Power Electronics in Renewable Energy 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. 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 also 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 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. An other is to use high efficient power electronics in power generation, power transmission/distribution and end-user application. This paper discuss some of the most emerging renewable energy sources, wind energy and photovoltaic, which by means of power electronics are changing from being minor energy sources to be acting as important power sources in the energy system.**

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 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.

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 size wind turbines that are being installed. It also means that wind power production in the beginning did not have any impact on the power system control but now due to their size they have to play an active 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]-[63] 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 shown for a wind turbine. They are now also installed in remote areas with good wind conditions (off-shore, on-shore) and different possible configurations are shown and compared. Next the PV-technology is discussed including the necessary basic power electronic conversion. Power converters are given and more advanced control features described. Finally, a general technology status of the wind power and the PV technology is presented demonstrating still more efficient and attractive power sources for the future.

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

The power converter is the interface between the load/generator and the grid. The power may flow in both

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directions, of course, dependent on topology and applications.

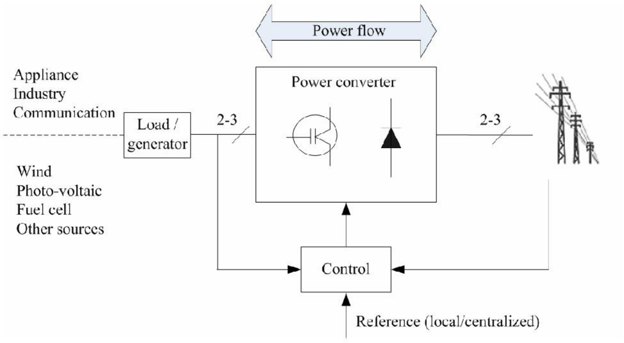


Fig. 1. Power electronic system with the grid, load/source, power converter and control.

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. It clearly shows that power electronic conversion is shrinking in volume and weight. It also shows that more integration is an important key to be competitive as well as more functions become available in such a product.

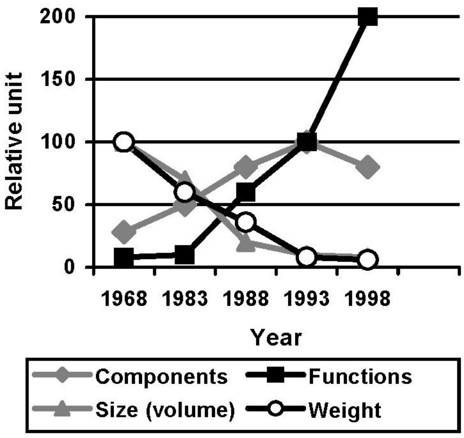


Fig. 2. Development of a 4 kW standard adjustable speed drive for 30 years [5]. The evolution over the years as a relative number of components, functions, volume and weight are shown.

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.

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.

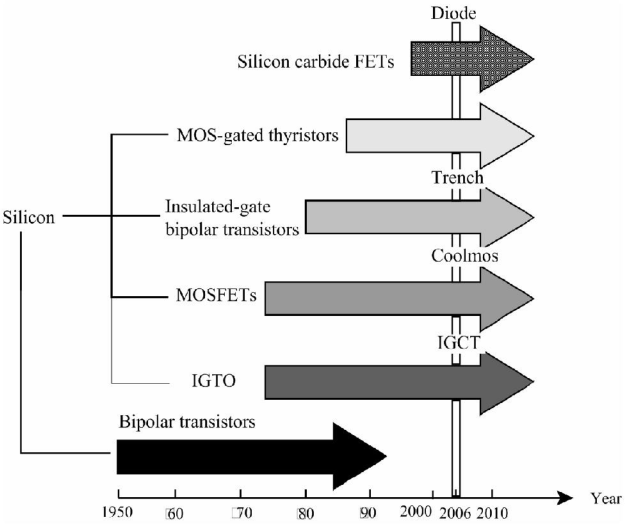


Fig. 3. Development of power semiconductor devices in the past and in the future [34].

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

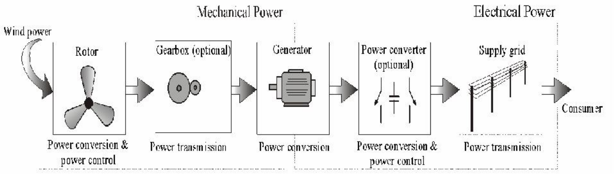


Fig. 4. Converting wind power to electrical power in a wind turbine [17].

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 in Fig. 5 is shown a technological roadmap starting with wind energy/power and converting the mechanical power into electrical power. 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.

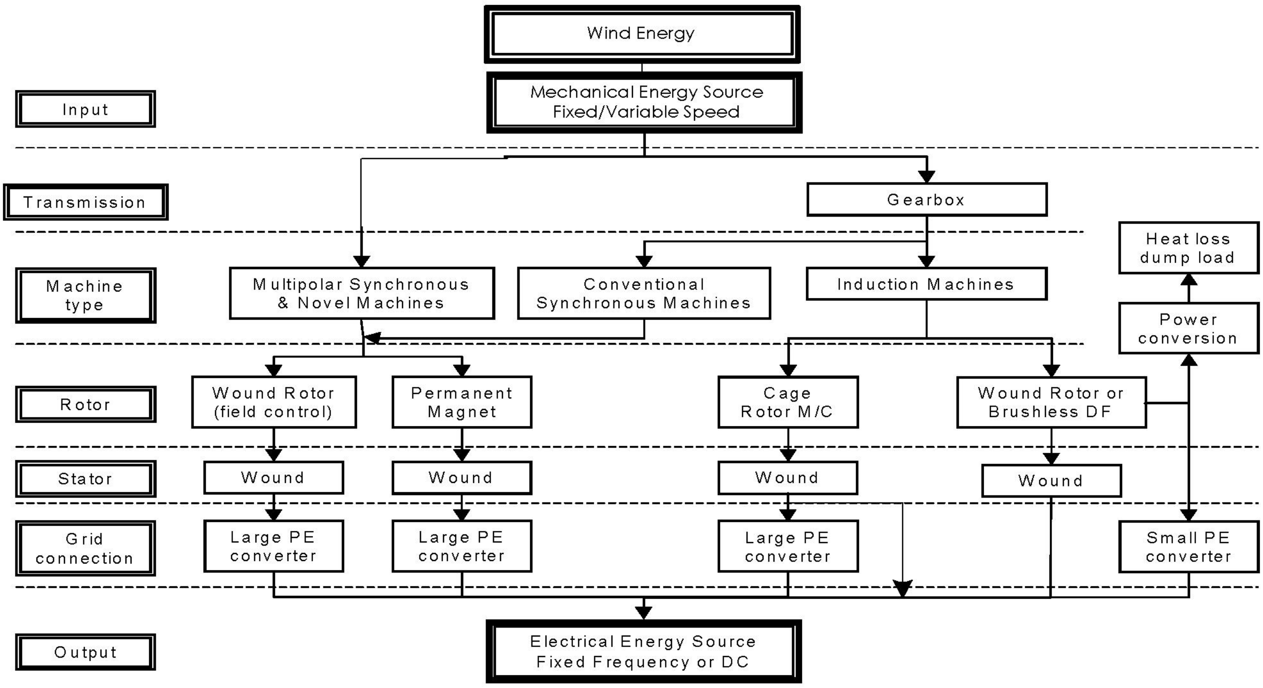


Fig. 5. Technological road map for wind energy conversion ([15] and [22]).

A. *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 and it is now proven technology. It is important to be able to control and limit the converted mechanical power at higher wind speed, as the power in the wind is a cube of the wind speed. The power limitation may be done either by stall control (the blade position is fixed but stall of the wind appears along the blade at higher wind speed), active stall (the blade angle is adjusted in order to create stall along the blades) or pitch control (the blades are turned out of the wind at higher wind speed). The wind turbine 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 speed of the wind turbine is fixed.

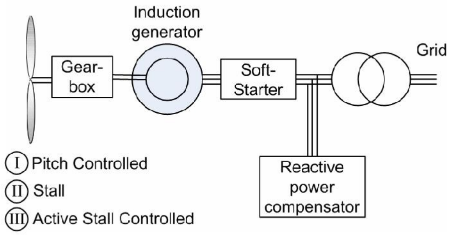


Fig. 6. Fixed speed wind turbine systems with aerodynamic power control and soft-starter for smooth grid connection.

The wind turbine systems in Fig. 6 are using induction generators, which operate at fixed speed (variation of 1-2%) almost independent of torque variation. The power is limited aerodynamically either by stall, active stall or by pitch control. All three systems are using a soft-starter 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 consumption from the turbine generators. 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.

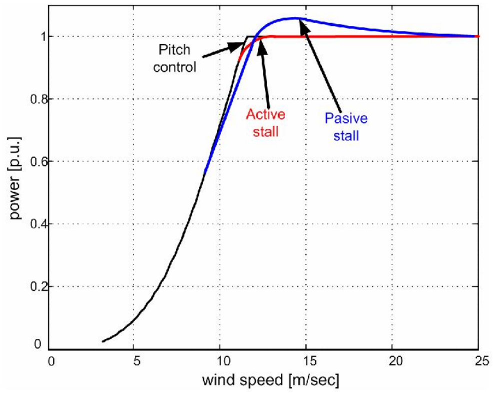


Fig. 7. Power characteristics of different fixed speed wind turbine systems.

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 completely on the aerodynamic design of the blades.

B. *Variable Speed Wind Turbines*

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

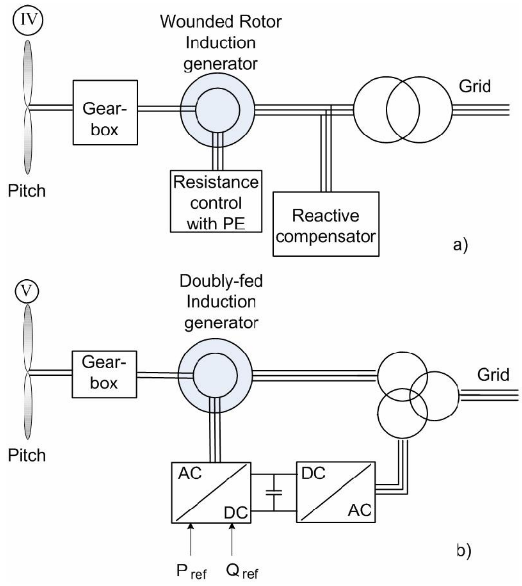


Fig. 8. Wind turbine systems with partially rated power electronics and limited speed range: a) rotor resistance converter (System IV) and b) doubly-fed induction generator (System V).

Fig. 8 shows a wind turbine system where the generator is an induction generator with a wounded rotor. An extra resistance is added into the rotor, which can be controlled by power electronics. This is a dynamic slip controller and gives a variable speed range of 2 - 5 %. The power converter for the rotor resistance control is 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 active 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 flowing through both the rotor and the stator. If the generator is running sub-synchronously electrical power is 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 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 systems with a full-scale power converter between the generator and grid, which are the ultimate power electronic solutions. Extra losses appear in the power conversion but it may be gained by the added technical performance. Fig. 9 shows four possible, but not exhaustive, solutions using full-scale power converter solutions.

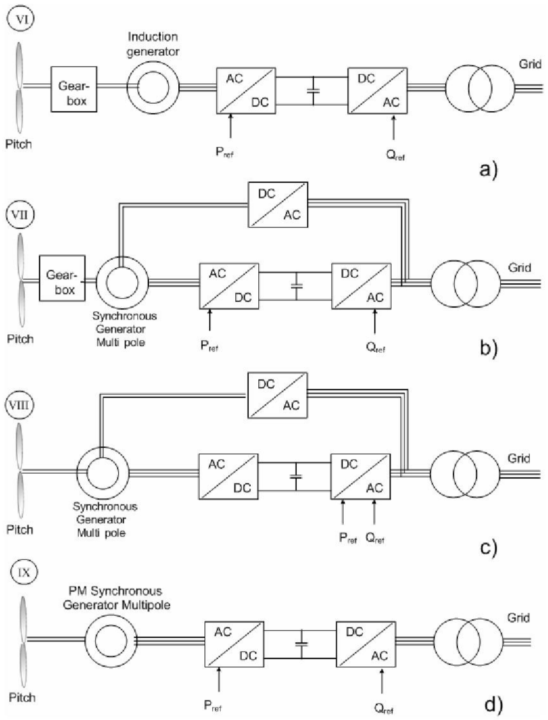


Fig. 9. Wind turbine systems with full-scale power converter:
a) Induction generator with gearbox (System VI),
b) Synchronous generator with gearbox (System VII),
c) Multi-pole synchronous generator (System VIII),
d) Multi-pole permanent magnet synchronous generator (System IX).

The solutions shown in Fig. 9a and Fig. 9b are characterized by having a gear-box. The 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-box are shown in Fig. 9c and Fig. 9d. The last solution is using permanent magnets, which are 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 extra sensitive electronic parts.

Comparing the different wind turbine systems in respect to performance shows a contradiction between cost and the performance to the grid. A technical comparison of the presented wind turbine systems, where issues on grid control, cost, maintenance, internal turbine performance is presented in Appendix 1. By introducing power electronics many of the wind turbine systems are getting performance like a complete power plant. In respect to control performance the wind turbine systems 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 and Appendix 1 indicate other important aspects of 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 global market share in 2002 between the dominant system topologies is shown in Fig 10.

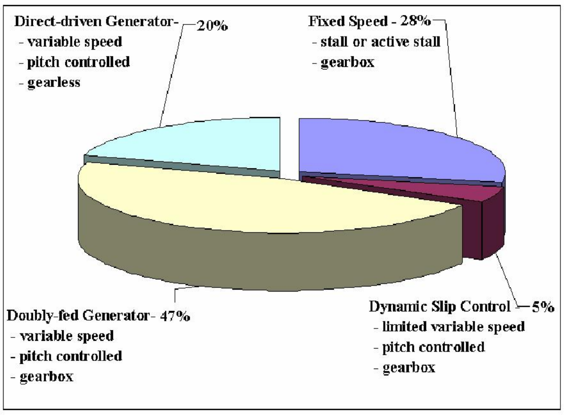


Fig. 10. Wind turbine system topologies market in 2002 [4].

As it can be seen the most sold technology in 2002 is the doubly-fed induction generator system which occupies about 50% of the whole market. More than 75% of all sold wind turbines are controlled by power electronics. That is even more in 2005.

C. *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 (System V) is shown in Fig. 11.

Below maximum power production the wind turbine will typically vary the speed proportional with the wind speed and keep the pitch angle θ 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 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. 11. 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. 12.

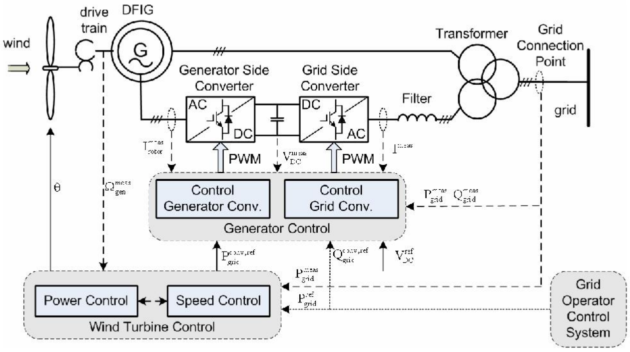


Fig. 11. Control of wind turbine with doubly-fed induction generator system – System V in Fig. 8 ([35]).

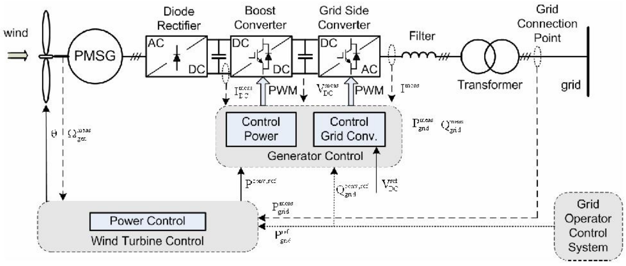


Fig. 12. Control of active and reactive power in a wind turbine with multi-pole synchronous generator - System IX in Fig 9.

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 high dynamics.

D. *Offshore wind farms 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, will play an important role on the power quality and the control of complex power systems.

Consequently, very high technical demands are expected to be met by these generation units, such as to perform frequency and voltage control, regulation of active and reactive power, quick responses under power system transients and dynamic situation. One example is to reduce the power from nominal power to 20 % power within 2 seconds. The power electronic technology is again an important part in both system configurations in order to fulfill future demands.

One off-shore wind farm equipped with power electronic converters can perform both active and reactive power control and also operate the wind turbines in variable speed to maximize the energy captured as well as reduce the mechanical stress and noise. This solution is shown in Fig. 13a and such solution is in operation in Denmark as a 160 MW off-shore wind power station.

For long distance power transmission from off-shore wind farm, HVDC may be an interesting option. In an HVDC transmission, the low or medium-level 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. 13c.

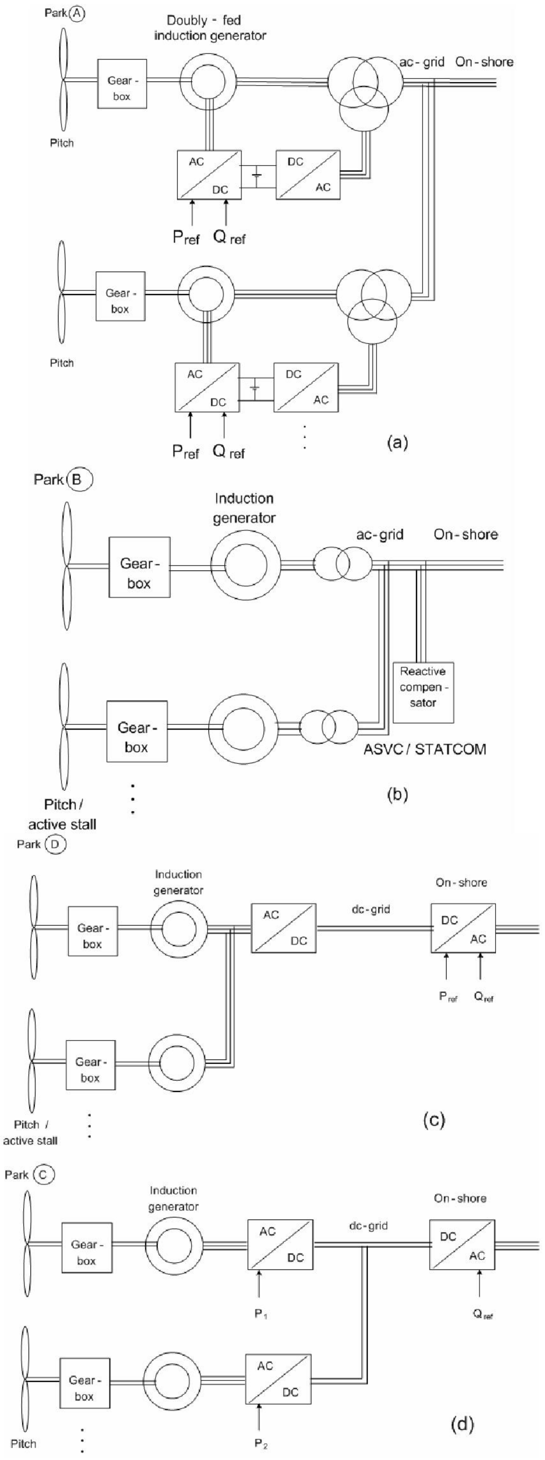


Fig. 13. Wind farm solutions: a) DFIG system with AC-grid (System A), b) Induction generator with AC-grid (System B), c) speed controlled induction generator with common dc-bus and control of active and reactive power (System C) and d) speed controlled induction generator with common ac-grid and dc transmission (System D).

For certain power levels, 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. 13d, 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 Appendix 2.

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 will be different depending on the planned site.

IV. SOLAR ENERGY POWER CONVERSION.

Photovoltaic (PV) power supplied to the utility grid is gaining more and more visibility due to many national incentives [55]. With a continuous reduction in system cost (PV modules, DC/AC inverters, cables, fittings and man-power), the PV technology has the potential to become one of the main renewable energy sources for the future electricity supply.

The PV cell is an all-electrical device, which produces electrical power when exposed to sunlight and connected to a suitable load. Without any moving parts inside the PV module, the tear-and-wear is very low. Thus, lifetimes of more than 25 years for modules are easily reached. However, the power generation capability may be reduced to 75% ~ 80% of nominal value due to ageing. A typical PV module is made up of around 36 or 72 cells connected in series, encapsulated in a structure made of e.g. aluminum and tedlar. An electrical model of PV cell is depicted in Fig. 14.

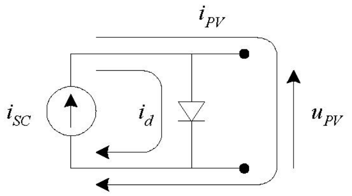


Fig. 14. Electrical model and characteristics of a PhotoVoltaic (PV) cell.

Several types of proven PV technologies exist, where the crystalline (PV module light-to-electricity efficiency: η = 10% - 15%) and multi-crystalline (η = 9% - 12%) silicon cells are based on standard microelectronic manufacturing processes. Other types are: thin-film amorphous silicon (η = 10%), thin-film copper indium diselenide (η = 12%), and thin-film cadmium telluride (η = 9%). Novel technologies such as the thin-layer silicon (η = 8%) and the dye-sensitised nano-structured materials (η = 9%) are in their early development. The reason to maintain a high level of research and development within these technologies is to decrease the cost of the PV-cells, perhaps on the expense of a somewhat lower efficiency. This is mainly due to the fact that cells based on today's microelectronic processes are rather costly, when compared to other renewable energy sources.

The series connection of the cells benefit from a high voltage (around 25 V ~ 45 V) across the terminals, but the weakest cell determines the current seen at the terminals.

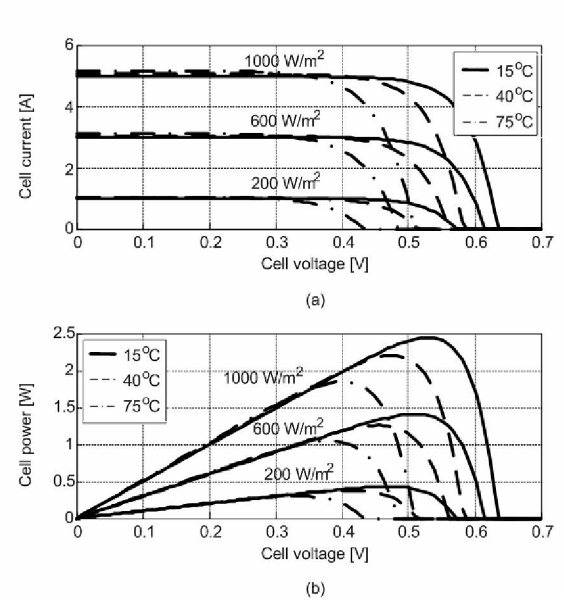


Fig. 15. Characteristics of a PV cell. Model based on the British Petroleum BP5170 crystalline silicon PV module.
Power at standard test condition (1000 W/m^2 irradiation, and a cell temperature of 25 °C): 170 W @ 36.0 V [7].

This causes reduction in the available power, which to some extent can be mitigated by the use of bypass diodes, in parallel with the cells. The parallel connection of the cells solves the 'weakest-link' problem, but the voltage seen at the terminals is rather low. Typical curves of a PV cell current-voltage and power-voltage characteristics are plotted in Fig. 15a and Fig. 15b respectively, with insolation and cell temperature as parameters. The graph reveals that the captured power is determined by the loading conditions (terminal voltage and current). This leads to a few basic requirements for the power electronics used to interface the PV module(s) to the utility grid.

A. Structures for PV systems

A general block diagram of a grid connected photovoltaic system is shown in Fig. 16. It consists of a PV array, a power converter with a filter, a controller and the grid.

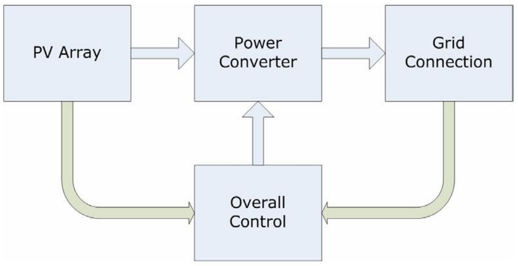


Fig. 16. Block diagram of a single-phase grid connected PV system including control.

The PV array can be a single panel, a string of PV panels or a multitude of parallel strings of PV panels. Centralized or decentralized PV systems can be used as depicted in Fig. 17.

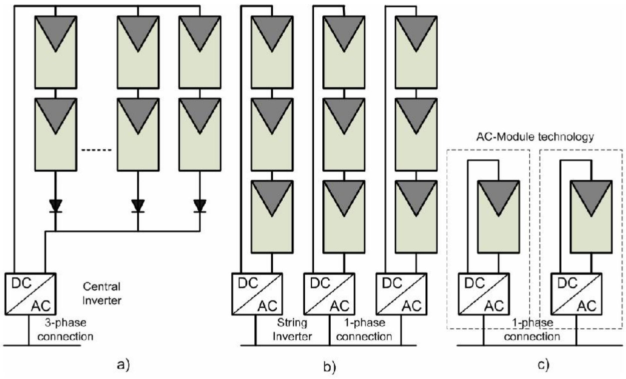


Fig. 17. Structures for PV systems: a) Central inverter, b) String inverter and c) Module integrated inverter.

1) Central inverters

In this topology the PV plant (typical > 10 kW) is arranged in many parallel strings that are connected to a single central inverter on the DC-side (Fig. 17a). These inverters are characterized by high efficiency and low cost pr. kW. However, the energy yield of the PV plant decreases due to module mismatching and potential partial shading conditions. Also, the reliability of the plant may be limited due to the dependence of power generation on a single component: a failure of the central inverter results in that the whole PV plant is out of operation.

2) String inverter

Similar to the central inverter, the PV plant is divided into several parallel strings. Each of the PV strings is assigned to a designated inverter, the so-called "string inverter" (see Fig. 17b). String inverters have the capability of separate Maximum Power Point (MPP) tracking of each PV string. This increases the energy yield by the reduction of mismatching and partial shading losses. These superior technical characteristics increase the energy yield and enhance the supply reliability. String inverters have evolved as a standard in PV system technology for grid connected PV plants.

An evolution of the string technology applicable for higher power levels is the multi-string inverter. It allows the connection of several strings with separate MPP tracking systems (via DC/DC converter) to a common DC/AC inverter. Accordingly, a compact and cost-effective solution, which combines the advantages of central and string technologies, is achieved. This multi-string topology allows the integration of PV strings of different technologies and of various orientations (south, north, west and east). These characteristics allow time-shifted solar power, which optimizes the operation efficiencies of each string separately. The application area of the multi-string inverter covers PV plants of 3-10 kW.

3) Module integrated inverter

This system uses one inverter for each module (Fig. 17d). This topology optimizes the adaptability of the inverter to the PV characteristics, since each module has its own Maximum Power Point (MPP) tracker. Although the module-integrated inverter optimizes the energy yield, it has a lower efficiency than the string inverter. Module integrated inverters are characterized by a more extended AC-side cabling, since each module of the PV plant has to be connected to the available AC grid (e.g. 230 V/ 50 Hz). Also, the maintenance processes are quite complicated, especially for facade-integrated PV systems. This concept can be implemented for PV plants of about 50- 400 W peak.

B. Topologies for PV inverters

The PV inverter technology has evolved quite a lot during the last years towards maturity [47]. Still there are different power configurations possible as shown in Fig. 18.

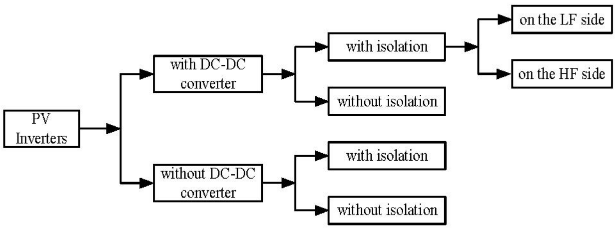


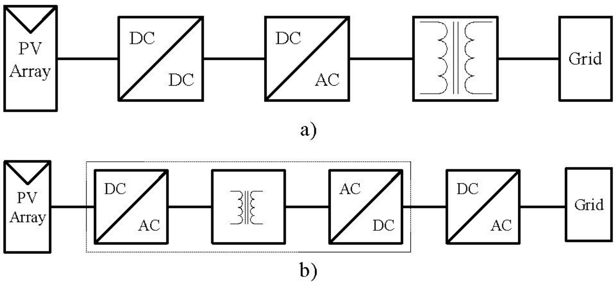
Fig. 18. Power configurations for PV inverters.

The question of having a dc-dc converter or not is first of all related to the PV string configuration. Having more panels in series and lower grid voltage, like in US and Japan, it is possible to avoid the boost function with a dc-dc converter. Thus a single stage PV inverter can be used leading to higher efficiencies.

The issue of isolation is mainly related to safety standards and is for the moment only required in US. The drawback of having so many panels in series is that MPPT is harder to achieve especially during partial shading, as demonstrated in [48]. In the following, the different PV inverter power configurations are described in more details.

1) PV inverters with DC-DC converter and isolation

The isolation is typically acquired using a transformer that can be placed on either the grid frequency side (LF) as shown in Fig. 19a or on the high-frequency (HF) side in the dc-dc converter as shown in Fig. 19b. The HF transformer leads to more compact solutions but high care should be taken in the transformer design in order to keep the losses low.



a)

b)

Fig. 19. PV inverter system with DC-DC converter and isolation transformer:
a) on the Low Frequency (LF) side and
b) on the High Frequency (HF) side

In Fig. 20 a PV inverter with an HF transformer using an isolated push-pull boost converter is presented [49].

In this solution the dc-ac inverter is a low cost inverter switched at the line frequency. The new solutions on the market are using PWM dc-ac inverters with IGBT's switched typically at 10-20 kHz leading to a better power quality performance.

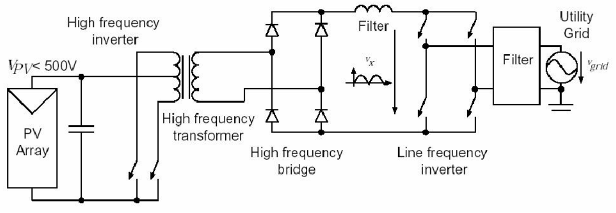


Fig. 20. PV inverter with a high frequency transformer in the dc-dc converter.

Other solutions for high frequency dc-dc converters with isolation include: full-bridge isolated converter, Single-Inductor push-pull Converter (SIC) and Double-Inductor Converter (DIC) [50].

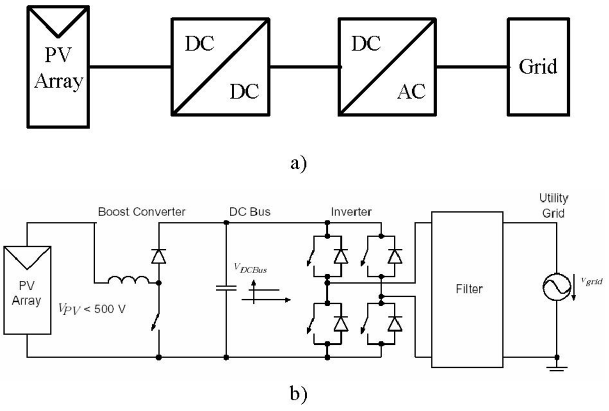
In order to keep the magnetic components small high switching frequencies in the range of 20 – 100 kHz are typically employed. The full-bridge converter is usually utilized at power levels above 750 W. The advantages of this topology are: good transformer utilization – bipolar magnetization of the core, good performance with current programmed control – reduced DC magnetization of transformer. The main disadvantages in comparison with push-pull topology are the higher active part count and the higher transformer ratio needed for boosting the dc voltage to the grid level.

The single inductor push-pull converter can provide boosting function on both the boosting inductor and transformer, reducing the transformer ratio. Thus higher efficiency can be achieved together with smoother input current. On the negative side higher blocking voltage switches are required and the transformer with tap point puts some construction and reliability problems.

Those shortcomings can be alleviated using the double inductor push-pull converter (DIC) where the boost inductor has been split in two. Actually this topology is equivalent with two inter-leaved boost converters leading to lower ripple in the input current. The transformer construction is more simple not requiring a tap point. The single disadvantage of this topology remains the need for an extra inductor.

2) PV inverters with DC-DC converter without isolation

In some countries as the grid-isolation is not mandatory, more simplified PV inverter design can be used, like shown in Fig. 21.



a)

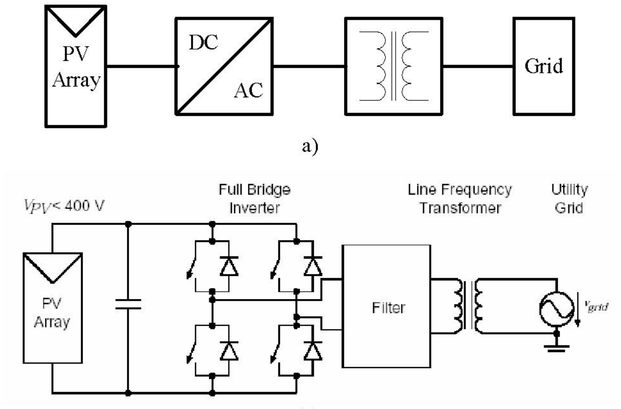
b)

Fig. 21. PV inverter system with DC-DC converter without isolation transformer a) General diagram and b) Practical example with boost converter and full-bridge inverter.

In Fig. 21b a practical example [51] using a simple boost converter is shown.

3) PV inverters without DC-DC converter

The block diagram of this topology is shown in Fig 22a.



a)

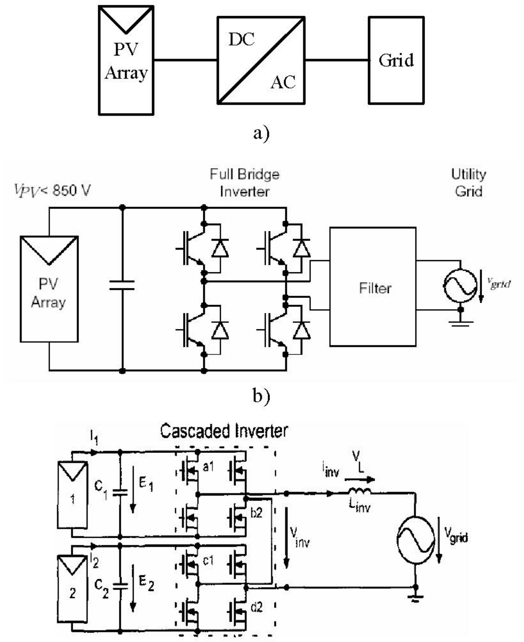
b)

Fig. 22. PV system without DC-DC converter and with isolation transformer: a) General diagram and b) Practical example with full-bridge converter and grid side transformer.

In Fig. 22b are presented two topologies of PV inverters in which a line frequency transformer is used. For higher power levels, self-commutated inverters using thyristors may be used [51].

4) PV inverters without DC-DC converter and without isolation

This topology is shown in Fig. 23a.



a)

b)

c)

Fig. 23. Transformer-less PV inverter system without DC-DC converter: a) general diagram, b) typical example with full-bridge inverter and c) multilevel inverter.

In Fig. 23b, a typical transformer-less topology is shown using PWM IGBT inverters. This topology can be used when a large number of PV panels are available connected in series producing in excess of the grid voltage peak at all times.

Another interesting PV inverter topology without boost and isolation can be achieved using a multilevel concept. Grid connected photovoltaic systems with a five level cascaded inverter is presented in Fig. 23c [49]. The redundant inverter states of the five level cascaded inverter allow for a cyclic switching scheme which minimizes the switching frequency, equalizes stress evenly on all switches and minimizes the voltage ripple on the DC capacitors

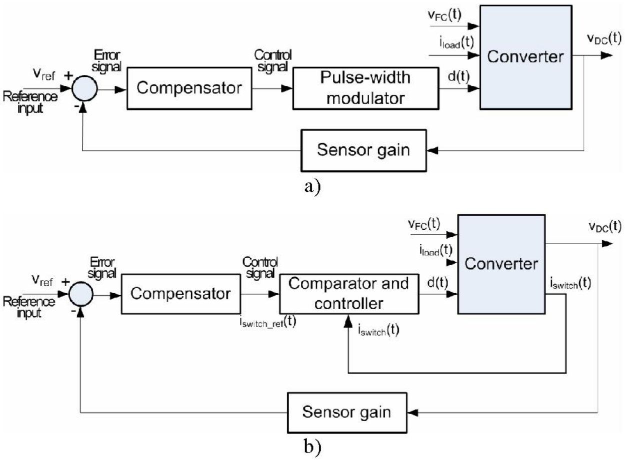
C. Control of PV inverters

1) Control of DC-DC boost converter

In order to control the output dc-voltage to a desired value, a control system is needed which automatically can adjust the duty cycle, regardless of the load current or input changes. There are at least two types of control for the dc-dc converters: the *direct duty-cycle* control and the *current control* [53].

Direct duty cycle - The output voltage is measured and then compared to the reference. The error signal is used as input in the compensator, which will calculate it from the duty-cycle reference for the pulse-width modulator

Current control - The converter output is controlled by the choice of the transistor peak current. The control signal is a current and a simple control network switches on and off the transistor such its peak current follows the control input. The current control, in the case of an isolated boost push-pull converter has some advantages against the duty-cycle control e.g. simpler dynamics (removes one pole from the control to output transfer function). Also as it uses a current sensor it can provide a better protection of the switch by limiting the current to acceptable levels.



a)

b)

Fig. 24. Control strategies for switched dc-dc converters a) direct duty-cycle control and b) current control.

Among the drawbacks of the current control it can be mentioned that it requires an extra current sensor and it has a susceptibility to noise and thus light filtering of the feedback signals is required.

2) Control of DC-AC converter

For the grid-connected PV inverters in the range of 1-5 kW, the most common control structure for the dc-ac grid converter is using a current-controlled H-bridge PWM inverter having a low-pass output filter. Typically L-filters are used but the new trend is to use LCL filters that have a higher order filter (3rd) which leads to a more compact design. The drawback is that due to its own resonance frequency it can produce stability problems and special control design is required [52]. A typical dc-ac grid converter with LCL filter is depicted in Fig. 25

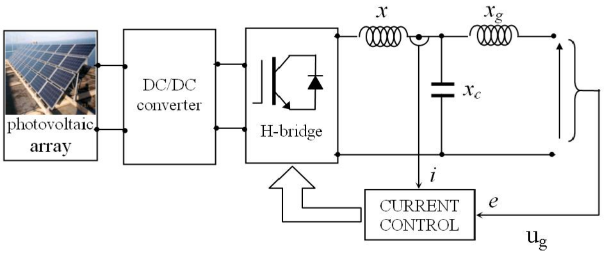


Fig. 25. H-bridge PV-converter system connected to the grid through an LCL-filter.

The harmonics level in the grid current is still a controversial issue for PV inverters. The IEEE 929 standard from year 2000 allows a limit of 5% for the current Total Harmonic Distortion (THD) factor with individual limits of 4% for each odd harmonic from 3rd to 9th and 2% for 11th to 15th while a recent draft of European IEC61727 suggests something similar. These levels are far more stringent than other domestic appliances such as IEC61000-3-2 as PV systems are viewed as generation sources and so they are subject to higher standards than load systems.

Classical PI control with grid voltage feed-forward (u_g) [11] as depicted in Fig. 26a is commonly used for current-controlled PV inverters, but this solution exhibits two well known drawbacks: inability of the PI controller to track a sinusoidal reference without steady-state error and poor disturbance rejection capability. This is due to the poor performance of the integral action.

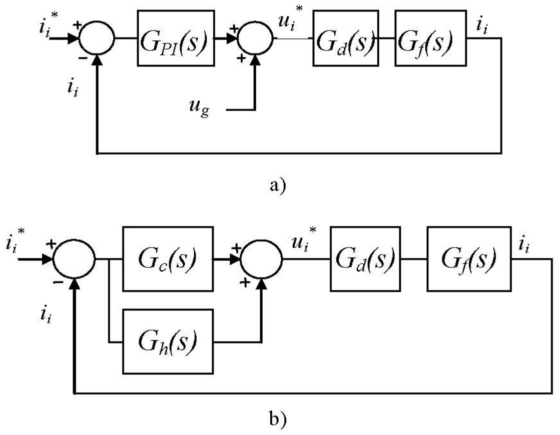


Fig. 26. The current loop of PV inverter: a) with PI controller and b) with P+Resonant (PR) controller.

In order to get a good dynamic response, a grid voltage feed-forward is used, as depicted in Fig. 26a. This leads in turn to stability problems related to the delay introduced in the system by the voltage feedback filter.

In order to alleviate these problems, a second order generalized integrator (GI) as reported in [63] can be used. The GI is a double integrator that achieves an infinite gain at a certain frequency, also called resonance frequency, and almost no gain exists outside this frequency. Thus, it can be used as a notch filter in order to compensate the harmonics in a very selective way. This technique has been primarily used in three-phase active filter applications as reported in [52]. Another approach reported in [52] where a new type of stationary-frame regulators called P+Resonant (PR) is introduced and applied to three-phase PWM inverter control. In this approach the PI dc-compensator is transformed into an equivalent ac-compensator, so that it has the same frequency response characteristics in the bandwidth of concern. The current loop of the PV inverter with PR controller is depicted in Fig. 26b

The harmonic compensator (HC) $G_h(s)$ as defined in [43] is designed to compensate the selected harmonics 3rd, 5th and 7th as they are the most prominent harmonics in the current spectrum. A processing delay typical equal to sampling time T_s for the PWM inverters [52] is introduced in $G_d(s)$.

Thus it is demonstrated the superiority of the PR controller in respect to the PI controller in terms of harmonic current rejection.

The issue of stability when several PV inverters are running in parallel on the same grid is becoming more and more important especially when LCL filters are used. Thus, special attention is required when designing the current control.

3) *MPPT*

In order to capture the maximum power, a maximum power point tracker (MPPT) is required. The maximum power point of PV panels is a function of solar irradiance and temperature as depicted in Fig. 15. This function can be implemented either in the dc-dc converter or in the dc-ac converter. Several algorithms can be used in order to implement the MPPT like:

a) *Perturb and Observe Method*

The most commonly used MPPT algorithm is Perturb and Observe (P&O), due to its ease of implementation in its basic form. Fig. 15 shows the characterstic of a PV array, which has a global maximum at the MPP. Thus, if the operating voltage of the PV array is perturbed in a given direction and $dP/dV > 0$, it is known that the perturbation is moving the operating point towards the MPP. The P&O algorithm would then continue to perturb the PV array voltage in the same direction. If $dP/dV < 0$, then the change in operating point moved the PV array away from the MPP, and the P&O algorithm reverses the direction of the perturbation. A problem with P&O is that it oscillates around the MPP in steady state operation. It can also track into the wrong direction, away from the MPP, under rapidly increasing or decreasing irradiance levels. There are several variations of the basic P&O that have been proposed to minimize these drawbacks. These include using an average of several samples of the array power and dynamically adjusting the magnitude of the perturbation of the PV operating point.

b) *Incremental Conductance Method*

The incremental conductance algorithm seeks to overcome the limitations of the P&O algorithm by using the PV array's incremental conductance to compute the sign of dP/dV without a perturbation. It does this using an expression derived from the condition that, at the MPP, $dP/dV = 0$. Beginning with this condition, it is possible to show that, at the MPP dI/dV = -I/V. Thus, incremental conductance can determine that the MPPT has reached the MPP and stop perturbing the operating point. If this condition is not met, the direction in which the MPPT operating point must be perturbed can be calculated using the relationship between dI/dV and -I/V. This relationship is derived from the fact that dP/dV is negative when the MPPT is to the right of the MPP and positive when it is to the left of the MPP. This algorithm has advantages over perturb and observe in that it can determine when the MPPT has reached the MPP, where perturb and observe oscillates around the MPP. Also, incremental conductance can track rapidly increasing and decreasing irradiance conditions with higher accuracy than perturb and observe. One disadvantage of this algorithm is the increased complexity when compared to perturb and observe. This increases real-time computational time, and slows down the sampling frequency of the array voltage and current.

c) Parasitic Capacitance Method

The parasitic capacitance method is a refinement of the incremental conductance method that takes into account the parasitic capacitances of the solar cells in the PV array. Parasitic capacitance uses the switching ripple of the MPPT to perturb the array. To account for the parasitic capacitance, the average ripple in the array power and voltage, generated by the switching frequency, are measured using a series of filters and multipliers and then used to calculate the array conductance. The incremental conductance algorithm is then used to determine the direction to move the operating point of the MPPT. One disadvantage of this algorithm is that the parasitic capacitance in each module is very small, and will only come into play in large PV arrays where several module strings are connected in parallel. Also, the DC-DC converter has a sizable input capacitor used to filter out the small ripple in the array power. This capacitor may mask the overall effects of the parasitic capacitance of the PV array.

d) Constant Voltage Method

This algorithm makes use of the fact that the MPP voltage changes only slightly with varying irradiances, as depicted in Fig. 15. The ratio of VMP/VOC depends on the solar cell parameters, but a commonly used value is 76%. In this algorithm, the MPPT momentarily sets the PV array current to zero to allow a measurement of the array's open circuit voltage. The array's operating voltage is then set to 76% of this measured value. This operating point is maintained for a set amount of time, and then the cycle is repeated. A problem with this algorithm is the available energy is wasted when the load is disconnected from the PV array, also the MPP is not always located at 76% of the array's open circuit voltage.

4) Anti-islanding

In addition to the typical power quality regulations concerning the harmonic distortion and EMI limits, the grid-connected PV inverters must also meet specific power generation requirements like the islanding detection, or even certain country-specific technical recommendations for instance the grid impedance change detection (in Germany). Such extra-requirements contribute to a safer grid-operation especially when the equipment is connected in dispersed power generating networks but impose additional effort to readapt the existing equipments.

The European standard EN50330-1 [46] describes the ENS (the German abbreviation of Mains monitoring units with allocated Switching Devices) requirement, setting the utility fail-safe protective interface for the PV converters. The goal is to isolate the supply within 5 seconds after an impedance change of Z = 0.5 Ω, which typically is associated with a grid failure. The main impedance can be detected by means of tracking and step change evaluation at the fundamental frequency. Therefore, a method of measuring the grid impedance value and its changes should be implemented into existing PV-inverters.

One solution is to attach a separate device developed only for the measuring purpose as depicted in Fig. 27a.

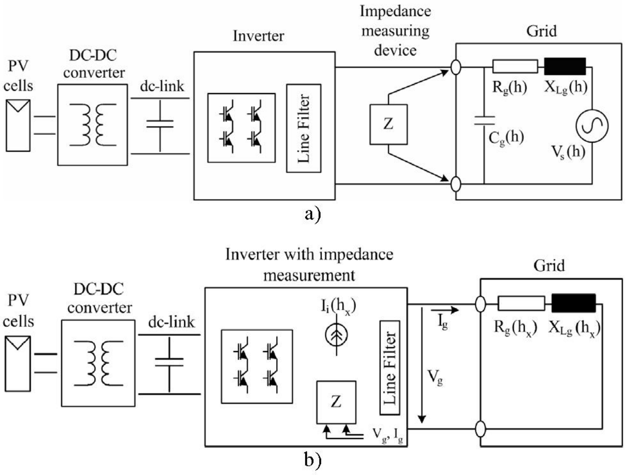


Fig. 27. Grid-impedance measurement for PV inverters: a) using external device; b) embedded on the inverter control using harmonic injection.

This add-on option is being commonly used in the commercial PV inverters, but the new trend is to implement this function embedded into the inverter control without extra hardware. Numerous publications exist in this field, which offer measuring solutions for the grid impedance for a wide frequency range from dc up to typically 1 kHz. Unfortunately, these methods cannot always easily be embedded into a non-dedicated real-time platform, i.e. PV-inverters featuring a low-cost DSP. Specific limitations like real-time computation, A/D conversion accuracy and fixed-point numerical limitation, are occurring.

V. STATUS AND TRENDS

A. Wind Power

According to the Brussels based Global Wind Energy Council (GWEC) (www.gwec.net) the global wind energy sector experienced another record year in 2005. In year 2005 saw the installation of 11,531 MW, which represent a 40.5% increase in annual additions to the global market, up from 8,207 MW in the previous year. The total value of new generating equipment installed was more than €12 billion, or US$14 billion. The new installed capacities in 2005 are shown in Fig. 28.

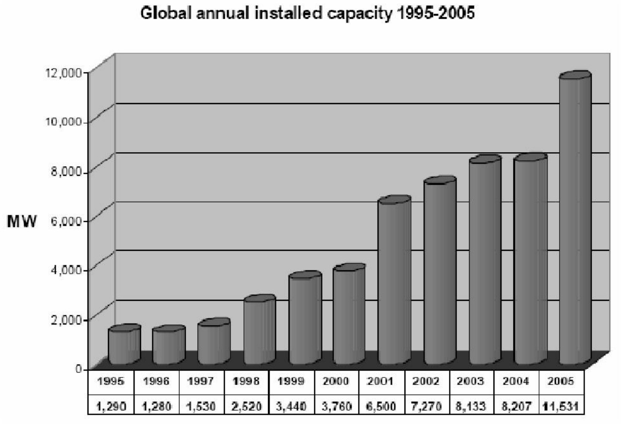


Fig. 28. Wind power annual installed capacity in the last ten years.

The total installed wind power capacity was close to 60,000 MW worldwide, an increase of 24% compared to 2004 as shown in Fig. 29.

The countries with the highest total installed capacity are Germany, Spain and Denmark (see Fig. 30). A number of other countries, including Italy, the UK, the Netherlands, China, Japan and Portugal have also reached the 1,000 MW mark of installed capacity

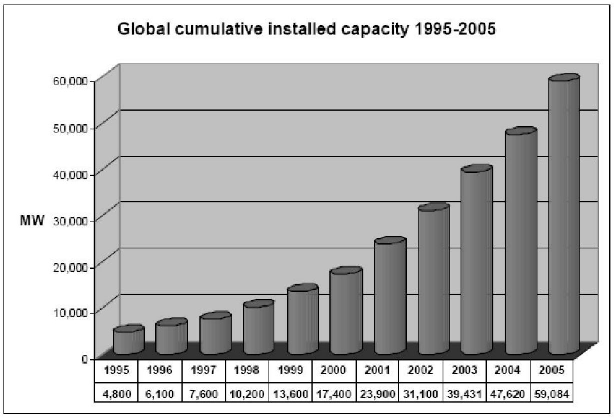


Fig. 29. Wind power cumulative installed capacity.

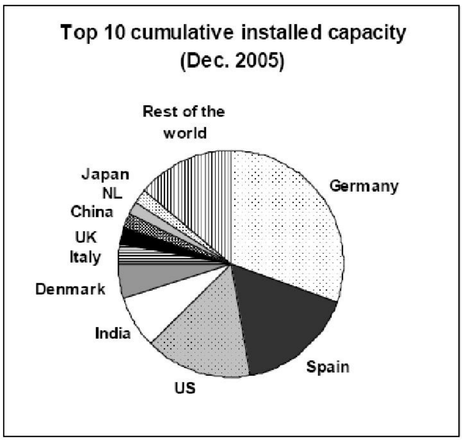


Fig. 30. Top 10 cumulative installed capacity

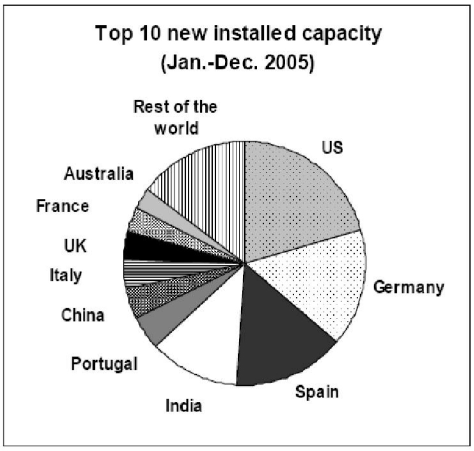


Fig. 31. Top 10 new installed capacity in 2005.

Europe is still leading the market with over 40,500 MW of the installed capacity at the end of 2005 in the EU, representing 69% of the global market. The European market has already reached the 2010 target of 40,000 MW set by the European Commission (see Fig. 31 and Fig. 32).

In 2005, the European wind capacity grew by 18%, providing nearly 3% of the EU's electricity consumption in an average wind year. By 2010, wind energy alone will save enough greenhouse gas emissions to meet one third of the European Union's Kyoto obligation

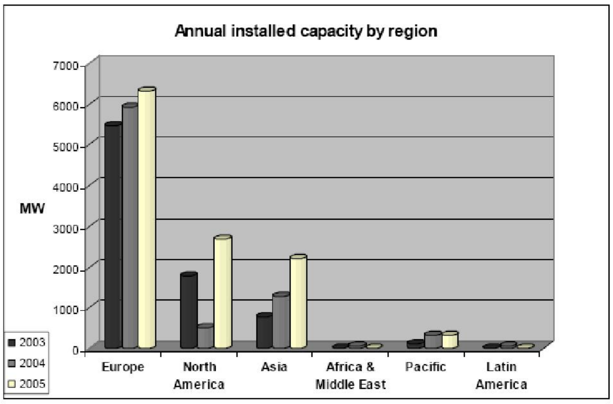


Fig. 32. Annual installed capacity by continents.

Nearly a quarter of new capacity was installed in North America, where the total capacity increased by 37% in 2005, gaining more momentum in both US and Canada. The US wind energy industry established a record of installed capacity with nearly 2,500 MW, while the Canadian wind capacity increased by 53%.

Asia has also experienced strong growth of more than 46% of the installed capacity, bringing the continent up to a total of nearly 7,000 MW. In 2005, the continent accounted for 19% of new installations. India has more than 1,430 MW of new installed capacity, which takes its total figure up to 4,430 MW.

The Chinese market has been boosted; nearly 500 MW of new capacity was installed in 2005, more than a double of the 2004 number. It is estimated that 2,000 MW of wind capacity could be installed by the end of 2006. The goal for wind power in China by the end of 2010 is 5,000 MW.

The Australian market nearly doubled in 2005 with 328 MW of new installed capacity, bringing the total up to 708 MW. The African market also saw some growth in 2005. The main countries experiencing growth are Marocco (64 MW, up from 54 MW) and Egypt, which is planning to install 850 MW of wind power by 2010.

The expectations for the future are also very positive as many countries have progressive plans. Fig. 33 gives an estimate for the installed wind power in 2010 based on official statements from different European countries

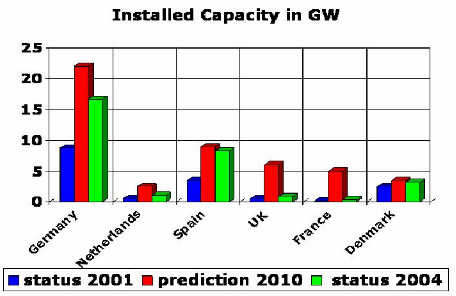
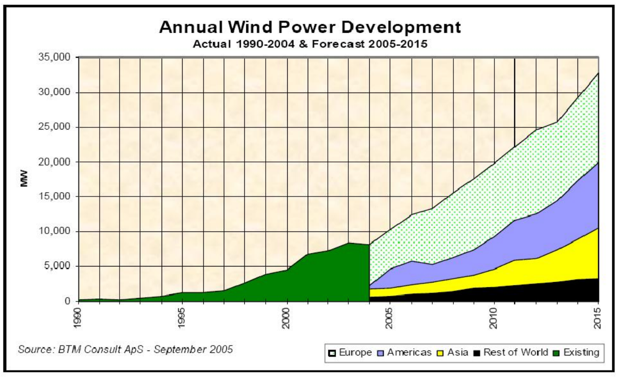


Fig. 33. Wind power installed capacity forecast 2010 in Europe (Source BTM Consult ApS).

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 forecast for worldwide total installed capacity is looking very promising with a doubling around 2010 and a three doubling around 2015, as shown in Fig. 34.



Source: BTM Consult ApS - September 2005

Fig. 34. Wind power installed capacity forecast 2005 – 2015 worldwide by region.

The power scaling has been an important tool to reduce the price pr. kWh. Fig. 35 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 the off-shore wind-farms seem to be able to produce much more energy

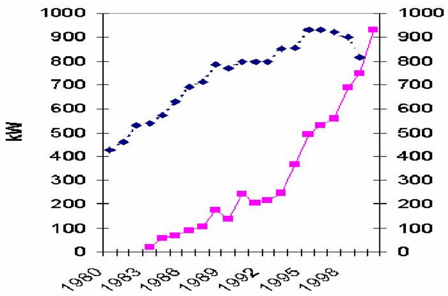


Fig. 35. Average size of wind turbines and produced energy pr. m2 swept area pr. year in Denmark (source Risoe National Lab).

The key to reduce price is to increase the power level 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. 36. It is expected 10 MW wind turbines will be present in 2010.

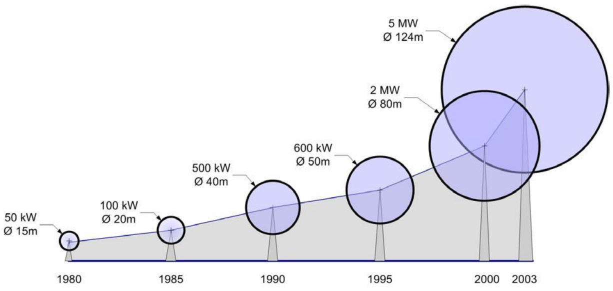
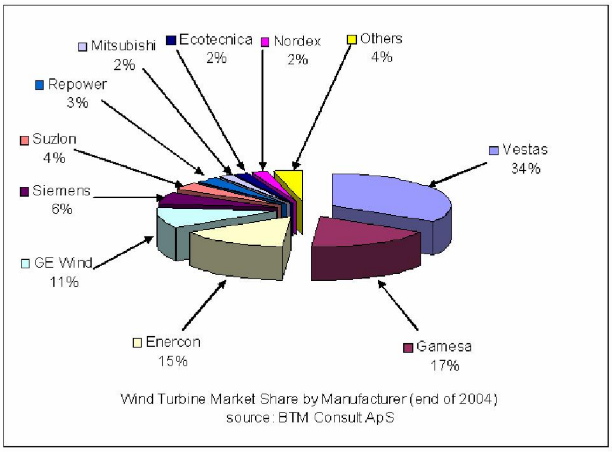


Fig. 36. Development of wind turbines during the last 25 years.

The wind turbine worldwide market is presently dominated by Vestas Wind Systems A/S from Denmark but other global players such as Gamesa Eolica, Enercon, Siemens and GE-Wind are increasing rapidly as illustrated in Fig. 37.



Wind Turbine Market Share by Manufacturer (end of 2004)
source: BTM Consult ApS

Fig. 37. Top 10 wind turbine manufacturers and their market shares.

B. Solar Power

PV solar electricity is also a booming industry; since 1980, when terrestrial applications began, annual installation of photovoltaic power has increased to above 750 MWp, the cumulative installed PV power in 2004 reaching approximately 2.6 GWp [54] and [55].

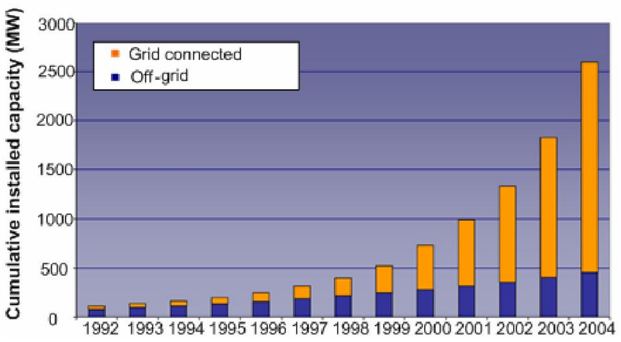


Fig. 38. Cumulative installed capacity from 1992 to 2004 in the IEA-PVPS reporting countries (source: IEA-PVPS, http://www.iea-pvps.org).

The annual rate of growth has varied between 20% in 1994 to over 40% in 2000, but the growth between 2002 and 2003 of 36% has been similar to the latest three years. As in the previous years the vast majority of new capacity was installed in Japan, Germany, and USA, with these three countries accounting for about 88% of the total installed in the year [55].

Historically the main market segments for PV were the remote industrial and developing country applications where PV power over long term is often more cost-effective than alternative power options such as diesel generator or mains grid extension. According to the IEA-PVPS, since 1997, the proportion of new grid-connected PV installed in the reporting countries rose from 42% to more than 93% in 2004 [55] (see Fig. 38) .

Worldwide, the cumulative share of off-grid to grid-connected applications is approximately 1:4 at the present time [54] and [55]. However, this is not the case in every reporting country. In Sweden, Norway and Finland, the most common applications are for vacation cottages, while in Australia, Mexico, and France achieving rural electrification is a key objective. In Canada, Israel and Korea, commercial and telecommunications applications dominate [55].

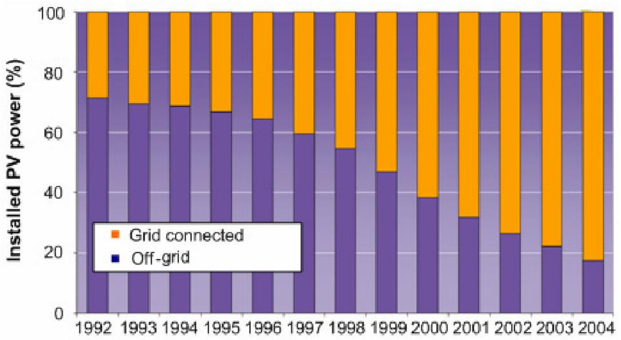


Fig. 39. Percentages of grid connected and off-grid PV power in the IEA PVPS reporting countries (source: IEA-PVPS, http://www.iea-pvps.org).

According to [61], the prices for PV modules are around €5.7/Wp in Europe, with the lowest prices of: €3.10/Wp for monocrystalline modules, €3.02/Wp for polycrystalline modules and €2.96/Wp for thin film modules.

The prices for PV modules in the recent years are shown in Fig. 41.

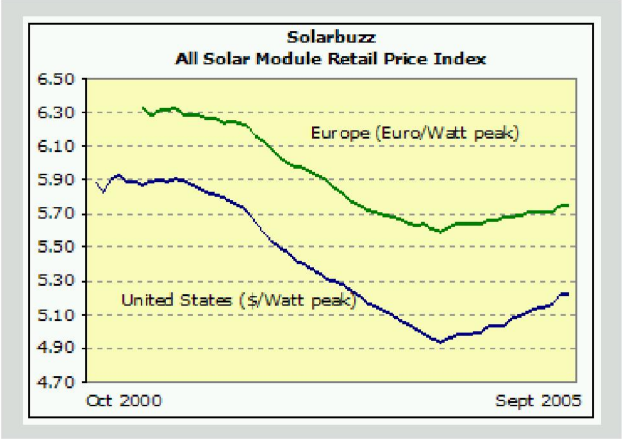


Fig. 40. Photovoltaic module prices from Oct. 2000 to Sept 2005.

In addition to the PV module cost, the cost and reliability of PV inverters are basic issues if market competitive PV supply systems are the aim. The inverter cost share represents about 10-15% of the total investment cost of a grid connected system. The development of PV inverter specific cost (€/WAC) in small to medium power range (1-10 kW) is illustrated in Fig. 41. It can be seen that the inverter cost of this power class has decreased by more than 50% during the last decade. The main reasons for this reduction are the increase of the production quantities and the implementation of new system technologies (e.g. string-inverters). A further 50 % reduction of the specific cost is anticipated during the coming decade. The corresponding specific cost is expected to achieve about 0.3 €/WAC by the year 2010, which requires the implementation of specific measures for the development and the manufacturing processes [60].

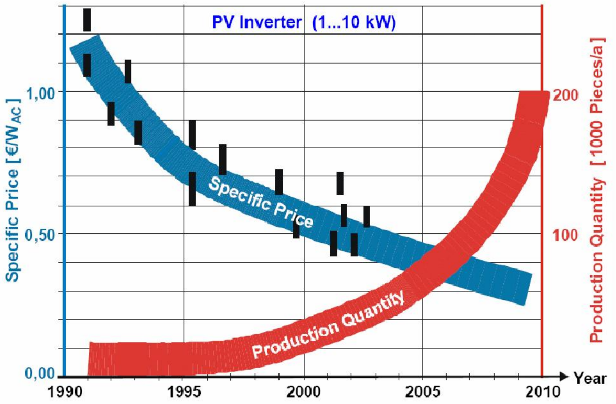


Fig. 41. Development and prognoses of specific cost and production quantity for the PV inverter of nominal powers between 1 and 10 kW during two decades (¦ indicates specific prices of products on the market [60].

VI. CONCLUSIONS

The paper discusses the applications of power electronic for both wind turbine and photovoltaic technologies. 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 significantly 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.

Furthermore, PV systems are discussed including technology, inverters and their control methods.

Finally, a status of the wind turbine market as well as for the PV systems is given and some future trends are highlighted. Both, wind and PV, will be important power sources for the future grid system.

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Appendix 1 - 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	+	+	+	+

Appendix 2 - Comparison of Wind Farms

Farm configuration (Fig. 13)	**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	+	++	+	+