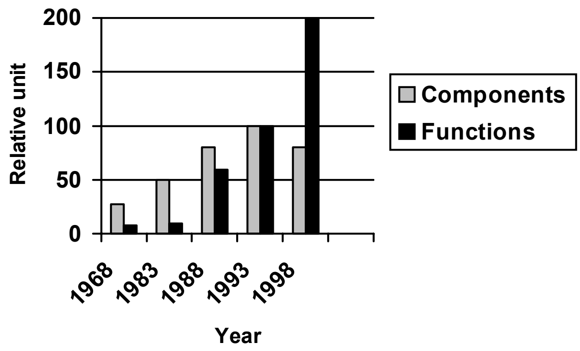


Fig. 1. Power electronic system with the grid, load/source, power onverter and control.

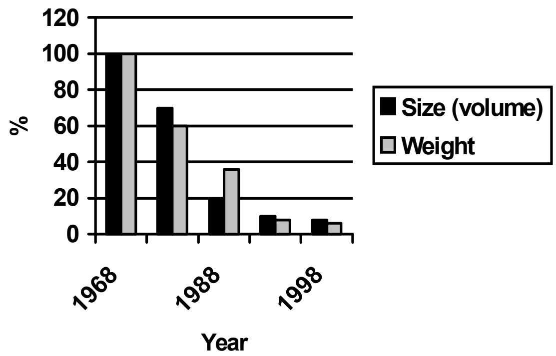
The power converter is the interface between the load/generator and the grid. The power may flow in both directions, of course, dependent on topology and applications. Three important issues are of concern using such a system. The first one is reliability; the second is efficiency and the third one is cost. For the moment the cost of power semiconductor devices is decreasing 2-5 % every year for the same output performance and the price pr. kW for a power electronic system is also decreasing. A high competitive power electronic system is adjustable speed drives (ASD) and 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.

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

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. Also important research is going on to change the material from silicon to silicon carbide. This may dramatically increase the power density of power converters but silicon carbide based transistors on a commercial basis with a competitive price will still take some years to appear on the market.



(a)



(b)

Fig. 2. Development of a 4 kW standard industrially adjustable speed drive during the last 25 years [5].

a) Relative number of components and functions

b) Relative size and weight

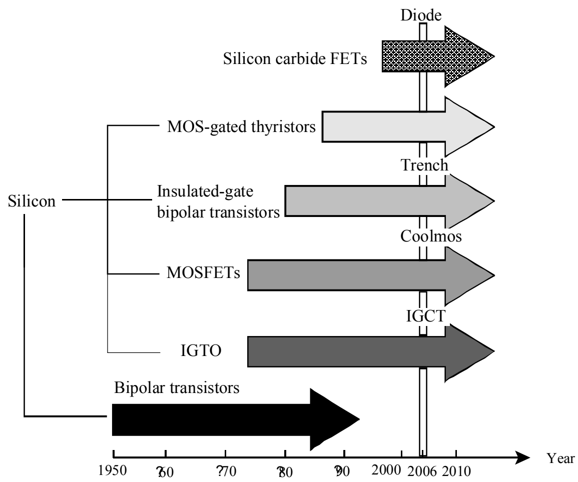


Fig. 3. Development of power semiconductor devices in the past and in the future [34]

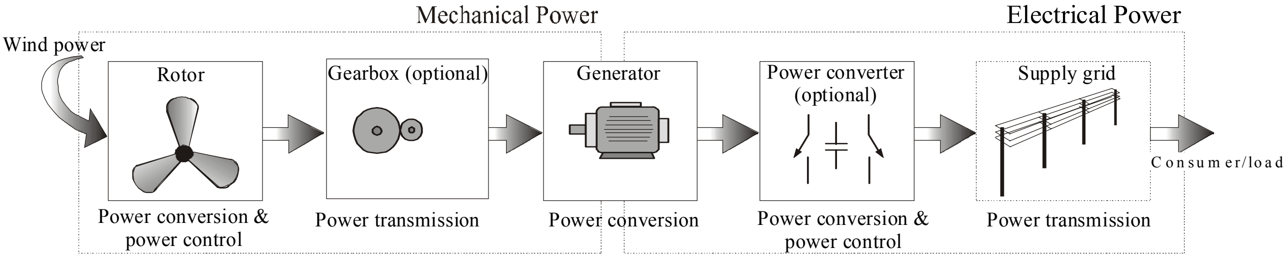


Fig. 4. Converting wind power to electrical power in a wind turbine [17].

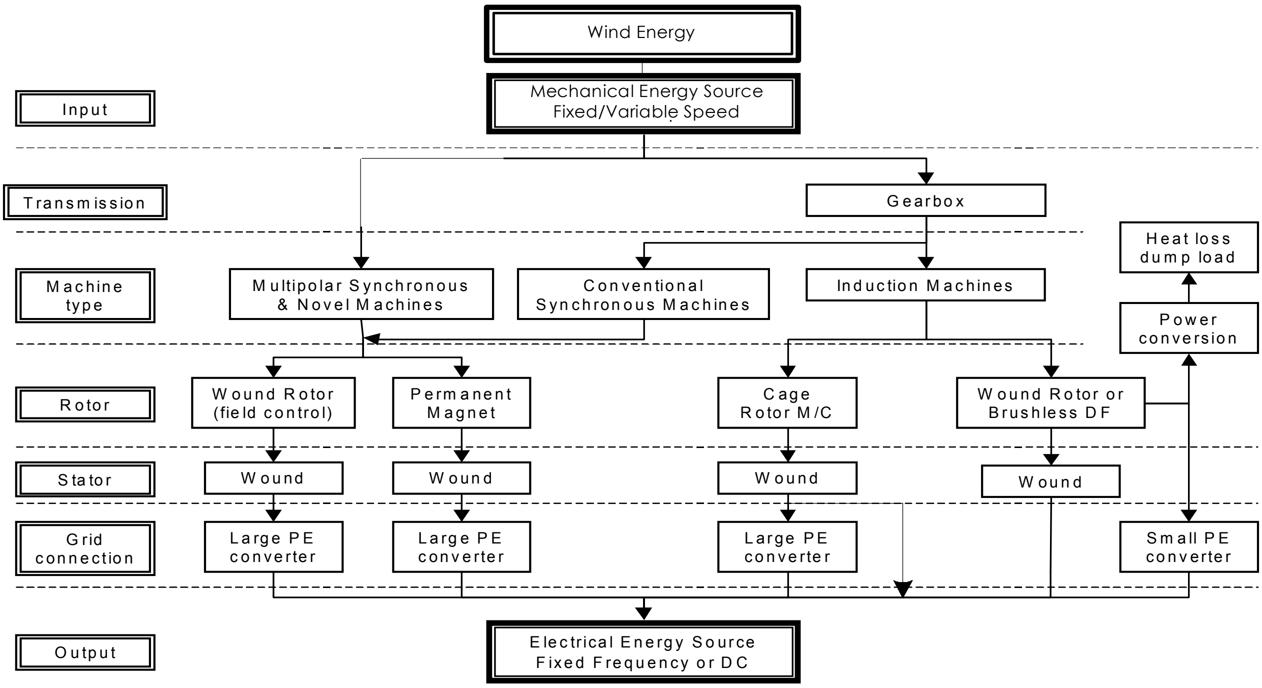


Fig. 5. Road-map for wind energy conversion. PE: Power Electronics. DF: Doubly-fed [15], [22].

III. Wind Energy Conversion

Wind turbines capture the 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 using a gear-box and a standard fixed speed generator as illustrated in Fig. 4.

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.

The possible technical solutions are many and Fig. 5 shows a technological roadmap starting with wind energy/power and converting the mechanical power into electrical power. It involves solutions with and without gearbox as well as solutions with or without power electronic conversion. The electrical output can either be ac or dc. In the last case a power converter will be used as interface to the grid. In the following sections, some different wind turbine configurations will be presented and compared.

IV. Fixed Speed Wind Turbines

The development in wind turbine systems has been steady for the last 25 years and four to five generations of wind turbines exist. It is now proven technology. The conversion of wind power to mechanical power is as mentioned before done aerodynamically. 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). The wind turbines technology can basically be divided into three categories: the first category is systems without power electronics, the second category is wind turbines with partially rated power electronics (small PE converter in Fig. 5) and the last is the full-scale power electronic interfaced wind turbine systems (large PE converter in Fig. 5). Fig. 6 shows different topologies for the first category of wind turbines where the wind turbine speed is fixed.

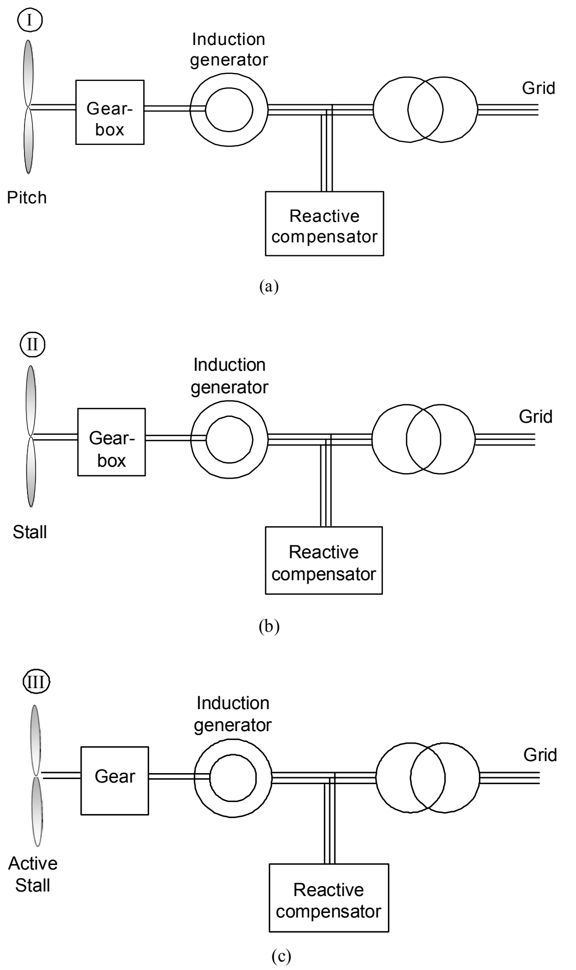


Fig. 6. Wind turbine systems without power converter but with aerodynamic power control.

a) Pitch controlled (System I)

b) Stall controlled (System II)

c) Active stall controlled (System III)

The wind turbine systems in Fig. 6 are using induction generators, which almost independent of torque variation operate at a fixed speed (variation of 1-2%). The power is limited aerodynamically either by stall, active stall or by pitch control. All three systems are using a soft-starter (not shown in Fig. 6) in order to reduce the inrush current and thereby limit flicker problems on the grid. They also need 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). Those solutions are attractive due to cost and reliability but they are not able very fast (within a few ms) to control the active power. Furthermore wind-gusts may cause torque pulsations in the drive-drain and load the gear-box significantly. The basic power characteristics of the three different fixed speed concepts are shown in Fig. 7 where the power is limited aerodynamically.

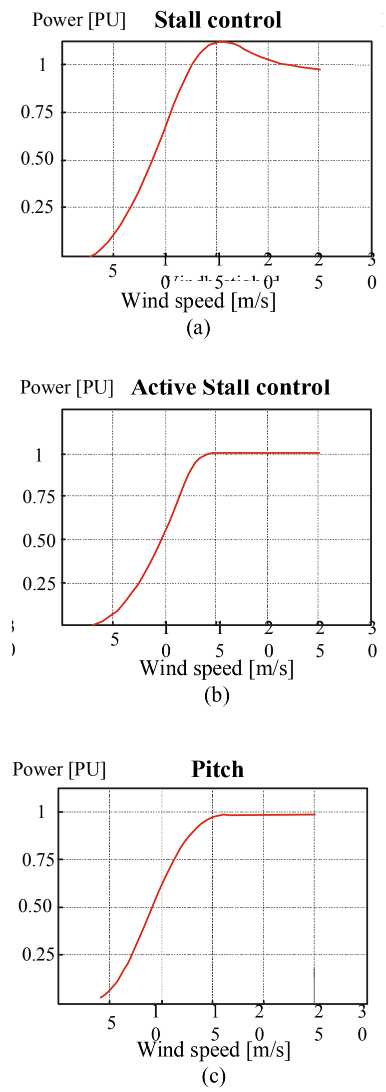


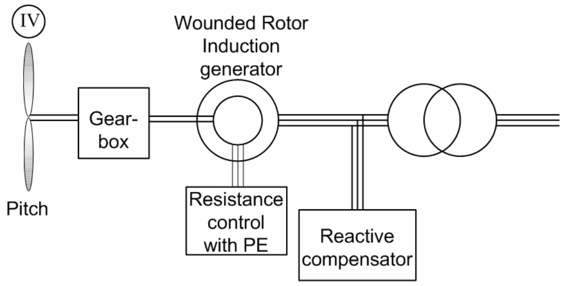
Fig. 7. Power characteristics of fixed speed wind turbines.

a) Stall control b) Active stall control c) Pitch control

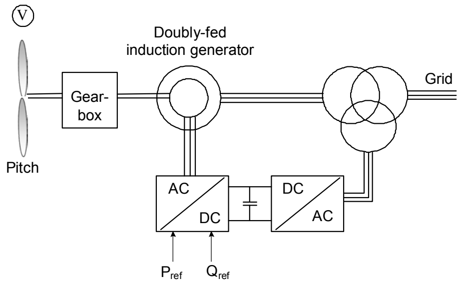
Fig. 7 shows that by rotating the blades either by pitch or active stall control it is possible precise to limit the power while the measured power for the stall controlled turbine shows a small overshoot. This depends a lot on the final aerodynamic design.

V. VARIABLE SPEED WIND TURBINES

The next category is wind turbines with partially rated power converters and by that improved control performance can be obtained. Fig. 8 shows two such solutions.



(a)



(b)

Fig. 8. Wind turbine topologies with partially rated power electronics and limited speed range.

a) Rotor-resistance converter (System IV)

b) Doubly-fed induction generator (System V)

Fig. 8 shows a wind turbine system where the generator is an induction generator with a wounded rotor. An extra resistance is added in the rotor, which can be controlled by power electronics. This is a dynamic slip controller and it gives typically a speed range of 2 - 5 %. The power converter for the rotor resistance control is for low voltage but high currents. At the same time an extra control freedom is obtained at higher wind speeds in order to keep the output power fixed. This solution still needs a softstarter and a reactive power compensator, which is in continuous operation.

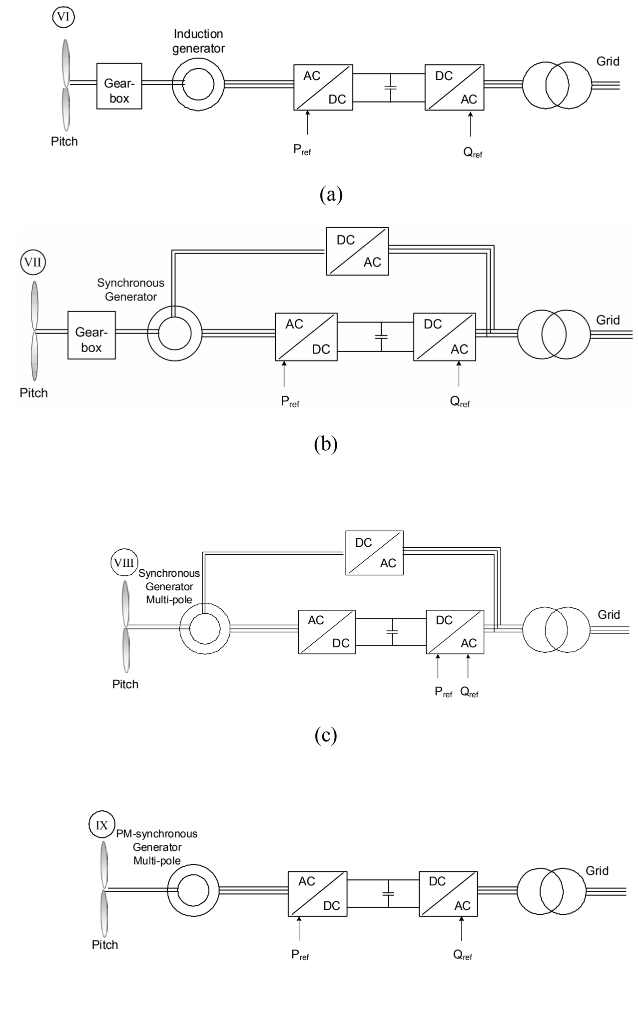
A second solution of using a medium scale power converter with a wounded rotor induction generator is shown in Fig. 8b. Slip-rings are making the electrical connection to the rotor. A power converter controls the rotor currents.

If the generator is running super-synchronously electrical power is delivered through both the rotor and the stator. If the generator is running sub-synchronously electrical power is only delivered into the rotor from the grid. A speed variation of ±30 % around synchronous speed can be obtained by the use of a power converter of 30 % of nominal power. Furthermore, it is possible to control both active (Pref) and reactive power (Qref), which gives a better grid performance, and the power electronics is enabling the wind turbine to act as a more dynamic power source to the grid.

The last solution needs neither a soft-starter nor a reactive power compensator. The solution is naturally a little bit more expensive compared to the classical solutions shown before in Fig. 7 and Fig. 8a. However, it is possible to save money on the safety margin of gear, reactive power compensation units as well it is possible to capture more energy from the wind.

The third category is wind turbines with a full-scale power converter between the generator and grid, which are the ultimate solutions technically. It gives extra losses in the power conversion but it may be gained by the added technical performance. Fig. 9 shows four possible, but not exhaustive, solutions with full-scale power converters.

System comparison of wind turbines									
System	**I**	**II**	**III**	**IV**	**V**	**VI**	**VII**	**VIII**	**IX**
Variable speed	No	No	No	No	Yes	Yes	Yes	Yes	Yes
Control active power	Limited	No	Limited	Limited	Yes	Yes	Yes	Yes	Yes
Control reactive power	No	No	No	No	Yes	Yes	Yes	Yes	Yes
Short circuit (fault-active)	No	No	No	No	No/Yes	Yes	Yes	Yes	Yes
Short circuit power	contribute	contribute	contribute	contribute	contribute	limit	limit	limit	limit
Control bandwidth	1-10 s	1-10 s	1-10 s	100 ms	1 ms	0.5-1 ms	0.5-1 ms	0.5-1 ms	0.5-1 ms
Standby function	No	No	No	No	Yes +	Yes ++	Yes ++	Yes ++	Yes ++
Flicker (sensitive)	Yes	Yes	Yes	Yes	No	No	No	No	No
Softstarter needed	Yes	Yes	Yes	Yes	No	No	No	No	No
Rolling capacity on grid	Yes, partly	No	Yes, partly	Yes, partly	Yes	Yes	Yes	Yes	Yes
Reactive compensator (C)	Yes	Yes	Yes	Yes	No	No	No	No	No
Island operation	No	No	No	No	Yes/No	Yes/No	Yes/No	Yes/No	Yes
Investment	++	++	++	++	+	0	0	0	0
Maintenance	++	++	++	++	0	+	+	+	+



(a)

(b)

(c)

(d)

Fig. 9. Wind turbine systems with full-scale power converters.

a) Induction generator with gear (System VI)

b) Synchronous generator with gear (System VII)

c) Multi-pole synchronous generator (System VIII)

d) Multi-pole permanent magnet synchronous generator (System IX)

The solutions shown in Fig. 9a and Fig. 9b are characterized by having a gear. A synchronous generator solution shown in Fig. 9b needs a small power converter for field excitation. Multi-pole systems with the synchronous generator without a gear are shown in Fig. 9c and Fig. 9d. The last solution is using permanent magnets, which are still becoming cheaper and thereby more attractive. All four solutions have the same controllable characteristics since the generator is decoupled from the grid by a dc-link.

The power converter to the grid enables the system to control active and reactive power very fast. However, the negative side is a more complex system with more sensitive electronic parts.

Comparing the different wind turbine systems in respect to performance shows a contradiction between cost and the performance to the grid. Table I shows a technical comparison of the presented wind turbine systems, where issues on grid control, cost, maintenance, internal turbine performance are given. By introducing power electronics many of the wind turbine systems get a performance like a power plant. In respect to control performance they are faster but of course the produced real power depends on the available wind. The reactive power can in some solutions be delivered without having any wind producing active power.

Fig. 9 is also indicating other important issues for wind turbines in order to act as a real power source for the grid. They are able to be active when a fault appears at the grid and where it is necessary to build the grid voltage up again; 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. The market share in 2001 (Globally and in Germany) between the dominant system topologies is shown Table II.

TABLE II.
WIND TURBINE TOPOLOGIES MARKET IN 2002.
(Source: [4])

Turbine Concept	**World-Market Share**
Fixed speed (Stall or active stall, gearbox), System I, II, III	28%
Dynamic slip control (Limited variable speed, pitch, gearbox), System IV	5%
Doubly-fed generator (Variable speed operation, pitch control, gearbox), System V	47%
Direct-driven (variable speed operation, pitch control), System VIII	20%
TOTAL	**100%**

As it can be seen the most sold technology in 2001 is the doubly-fed induction generator system which occupies about 50% of the whole market. More than 75% of all sold wind turbines in 2001 are controlled by power electronics. That is even more in 2003.

VI. CONTROL OF WIND TURBINES

Controlling a wind turbine involves both fast and slow control. Overall the power has to be controlled by means of the aerodynamic system and has to react based on a set-point given by dispatched center or locally with the goal to maximize the production based on the available wind power.

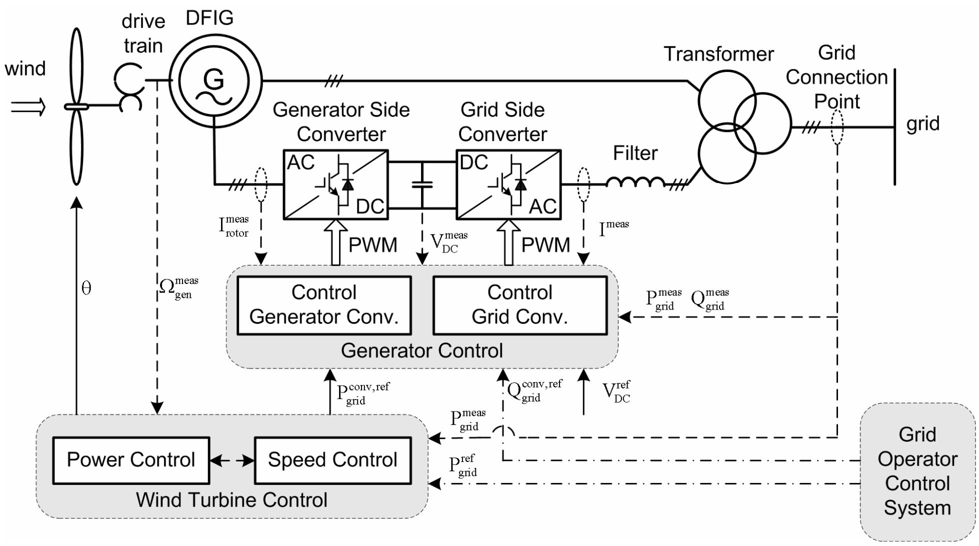
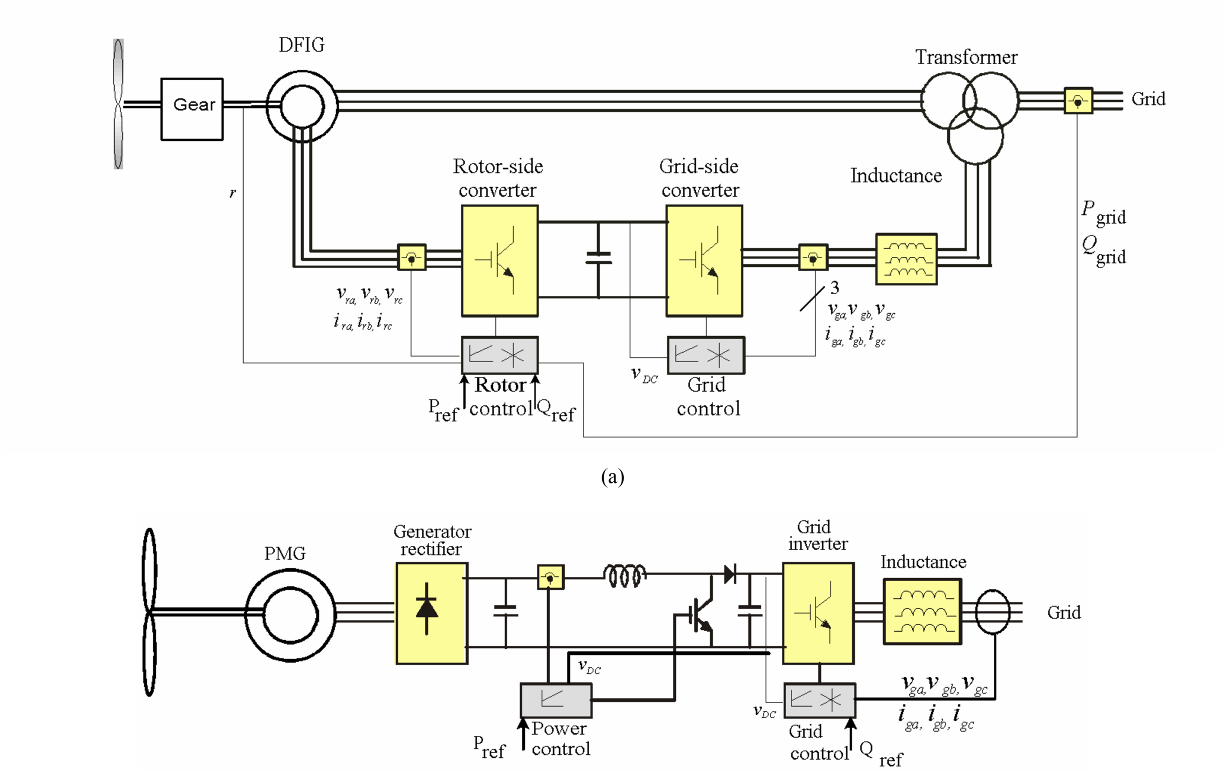


Fig. 10. Control of wind turbine with doubly-fed induction generator system [35].



(b)

Fig. 11. Basic control of active and reactive power in a wind turbine [17].

a) Doubly-fed induction generator system (System V)

b) Multi-pole synchronous PM-generator system (System IX)

The power control system 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. 10.

Below maximum power production the wind turbine will typically vary the speed proportional with the wind speed and keep the pitch angle □ fixed. 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 will limit 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. 11a. The power converters to the grid-side and the rotor-side are voltage source inverters.

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. It is possible to control the active power from the generator. The topology is shown in Fig. 11b. A grid inverter is interfacing the dc-link to the grid. Here it is also possible to control the reactive power to the grid. Common for both systems are they are able to control reactive to control the reactive power to the grid. Common for both systems are they are able to control reactive and active power very fast and thereby the turbine can take part in the power system control.

VII. OFFSHORE WIND FARM TOPOLOGIES

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 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 fulfill the future demands.

One off-shore wind farm equipped with power electronic converters can perform both real 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. 12a and it is in operation in Denmark as a 160 MW off-shore wind power station.

For long distance transmission of power from off-shore wind farm, HVDC may be an interesting option. In an HVDC transmission, 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 onshore system where the dc voltage is converted back into ac voltage as shown in Fig. 12c. For certain power level, an HVDC transmission system, based on voltage source converter technology, may be used in such a system instead of the conventional thyristor based HVDC technology.

The topology may even be able to vary the speed on the wind turbines in the complete wind farm.

Another possible dc transmission system configuration is shown in Fig. 12d, 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 comparison of the topologies is given in Table III.

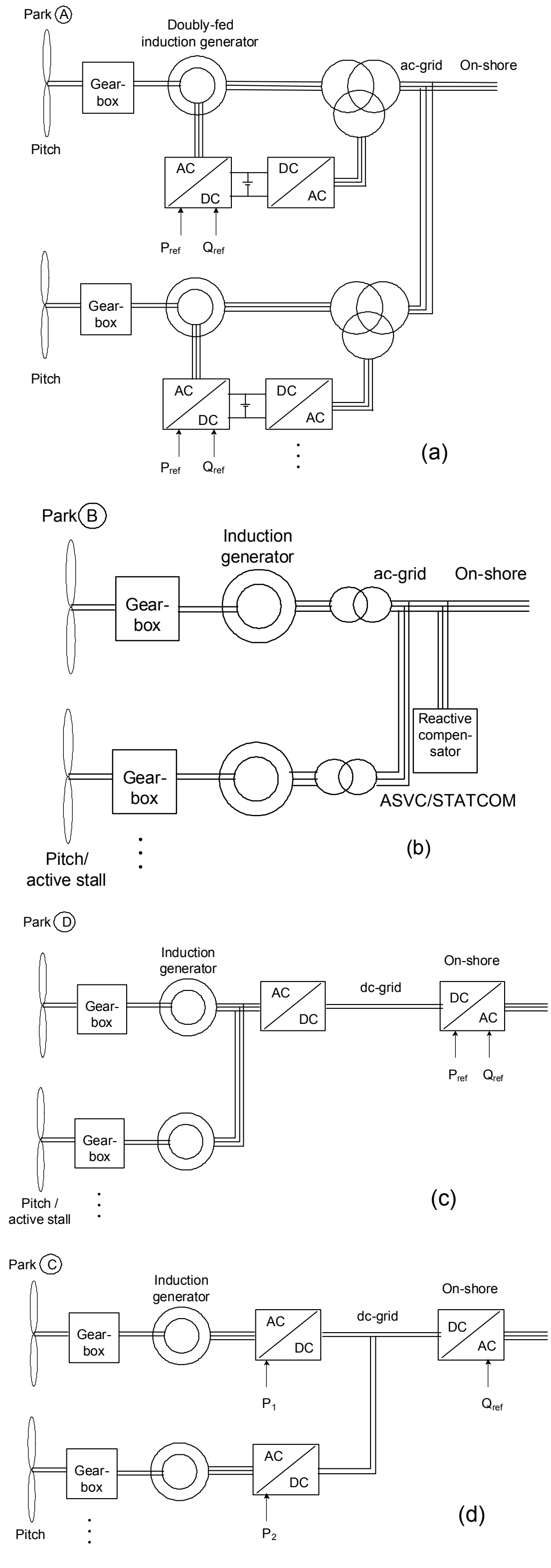


Fig. 12. Wind farm solutions.

a) Doubly-fed induction generator system with ac-grid (System A)

b) Induction generator with ac-grid (System B)

c) Speed controlled induction generator with common dc-bus and control of active and reactive power (System C)

d) Speed controlled induction generator with common ac-grid and dc transmission (System D)

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.

VIII. Wind Power Trends

The installed power in wind energy has grown rapidly in many years. Today more than 45000 MW are installed globally with recently an annual market of 8000 MW. This is illustrated in Fig. 13.

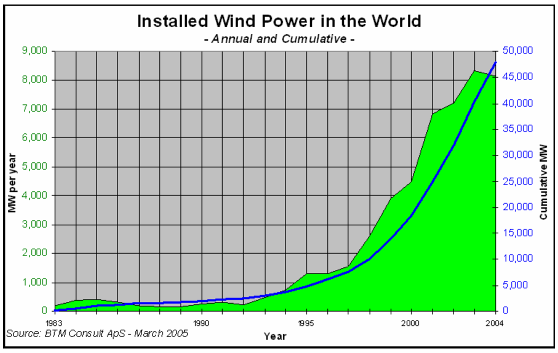


Fig. 13. Annually installed and accumulated wind power globally.

(Source: Risoe National Laboratory, Denmark)

The expectations for the future are also very positive as many countries have progressive plans. Table IV gives an estimate for the installed wind power in 2010 based on official statements from different European countries.

It can be seen that many countries will increase their wind power capacity in large scales. In Denmark the installed capacity is expected to approach saturation as the problems of a too high capacity compared to the load level are appearing. However, energy cost rise can change this.

The power scaling has been an important tool to reduce the price pr. kWh. Fig. 14 shows the average size of the installed wind turbines in Denmark as well as their produced energy pr. m2 swept area pr. year. It can be seen that the technology is improving and it is possible to produce more than 900 kWh/m2/year. This depends of course on location and from experience off-shore wind-farms are able to produce much more energy

The influence on the power scaling can also be seen at the prices pr. kWh for different wind-turbine sizes in two different landscape classes and it is shown in Fig. 15. The key to reduce price is to increase the power and today prototype turbines of 4-5 MW are seen around the world being tested. Finally, the development of wind turbines is illustrated in Fig. 16. It is expected 10 MW wind turbines will be present in 2010.

IX. Conclusions

The paper discusses the applications of power electronic for the wind turbine technology. The development of modern power electronics has been briefly reviewed. The applications of power electronics in various kinds of wind turbine generation systems and offshore wind farms are also illustrated, showing that the wind turbine behavior/performance is very much improved by using power electronics. They are able to act as a contributor to the frequency and voltage control by means of active and reactive power control. Also it can be concluded the power scaling of wind turbines is important in order to be able to reduce the energy cost.

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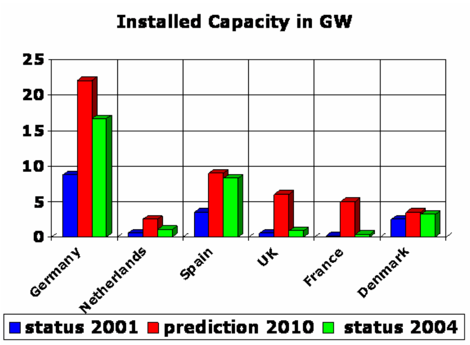
Tabel III. Comparison of Wind Farms

Farm configuration (Fig. 12)	A	B	C	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
Standby-function	Yes	No	Yes	Yes
Softstarter needed	No	Yes	No	No
Rolling capacity on grid	Yes	Partly	Yes	Yes
Redundancy	Yes	Yes	No	No
Investment	+	++	+	+
Maintenance	+	++	+	+



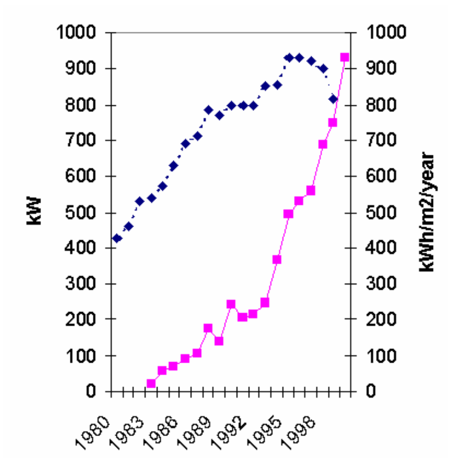


Fig. 14. Average size of wind turbines and produced energy pr. m2 swept area pr. year in Denmark.

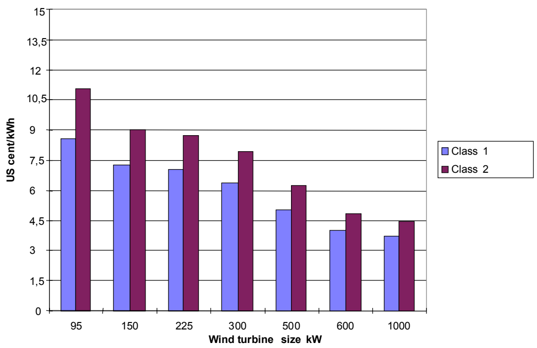


Fig. 15. Price pr. produced kWh at different landscape classes. (Source: Risoe National Laboratory, Denmark)

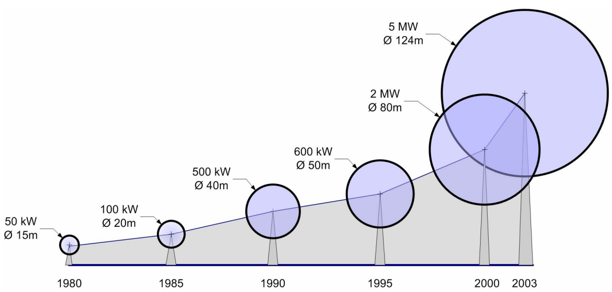


Fig. 16. Development of wind turbines during the last 25 years.

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