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Smart grid and renewable energy systems

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Published in:
Proceedings of the International Conference on Electrical Machines and Systems, ICEMS 2011

DOI (link to publication from Publisher):
10.1109/ICEMS.2011.6073290

Publication date:
2011

Document Version
Early version, also known as pre-print

Link to publication from Aalborg University

Citation for published version (APA):
Blaabjerg, F., & Guerrero, J. M. (2011). Smart grid and renewable energy systems. In *Proceedings of the International Conference on Electrical Machines and Systems, ICEMS 2011* (pp. 1-10). IEEE Press. https://doi.org/10.1109/ICEMS.2011.6073290

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Smart Grid and Renewable Energy Systems

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***Abstract* – The electrical energy consumption continues growing and more applications relay on electricity. We can expect that more 60 % of all energy consumption will be converted and used as electricity. Therefore, it is a demand that production, distribution and use of electrical energy are done as efficient as possible. Further, the recent challenges with nuclear power plants are arguing to find more sustainable energy generation solutions. Of many options, two major technologies will play important roles to solve parts of those future challenges. One is to change the electrical power production from conventional, fossil based energy sources to renewable energy sources. Another is to use high efficient power electronics in power generation, power transmission/distribution and end-user application. This paper discus trends of the future grid infrastructure as well as the most emerging renewable energy sources, wind energy and photovoltaics. Then main focus is on the power electronics and control technology for wind turbines as they are the largest renewable power contributor, allowing their penetration into a SmartGrid to be even higher in the future.**

I. INTRODUCTION

Distributed power Generation (DG) is emerging as a new paradigm to produce on-site highly reliable and good quality electrical power. Thus, DG systems are presented as a suitable form to offer highly reliable electrical power supply. The concept is particularly interesting when different kinds of energy resources are available, such as photovoltaic (PV) panels, fuel cells (FCs), or wind turbines. The DG of different kinds of energy systems allows for the integration of renewable and nonconventional energy resources. Hence, the DG is becoming a part of strategic plans for most countries to address current challenges associated with energy management. Today, electrical and energy engineering have to face a new scenario in which small distributed power generators and dispersed energy storage devices have to be integrated together into the grid. The new electrical grid will deliver electricity from suppliers to consumers using communication technology to control appliances at consumer's homes to save energy, reducing cost and increasing reliability and transparency. The idea behind this concept is to have devices that plug into your outlet and you would plug your appliance into this device. These devices would communicate and report to the electric companies at what time your appliance used energy and how much energy was used. This will in turn charge you more for the electricity that you use during peak hours of late afternoon and early evening. In this sense, the expected whole energy system will be more interactive, intelligent, and distributed. Thus wide-spread use of renewable energy sources in distribution networks is seen [1]. E.g. Denmark has a high power capacity penetration (> 30 %) of wind energy in major areas of the country and today 28 % 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 is the uncontrollability as they are completely weather-based. 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 without any load control. This is further strengthened as no real large scale electrical energy storage systems exist.

The wind turbine technology is one of the most emerging renewable energy technologies [3]-[12]. It started in the 1980'es with a few tens of kW production power per unit 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 operation. 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 was no control of the active and reactive power except from some capacitor banks, which are important control devices to regulate the frequency and the voltage in the grid system. As the power range of the turbines increases those control parameters become very important and power electronics [5] is introduced as an interface between the wind turbine and the grid. The power electronics is able to change 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 but now the price pr. produced kWh is so low, that solutions with power electronics are very attractive [3]-[35].

The development of photovoltaics has also been progressive. Every year the price pr. produced kWh is decreasing by improving the solar cells themselves as well as making the PV-inverters more efficient and reducing the prize. The PV-technology is working along a couple of technology lines – all are needing large investment to move from basic research to use in commercial large scale products. Power electronics is again the key to enable the photovoltaics technology to be connected to the grid system [47]-[63].

Both technologies are changing the grid to be much more uncontrolled and heterogeneous. Power system operators are developing new methods to control the grid – e.g. in a smart-grid structure where new demands to communication, control, safety, protection and so on are becoming defined [2].

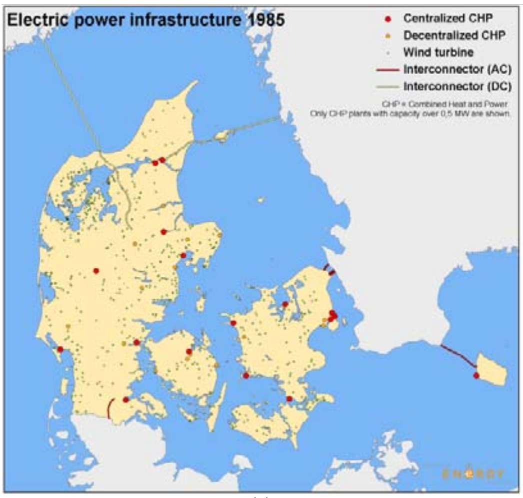
The scope of this paper is to give an overview and discuss some trends in wind turbine and photovoltaics technologies as well as to put it into a smart grid context where both power production and power consumption is controlled. First, an example of a power system is shown where the society is close to have a DG based infrastructure based on wind turbines and smaller combined heat and power plants. Then the future grid infrastructure is proposed and discussed. Next, the basic market developments are discussed for photovoltaics and wind turbines which for the moment are the most emerging technologies. Next different wind turbine configurations are explained, including a comparison. Different control methods are further explained for state-of-the art wind turbines including the grid codes which are pushing the technology as well as it is makes a smart grid infrastructure possible. Different technologies to improve the power quality in the power systems are also necessary and discussed. Finally, a discussion about the future is provided.

II. The Danish Electrical Power System – A Paradigm for Distributed Generation

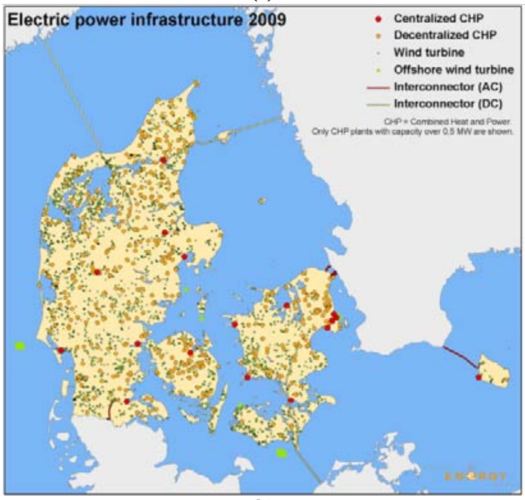
Figs. 1(a) and 1(b) show Denmark power producers and interconnectors in 1985 and 2009 respectively. This clearly demonstrates the development from central to decentralized power production in Denmark. Over the years there has been a regular expansion of the domestic electricity-transmission network and not least exchange connections to neighboring countries. Initially the Nordic electricity grid was interconnected in order to mutually exploit different production forms. Today the transmission network and connections to other countries are also important to the adaptation of large volumes of wind power into the electricity grid.

Converting to different types of biomass fuel (wood, waste, straw) in the combined heat and power production also has great importance to renewable energy production. The share of renewable energy in final energy consumption has increased steadily since 1980 and today amounts to about 19%. Since 1980, the Danish economy has grown by 78%, while energy consumption has remained almost unchanged.

Looking at electricity supply alone, renewable energy accounts for about 28%, which is chiefly due to the incorporation of wind energy in electricity production both in the form of large offshore wind farms and onshore wind turbines.



(a)



(b)

Fig. 1. Decentralization of energy production in Denmark: (a) 1985 and (b) 2009 (Source: Danish Energy Agency).

III. Future Grid System Configuration

Power electronics has changed rapidly over the last 30 years, and the number of applications has been increasing, mainly because of 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. 2 shows a typical power electronic system consisting of a power converter, primary source, and control unit. The power converter is the interface between the primary source 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: reliability, efficiency, and cost. For the moment, the cost of power semiconductor devices is decreasing between 1% and 5% every year for the same output performance, and the price per kilowatt for a power electronic system is also decreasing. The trend of power electronic conversion is shrinking in volume and weight. This shows that integration is an important key to be competitive, as more available functions can be implemented in such a product. Accordingly, power electronics will be a key point to allow the change from the traditional centralized grid to a more distributed and smart grid, as depicted in Fig. 3.

In this sense, a Microgrid clustering concept proposed in [1], based on the hierarchical control of microgrids interconnected between forming SmartGrids, is becoming more and more important, see Fig. 4. The proposal is based on making the power electronics interfaces behave like synchronous generators, and regulate every microgrid independently by means of a three level hierarchical control: i) the primary control is based on the droop control method, including an output impedance virtual loop; ii) the secondary control allows restoring the deviations produced by the primary control; and iii) the tertiary control manages the power flow between the microgrid and the external electrical distribution system.

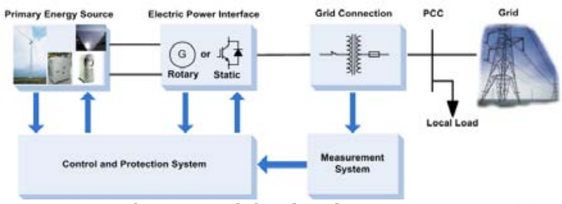
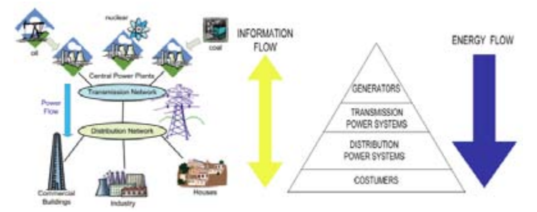
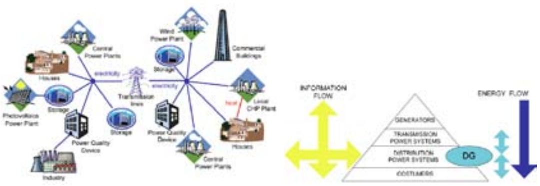


Fig. 2. Power plants toward distributed power generation: (a) traditional power systems and (b) decentralized future power systems.



(a)



(b)

Fig. 3. Power plants toward distributed power generation: (a) traditional power systems and (b) decentralized future power systems.

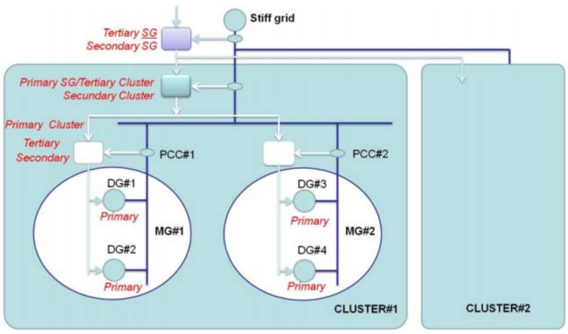


Fig. 4. Multi-Microgrid clustering [1] for SmartGrid.

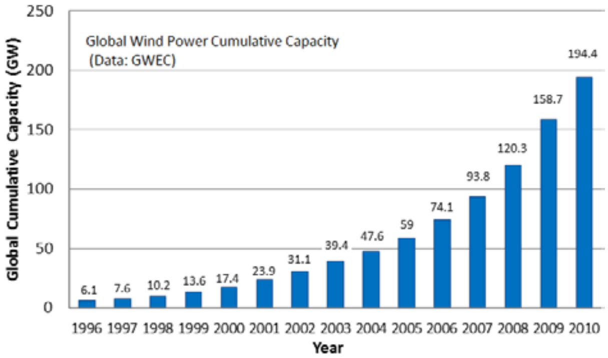


Fig. 5. Annual global cumulative installed wind power capacity from 1996 to 2010 (source: GWEC).

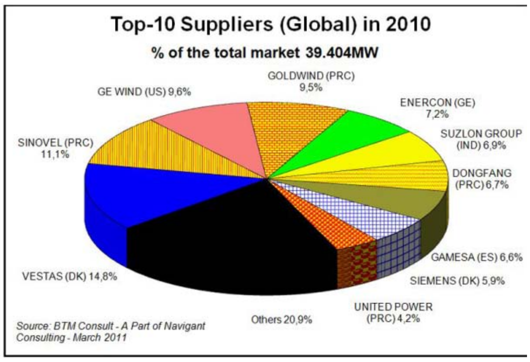


Fig. 6. Wind turbine market share distributed by manufacturers in 2010. (source: BTM Consult).

IV. Nowadays Status of Wind Power and Photovoltaics

A. *Wind power*

The wind power has grown to a cumulative worldwide installation level of 200 GW with over 39.4 GW of newly installed wind power capacity in 2010, according to BTM Consult. Now there are predictions that the installed capacity could grow one order of magnitude to 2300 GW by 2030, according to a study published by the Global Wind Energy Council and Greenpeace International. The worldwide penetration of wind power in 2010 was 1.92%. China was the largest market in 2010 with over 19 GW installed and in general EU, USA and China are sharing around one third each of the total market. The evolution of the wind turbine market is shown in Fig. 5.

The Danish company Vestas Wind Systems A/S was in 2010 still on the top position among the largest manufacturers of wind turbines in the world, closed followed by the Chinese company Simovel, as the second largest in the world. GE Wind, the Chinese company Goldwind and German Company Enercon are in third, fourth and fifth positions, respectively. It is interesting to notice that three Chinese manufacturers are in the Top 10 and with a total share of 23.3%. Fig. 6 shows the wind turbine top-suppliers in 2010.

Nowadays, the most attractive concept seemed to be the variable speed wind turbine with pitch control [3]-[22]. Still some manufacturers are providing the 'classical' active stall, fixed speed turbines especially for countries where the grid codes do not demand dynamic reactive power control (presently e.g. in China, parts of USA). However, recently Siemens Wind

Power released a multi-megawatt class variable speed Full-Scale power Converter (FSC) with a permanent magnet generator. The most used generator type is changing from being an induction generator to be with Permanent Magnet Synchronous Generators (PMSG) where a full scale power conversion is necessary. All wind turbine manufacturers are using a step-up transformer for connecting the generator to the grid. Today the DFIG is still dominating the market but in the future FSC is expected to take over. The transition is mainly valid for larger wind turbines (3-6 MW).

B. Solar power

PhotoVoltaic (PV) based solar power is like the wind turbines a booming industry; since 1980, when the terrestrial applications began. The annual installation of PV power has increased to above 7 GWp leading to cumulative installed PV power by the end of 2009 reaching to approximately 15 GWp according to EPIA which actually is 10 % of the wind power capacity. Fig. 7 shows the cumulative PV installed capacity.

The annual growth rate is still very high (>30%) especially for the last 3 years. As in the previous years the vast majority of new capacity was installed in EU with Germany as dominating the market followed by Spain and Italy. USA market is also growing fast According to Photon Magazine, the prices for PV modules are decreased by the end of 2009 to around 1.5-2 €/Wp with stronger trends for using thin film technology in order to reach the psychological threshold of 1 €/Wp, which really will trigger the mass-penetration of PV as an energy and power source. In addition to the PV module cost, the cost and reliability of PV inverters are also important issues. The inverter cost share represents about 10-15% of the total investment cost of a grid connected PV system.

The prices for PV inverters in the 1-10 kW range are shown in Fig. 8. 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 which requires the implementation of specific measures in the development and the manufacturing processes.

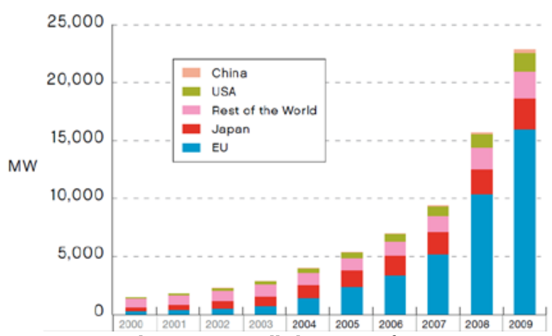


Fig. 7. Cumulative PV installed capacity from 2000 to 2009 (source: EPIA, http://www.epia.org) [63].

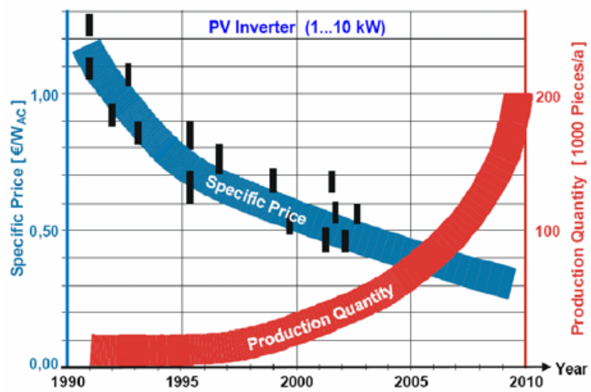


Fig. 8. Development of specific cost and production quantity for the PV inverter of nominal powers between 1 and 10 kW during two decades (¦ indicates specific prices of products on the market) (source: EPIA, http://www.epia.org) [63]..

V. Wind Power conversion

Wind turbines capture power from the wind by means of aerodynamically designed blades and convert it to rotating mechanical power. As the blade tip-speed should be lower than half the speed of sound the rotational speed will decrease as the radius of the blade increases. For multi-MW wind turbines the rotational speed is 8-13 rpm. So far 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. 9.

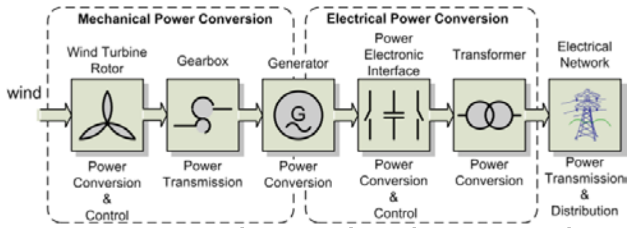


Fig. 9. Converting wind power to electrical power in a wind turbine with the option to use a gearbox and a power converter [5].

The gear-box is optional as multi-pole generator systems are also becoming competitive solutions. Between the grid and the generator a power converter is inserted which gives the flexibility to control the power to the grid and the power from the generator.

There exist many technical solutions for wind energy/power and convert the mechanical power into electrical power. The electrical output can either be ac or dc. In the last case a power converter has to be used as interface to the grid which also gives maximum controllability. In the following the two most used technologies will be discussed and compared with fixed speed technologies without full scale power converter (Type A and Type B in Table I)

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

This configuration is known as the doubly-fed induction generator (DFIG) concept, which gives a variable speed controlled wind turbine with a wound rotor induction generator (WRIG) and partial power-scale frequency converter (rated to approx. 30% of nominal generator power) on the rotor circuit. The topology is shown in Fig. 10.

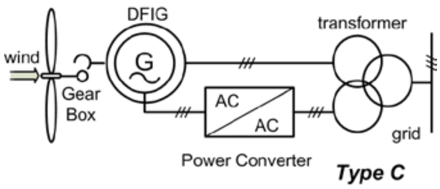


Fig. 10. Variable speed wind turbine with partial scale power converter.

The stator is directly connected to the grid, while a partial-scale power converter controls the rotor frequency and thus the rotor speed. The power rating of this partial-scale frequency converter defines the speed range (typically ±30% around synchronous speed). Moreover, this converter performs the reactive power compensation and a smooth grid connection. The control range of the rotor speed is wider compared to the variable rotor resistance type. The smaller frequency converter makes this concept attractive from an economical point of view. In this case the power electronics is enabling the wind turbine to act as a dynamic power source to the grid. However, its main drawbacks are the use of slip-rings and the protection schemes/controllability in the case of grid faults.

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

This configuration corresponds to the full variable speed controlled wind turbine, with the generator connected to the grid through a full-scale frequency converter as shown in Fig. 11.

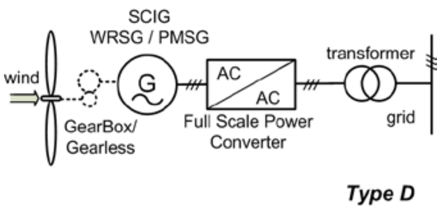


Fig. 11. Variable speed wind turbine with full-scale power converter.

The frequency converter performs the reactive power compensation and a smooth grid connection for the entire speed range. The generator can be electrically excited (wound rotor synchronous generator WRSG) or permanent magnet excited type (permanent magnet synchronous generator PMSG). The stator windings are connected to the grid through a full-scale power converter.

Some variable speed wind turbine systems are gearless – see the dotted gearbox in Fig.11. In these cases, a more heavy direct driven multi-pole generator may be used.

C. System Comparison of Wind Turbines

Comparing the different wind turbine topologies in respect to their performances it will reveal a contradiction between cost and performance to the grid. A technical comparison of the main wind turbine concepts, where issues on grid control, cost, maintenance, internal turbine performance is given in Table I. More details can be found in [9], [12].

TABLE I.
System comparison of wind turbine configurations.

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

VI. Control of Wind Turbines and Grid Requirements

Controlling a wind turbine involves both fast and slow control dynamics [23]-[35]. Overall the power has to be controlled by means of the aerodynamic system and has to react based on a set-point given by a dispatched center or locally with the goal to maximize the power production based on the available wind power. The power controller should also be able to limit the power. An example of an overall control scheme of a wind turbine with a doubly-fed generator system is shown in Fig. 12.

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 turbine speed 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 induction 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 PI-controllers, as it is illustrated in Fig. 12. The power converters to the grid-side and the rotor-side are both voltage source converters.

Another solution for the electrical power control is to use the multi-pole synchronous generator and a full scale power converter. A passive rectifier and a boost converter can be used in order to boost the voltage at low speed. The system is industrially used today and it is shown in Fig. 13.

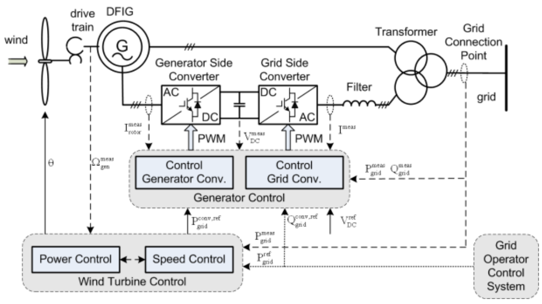


Fig. 12. Control of a wind turbine with doubly-fed induction generator (WT Type C).

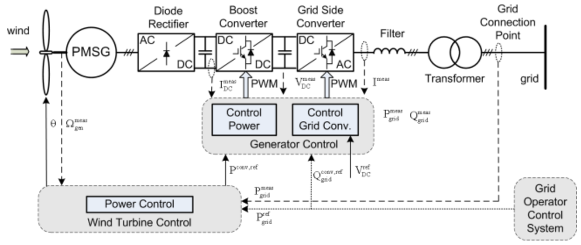


Fig. 13. Control of active and reactive power in a wind turbine with multi-pole synchronous generator (WT Type D).

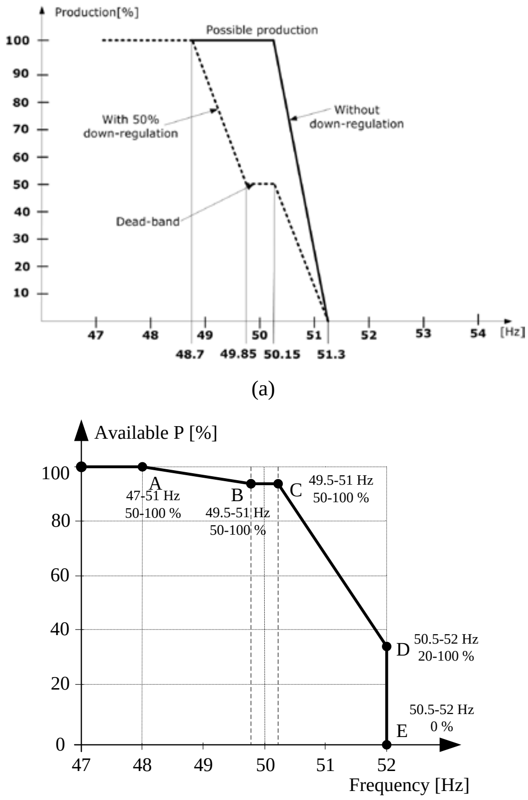
A grid-side converter is interfacing the dc-link to the grid. Common for both discussed systems are that they are able to control active and reactive power to the grid with high dynamics. Another advantage of the system in Fig. 13 is that the dc-link partly is performing a decoupling between the wind turbine and the grid. The dc-link will also give an option for the wind turbine to have an added energy storage connected which can accommodate for extra active power demand (both positive and negative) from the utility side – further improving the system capabilities of the wind turbine.

Most European countries have dedicated grid codes for wind power and they are updated regularly [36]-[46]. These requirements reflect, in most of the cases, the penetration of wind power into the electrical network.

The requirements for wind power cover a wide range of voltage levels from medium voltage to very high voltage. The grid codes for wind power address also issues that make wind farms to act as a conventional power plant into the electrical network and to able to act as a source for a SmartGrid. These requirements have focus on power controllability, power quality, fault ride-through capability and grid support during network disturbances. Examples of Active and Reactive Power Control, Power Quality and Ride-Through operation capabilities are given.

A. Active power control

According to most grid codes the wind turbines must be able to control the active power in the Point-of-Common-Coupling (PCC) in a given power range. The active power is typically controlled based on the system frequency e.g. Denmark, Ireland, Germany so that the power delivered to the grid is decreased when the grid frequency rises above 50 Hz. A typical characteristic for the frequency control in the Danish and Irish grid code is shown in Fig. 14.



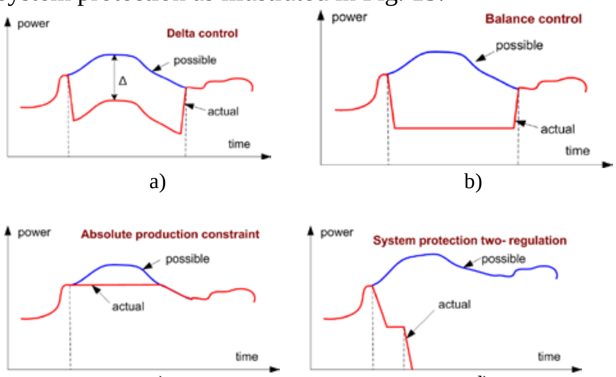
(a)

(b)

Fig. 14. Frequency control characteristic for the wind turbines connected to the Danish grid (a) and Irish system (b).

On the contrary other grid codes, e.g. Great Britain specifies that the active power output must be kept constant for the frequency range of 49.5 Hz to 50.5 Hz, and a drop of maximum 5% in the delivered power is allowed when the frequency drops to 47 Hz [46].

Wind farms connected at the transmission level shall act as a conventional power plant providing a wide range of controlling the output power based on Transmission System Operator's (TSO) demands and also participate in primary and secondary control. Seven regulation functions are required in the wind farm control. Among these control functions, each one is prioritized and the following can be mentioned: delta control, balance control, absolute production and system protection as illustrated in Fig. 15.



a) b)

c) d)

Fig. 15. Regulation functions for active power control implemented in wind farm controller required by the Danish grid codes. a) delta control, b) balance control, c) absolute production constraint and d) system protection.

B) Reactive power control and voltage stability

Reactive power is typically controlled in a given range. The grid codes specify in different ways this control capability. The Danish grid code gives a band for controlling the reactive power based on the active power output as shown in Fig. 16.

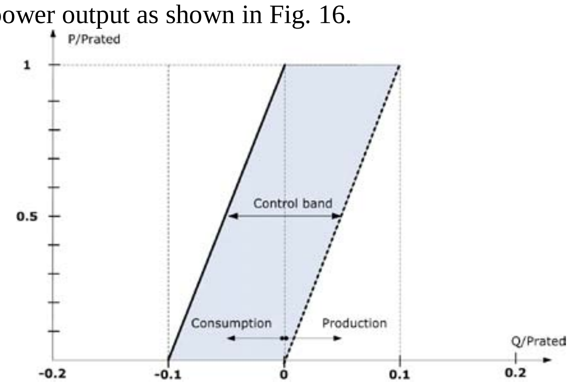


Fig. 16. Danish grid code demands for the reactive power exchange in the PCC [36], [37].

The German transmission grid code for wind power specifies that the wind power units must provide a reactive power provision in the connection point without limiting the active power output as shown in Fig. 17.

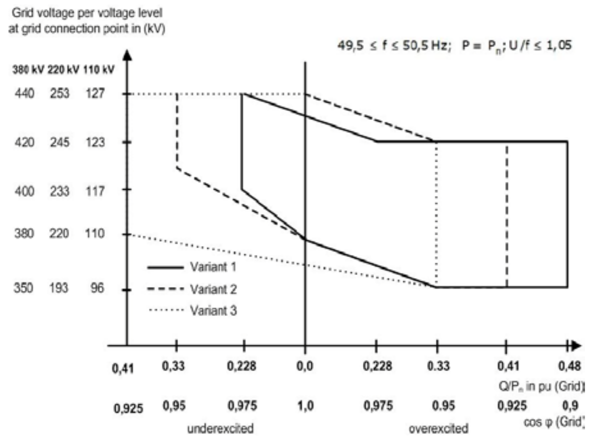


Fig. 17. Requirements for reactive power provision of generating units without limiting the active power output in the German transmission grid code [55].

As it can be noticed in Fig. 17 there are actually three possible V-Q profiles depending on the specific strength of the transmission system close to the PCC. This basic form of voltage control should be realized very slowly with a time constant in the range of two minutes [46].

C) Power Quality

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

Mainly two standards are used for defining the power quality parameters namely: IEC 61000-4-30 and EN 50160. Specific values are given for fast variations in voltage, short term flicker severity, long term flicker severity and the total harmonic distortion. A schedule of individual harmonics distortion limits for voltage are also given based on standards or in some cases e.g. Denmark custom harmonic compatibility levels are defined. Inter-harmonics may also be considered.

D) Ride through capability

All considered grid codes require fault ride-through capabilities for wind turbines to overcome grid faults. Voltage profiles are given specifying the depth of the voltage dip and the clearance time as well. One of the problems is that the calculation of the voltage during all types of unsymmetrical faults is not very well defined in some grid codes. The voltage profile for ride-through capability can be summarized as shown in Fig. 18.

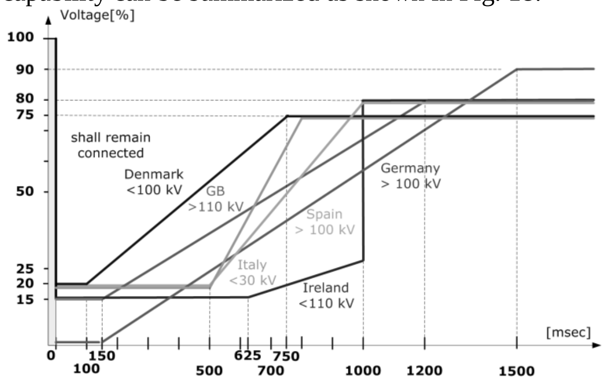


Fig. 18. Voltage profile for fault ride-through capability in European grid codes for wind power [61].

Ireland's grid code is very demanding in respect to the fault duration while Denmark has the lowest short circuit time duration with only 100 ms. However, the grid code in Denmark requires that the wind turbine shall remain connected to the electrical network during successive faults, which is a technical challenge. On the other hand Germany and Spain requires grid support during faults by reactive current injection up to 100% of the rated current.

As the power range is increasing for the PhotoVoltaic systems too some of the same demands will be given to PV systems and they might challenge some of the power configurations for PV's.

VII. Power Quality Improvement with Power Electronic Devices

When integrating renewable energy into the electrical grid, some situations related to the voltage stability and even the voltage collapse can limit the power injected into the grid. For example, when a voltage dip occurs, some of the wind turbine technologies need reactive power, which in some cases can be supplied by synchronous generators. However, this solution cannot be generalized. Dynamic compensation methods are often used, both inside the wind farm, normally near the PCC, or outside the wind farm, to mitigate these problems [12].

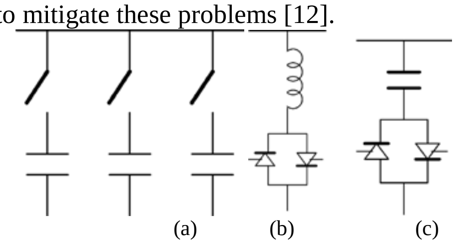


Fig. 19. Reactive power providers. (a) MSC bank; SVC basic components: (b) TCR (c) TSC.

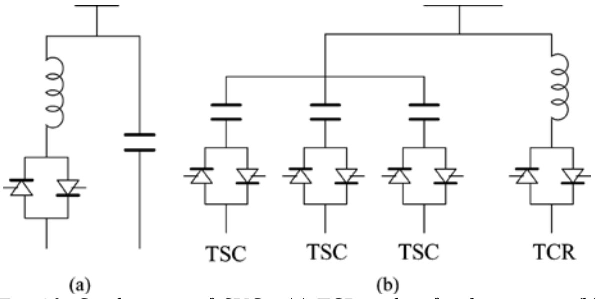


Fig. 20. Combination of SVCs. (a) TCR with a fixed capacitor. (b) TCR with TSC.

B. Compensation Inside a Wind Farm

Voltage stability problems may be derived from the need of reactive power of some wind turbines. This fact becomes more import during a voltage dip since in this case, the problem is to generate enough reactive power for the wind generators. Some existing solutions for transient and steady-state voltage control are as follows.

1) *Mechanical Switched Capacitors* (MSCs): This solution, depicted in Fig. 19(a), consists of a bank of shunt capacitors switched mechanically to provide reactive power compensation. The size of each capacitor may be limited in order to avoid large voltage transients. The main problems in the wind farm are that the excessive switching of the capacitor bank provokes failures, applies the inherent voltage steps stress on the wind turbines, and increases the required maintenance of the system.

2) *SVCs*: These systems use thyristor-controlled components, typically thyristor-controlled reactors (TCRs) and TSCs, also together with MSCs to obtain a dynamic controller of reactive power. Normally, SVCs are connected to the collector bus that connects the wind farm to the PCC to provide a desired power factor or voltage level. The SVC can adjust the reactive power, thus to basically solve the steady-state voltage problems.

Fig. 19(b) shows a TCR, which is a device consisting of three legs, each of them having an inductor and a static switch. The static switch is formed by two anti-parallel connected thyristors. The power is controlled by changing the current flow through the inductor by means of the switch. The ON-state of the thyristors can be adjusted by the firing angle. However, this device generates current harmonics due to the current waveform.

A TSC is shown in Fig. 19(c), which consists of a bank of switched capacitors. Each capacitor has an individual static switch, which is similar to a TCR device, but in this case, the switching takes place when the voltage across the thyristor is zero. Consequently, this device does not produce current harmonics. However, due to the use of switching capacitors, TSC may produce voltage transients.

The combinations between these components can provide good performances of compensation. For instance, TCR can be combined with fixed capacitors or with TSC, as shown in Fig. 20. In the first case, a TCR is used in combination with a fixed capacitor bank. This solution is often used for subtransmission and distribution. The current harmonics may be eliminated by tuning the fixed capacitors as passive filters.

The second case combines TCR and TSC in one compensator system. Hence, a continuously variable reactive power is obtained across the entire control range plus full control of both inductive and capacitive parts of the compensator.

3) *STATCOM*: This system, also named SVC Light by ABB, is based on a VSC, which is used to generate reactive power. The VSC uses power electronic devices such as IGBTs, IGCTs, or gate turn-OFF thyristors (GTOs), and they can also be configured as a multilevel bidirectional converter. As shown in Fig. 21, the VSC is connected to the grid to inject or absorb reactive power through an inductor *X*. This system is suitable to mitigate both steady-state and transient events. Compared with SVCs, STATCOMs provide faster response, less disturbances, and better performance at reduced voltage levels.

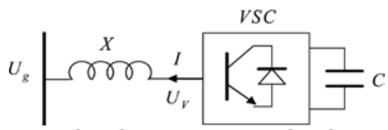


Fig. 21. STATCOM based on VSC connected to the PCC through an inductor.

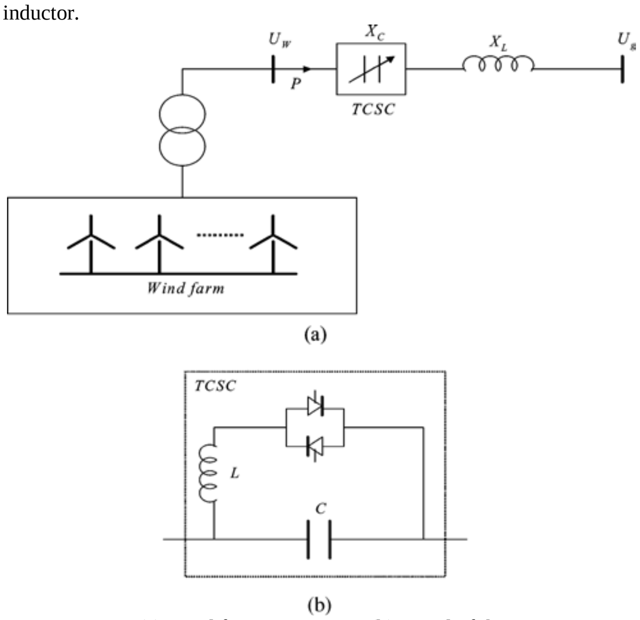


Fig. 22. TCSC. (a) Wind farm connection. (b) Detail of the TCSC.

C. Compensation Outside a Wind Farm

In order to send the active power generated by a wind farm into the grid, the power transmission control has to be taking into account. Power oscillations and voltage collapses should be avoided. Fig. 22 shows a possible solution to avoid these drawbacks, which uses a thyristor-controlled series compensation (TCSC) outside the wind farm. The TCSC changes the equivalent capacitor value by switching the parallel-connected inductor. This way, a variable capacitor can be obtained and can be adjusted to increase the dynamic stability of power transmission, improve the voltage regulation and the reactive power balance, and control the power flow of the grid lines.

From Fig. 22(a), it can be seen that the active power transmitted from the wind farm to the grid and the power angle can be plotted, as shown in Fig. 23. It can be observed that the reactance value limits the maximum power to be transmitted, and enforces a larger power angle that can lead to instabilities and oscillations. However, if a TCSC is added, both the total equivalent impedance of the power line and the power angle can be reduced, thus improving the steady-state and the transient system behavior. This system may be useful for wind farms located far away from the PCC, such as offshore wind farms.

All solutions are useful for providing a more flexible power system and grid structure towards a SmartGrid infrastucture

VIII. CONCLUSION

The paper discussed a new paradigm of grid infrastructure where it is moved from being just a down-streamed, large power producing units to be a grid structure where the power is dispersed produced – in many cases closer to the location of consumption. The most progressing technology is wind power but PV power plants are also emerging and the technology has the highest growth rate. The applications of power electronics in various kinds of wind turbine generation systems are illustrated showing that the wind turbine behavior and performance are significantly improved by using power electronics and will be able to enable a much more flexible grid structure. Wind turbines are able to act as a contributor to the frequency and voltage control in the grid by means of active and reactive power control using power electronics. The same will be the case for PV power plants. Further, power electronics devices for enhancing the penetration of wind power into the grid are presented and discussed.

Thus, power electronics is playing an essential role when integrating renewable technologies like photovoltaic and wind energy systems into the future SmartGrid structure.

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