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Power Electronics as an Enabling Technology for Renewable Energy Integration

F. Blaabjerg* and Z. Chen

Aalborg University, Institute of Energy Technology Pontoppidanstraede 101
DK-9220 Aalborg East, Denmark

ABSTRACT

The global electrical energy consumption is still rising and there is a steady demand to increase the power capacity, to produce, distribute and use the energy as0 efficient as possible and furthermore to set up incentives to save energy at the end-user. Two major technologies will play important roles to fulfill those targets. One is to change the electrical power production sources from the conventional, fossil (and short term) based energy sources to renewable energy resources. The other is to use high efficiency power electronics in power systems for high efficiency and high performance applications. This paper discusses both areas, in particular the power electronic application in wind power integration.

Keywords: wind turbines, power electronics, active and reactive power control, distributed power generation

1. Introduction

The electrical energy demand is steadily rising globally. In conventional electrical power generation stations, generators adopt a fixed speed and thereby a fixed grid frequency[1]. However, renewable power generation presents a quite different and challenging picture.

A number of renewable energy sources exist like wind energy, solar energy, wave energy, hydro-power and more sophisticated systems based on hydrogen, where it is assumed hydrogen is produced by renewable energy sources[2]-[6]. Also, at present, much R&D efforts are put into the fuel cell development because chemistry and material science have done a breakthrough Most renewable energy sources have a high variation of production due to uncontrollable sources (wind, sun, waves) and furthermore some of the sources generate a dc-voltage which can not be directly connected to the grid.

Power electronics[1][11] play an important role for the integration of renewable energy and this paper will discuss how the technology is enabling the renewable energy for a successful integration. The main focus in this paper is put on the wind power conversion systems.

In this paper, the variation characteristics of different renewable energy sources and the general structure of the systems interfacing the renewable power generation units into the ac supply systems will be discussed. Then the development in modern power electronic technology: semiconductors, converters and control techniques, will be presented. Thereafter the wind power system, which today is the most competitive renewable energy generation system, will be discussed in detail and finally the power electronic applications in the future power systems are

Manuscript received Dec. 10, 2002; revised Feb. 26, 2003.
Corresponding Author: fbl@iet.auc.dk
Tel : +45-9635-9254, Fax : +45-9815-1411

briefly discussed.

2. Renewable Energy Characteristics

As a result of the increasing environmental concern, more efforts have been made on electricity generation from renewable sources. A wide spread use of renewable energy sources in distribution networks and a high penetration level will be seen in the near future. Denmark has already obtained a high penetration (> 15%) of wind energy in major areas of the country. The main advantages of using renewable sources are the elimination of harmful emissions and the inexhaustible resources of the primary energy. However, the main disadvantage, apart from the high costs, such as photovoltaic, is the uncontrollability e.g. the dependency of the weather. Fig. 1 and Fig. 2 show the typical characteristics of the wind speed and insolation level[5]. These characteristics, together with the operation characteristics of the wind power and PV generation units shown in Fig. 3 and Fig. 4[5], will determine the power generated by the wind turbines and PV generators respectively.

It can be seen that the availability of renewable energy sources has strong daily and seasonal pattern. E.g. every day, the sun follows a path through the sky, making the irradiance reach its peak just after noon and zero over night. Therefore, for a solar panel, a minimum output power can be guaranteed during daytime. Even on a cloudy day, there is conversion from diffuse sunlight to electricity and this is enough for the solar panels to generate some electrical power. However, for a wind turbine, no output power guarantee can be given, because days with a wind speed less than the cut in speed of the wind turbine may occur, resulting in no power generation.

On the other hand, the power demand by the consumers could have a very different characteristic as shown in Fig. 5[6]. One can see a clear difference between the demand power and the output power probability of a wind turbine and a solar panel. Therefore, it can be concluded that it would be difficult to operate a power system installed with only renewable generation units due to the characteristic difference and the features of the high uncertainty of the renewable sources. The solutions could be the connection of these generation units into a power system with more

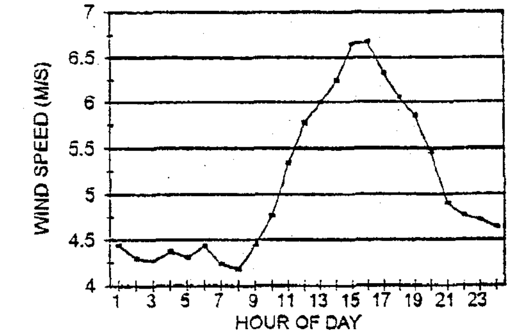


Fig. 1. Typical wind speed vs. time[5] during a day.

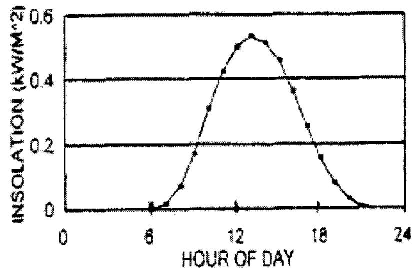


Fig. 2. Solar radiation vs time[5] during a day.

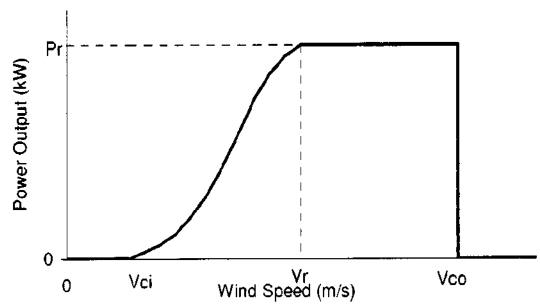


Fig. 3. Wind turbine power characteristics[5] where electrical output power as a function of wind speed is shown.

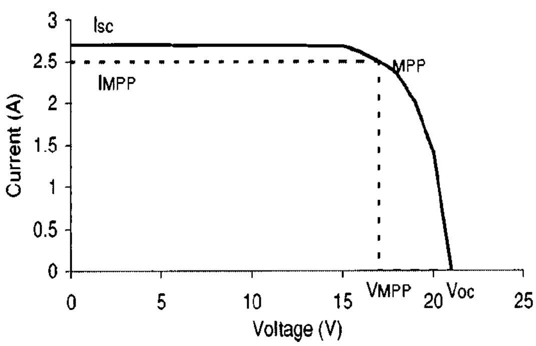


Fig. 4. Photovoltaic generator characteristics[5] showing a load curve.

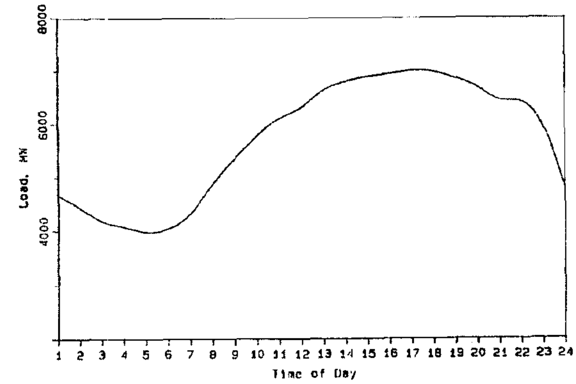


Fig. 5. Typical power system load curves during a day[6].

controllable conventional power stations and/or energy storage devices.

Presently, due to the technology limit on the large scale energy storage systems, the way of fully exploiting the renewable energy is the grid connection, where the power electronic technology plays a vital role to match the characteristics of the renewable generation units and the requirements of the grid connections, including frequency, voltage, control of active and reactive power, harmonic minimization etc., which will be discussed in the following sections.

3. Modern Power Electronics

Power electronics has changed rapidly during the last twenty years. The number of applications has been increasing, mainly due to the developments of the semiconductor devices and the microprocessor based control technology. For both cases higher performance is given for the same area of silicon, which has dramatically, reduced the price. Fig. 6 shows a typical power electronic system consisting of a power converter, a load/source and a control unit.

The converter is the interface between the load/generators and the grid. The power can flow in both directions. Three important issues are of concern using this topology. The first one is reliability; the second is efficiency and the third is price. For the moment the price of power semiconductor devices is decreasing 2-5 % every year for the same output performance.

Fig. 7 illustrates an example of the rapid development of power electronics in adjustable speed drives for the last 25 years. As it can be seen that the volume and weight have been reduced by at least a factor of 15 while the functions have increased dramatically. In order to improve reliability and reduce cost the number of components is going down by a higher level of integration.

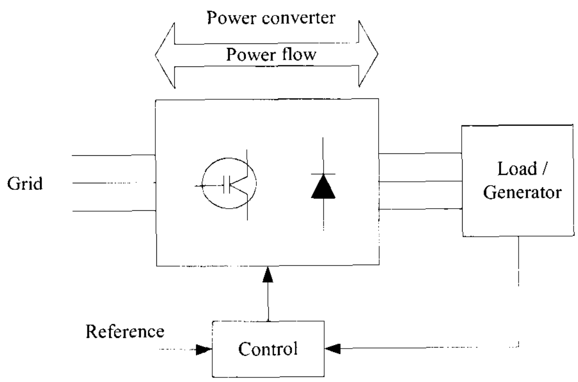


Fig. 6. Power electronic system with the grid, load, power converter and control.

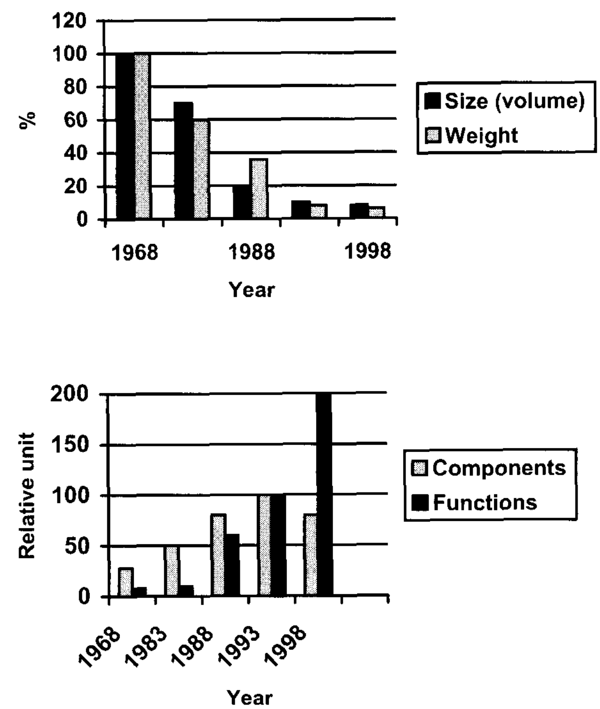


Fig. 7. Development of a 4 kW standard industrially adjustable speed drive the last 25 years[10].

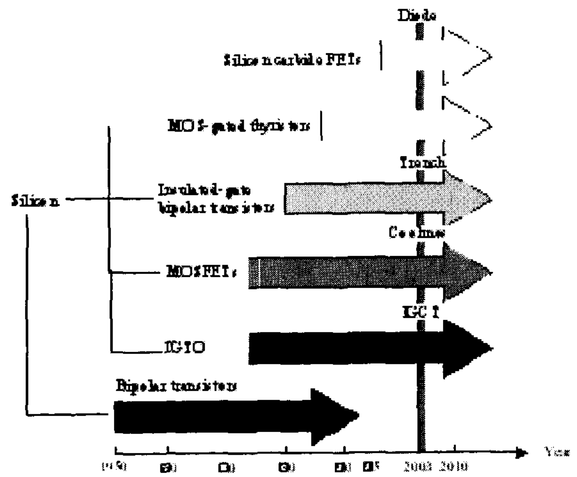


Fig. 8. Development of power semiconductor devices in the past and in the future.

The power electronic device technology is still undergoing important progress. Fig. 8 shows the present status of different devices and the area where the development is going on.

The only power device which is not under development any more is the 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 continuously increase. Also, important research is going on to change the material from silicon to silicon carbide. This will dramatically increase the power density of power converters.

4. Variable Speed Wind Turbines

The development in wind turbine systems has been steady for the last 25 years and four to five generations of wind turbines exist. It is proven technology. The wind turbines technology can basically be divided into three categories: the first category is the systems without power electronics, the second category is those with partially rated power electronics and the last is the full-scale power electronic interfaced wind turbine systems. Fig. 9 shows the first category of wind turbines.

The wind turbine systems in Fig. 9 using induction generators, which almost independent of torque variation, keep an almost fixed speed (variation of 1-2%). The power is limited aerodynamically either by stall, active stall or by pitch control. All three systems use a soft starter (not shown in Fig. 9) in order to reduce the inrush current.

They also need a reactive power compensator to reduce (almost eliminate) the reactive power demand from the turbine generators to the grid. It is usually done by activating continuously capacitor banks following load variation (5-25 steps). Those solutions are attractive due to cost and reliability.

The next category is wind turbines with partially rated power converters and much more improved control performance can be obtained. Fig. 10 shows two such solutions.

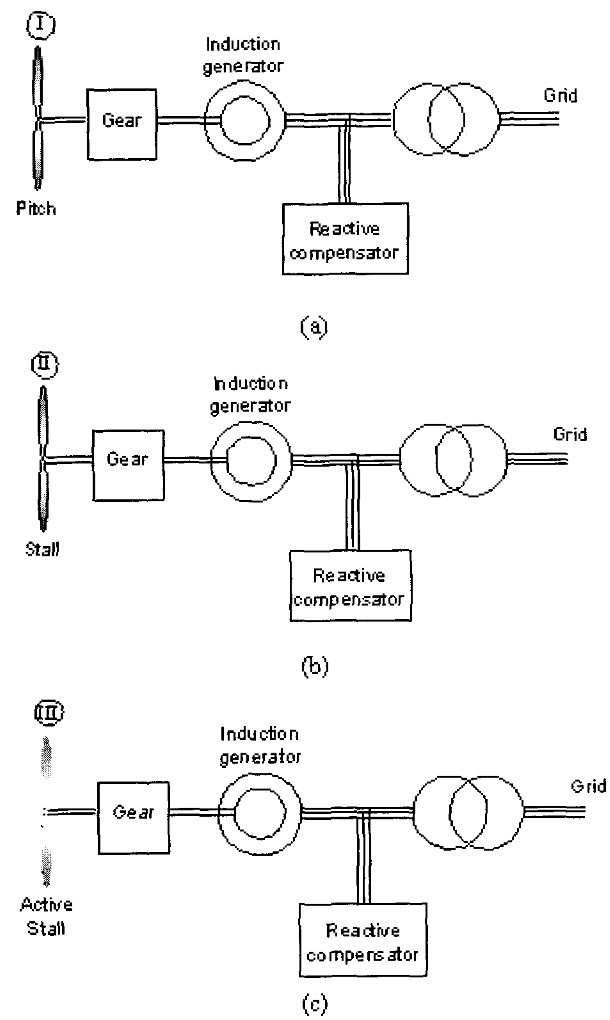
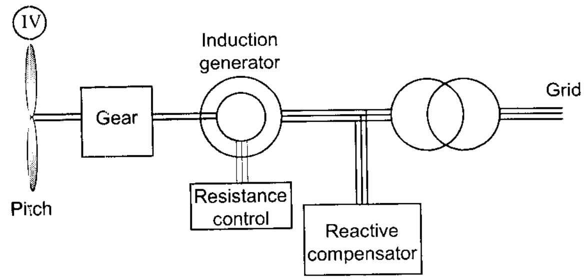
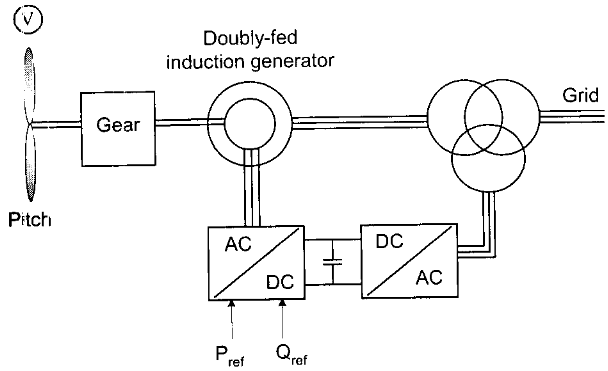


Fig. 9. Wind turbine systems without power converter but with aerodynamic power control.
(a) Pitch controlled (System I)
(b) Stall controlled (System II)
(c) Active stall controlled (System III)

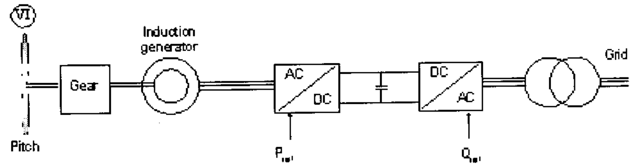


(a)



(b)

Fig. 10. Wind turbine topologies with partially rated power electronics.
(a) Rotor-resistance converter (System IV)
(b) Doubly-fed induction generator (System V)



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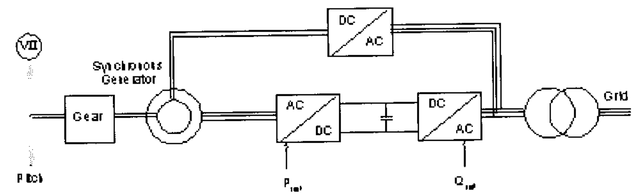

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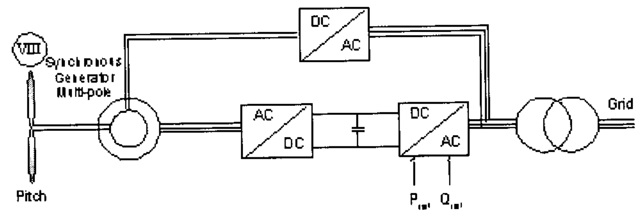

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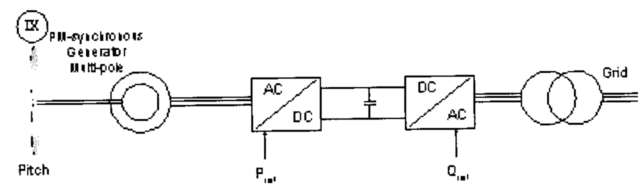

(d)

Fig. 11. Wind turbine systems with full-scale power converters.
(a) Induction generator with gear (System VI)
(b) Synchronous generator with gear (System VII)
(c) Multi-pole synchronous generator (System VIII)
(d) Multi-pole permanent magnet synchronous generator (System IX)

Fig. 10(a) shows a wind turbine system where the generator is an induction generator with a wounded rotor. An extra resistance is added in the rotor, which can be controlled by power electronics. This gives a speed range of 2-4 %. The power converter for the rotor resistance control is for low voltage but high currents. At the same time an extra control freedom is obtained at higher wind speeds in order to keep the output power fixed. This solution still needs a softstarter and a reactive power compensator.

A second solution of using a medium scale power converter with a wounded rotor induction generator is shown in Fig. 10b. Slip-rings are making the electrical connection to the rotor. A power converter controls the rotor currents. If the generator is running super - synchronously electrical power is delivered through both the rotor and the stator. If the generator is running sub-synchronously electrical power is only delivered into the rotor from the grid. A speed variation of 60 % around synchronous speed can be obtained by the use of a power converter of 20 % of nominal power. Furthermore, it is possible to control both active and reactive power, which gives a better grid performance, and power electronic is an enabling technology in these cases.

The last solution needs either a soft starter or a reactive power compensator. The solution is naturally a little bit more expensive compared to the classical solutions. However it is possible to save on the safety margin of gear, reactive power compensation and capture more energy from the wind.

Table 1. Comparison of wind turbine systems.
++ Very positive (low cost) + Positive 0 Not the best

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	Yes	No	No	Yes,	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	No	No	No	No
Control band width	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	No	No	No	No	No	No
Softstarter needed	Yes	Yes	Yes	Yes	No	No	No	No	No
Rolling capacity on grid	No	No	No	No	Yes	Yes	Yes	Yes	Yes
Reactive compensation (C)	Yes	Yes	Yes	Yes	No	No	No	No	No
Investment	++	++	++	++	+	0	0	0	0
Maintenance	++	++	++	++	0	+	+	+	+

The third category is wind turbines with full-scale converter between the generator and grid, which are the ultimate solutions technically. It gives extra losses in the power conversion but it may be gained by the added technical performance. Fig. 11 shows four possible solutions with full-scale power converters.

The solutions shown in Fig. 11(a) and Fig. 11(b) are characterized by having a gear. A synchronous generator solution shown in Fig. 11(b) needs a small power converter for field excitation. Multi-pole generator systems with the synchronous generator without a gear are shown in Fig. 11(c) and Fig. 11(d).

The difference in the last solution is using permanent magnets, which are still becoming cheaper. 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 very fast to control active and reactive power. However, the negative side is a more complex system with a more sensitive electronic part.

Comparing the different wind turbine systems in respect to performance shows a contradiction between cost and the performance to the grid. Table 1 shows a comparison of the presented wind turbine systems.

By introducing power electronics many of the wind turbine systems get a performance like a power plant. In respect to control performance they are faster but of course the real power depends on the available wind.

5. Power Electronics for Offshore Wind Farms

Energy planning in Denmark has scheduled a level of 50 % wind energy penetration in the year 2030 – mainly covered by large offshore wind farms. These wind farms present a significant power contribution on the national grid, and therefore, play a very important role on the power quality and the control of power systems. Consequently very high technical demands are expected to be met by these renewable generation units, such as to perform frequency and voltage control, regulation of active and reactive power, quick responses under power system transient and dynamic situations, for example, to reduce the power from the nominal power to 20 % power within 2 seconds. The power electronic technology is again a very important part in both the system configurations and the controls of the offshore wind farms in order to fulfill the future demands.

In Rejsby Hede, Denmark, a test installation with an 8 MVAr GTO based ASVC unit (Advanced Static VAr Compensation), as sketched in Fig. 12, has been installed in a 24 MW wind farm with 40 stall regulated wind turbines. The power electronic based ASVC controls the reactive power of the wind farm and therefore the system voltage. It can be noticed that for the wind turbines directly connected to the AC grid without power electronic interface, the real power cannot be easily controlled without a pitch control mechanism or dumping devices.

However, if the rotor is connected to the grid via power electronic converters as shown in § IV, the offshore wind farm equipped with doubly-fed induction generators can perform both real and reactive power control while operate the wind turbines in variable speed to maximize the energy capture and to reduce the mechanical stress and noise. The power electronic converters are normally only rated as a small part of the capacity of the system, say 20-30 %. Since the controllability is related to the rating of the power electronic converters, other compensation methods/devices may still be required. For long distance transmission of power from offshore wind farm, HVDC may be a viable option. In a HVDC transmission, the low or medium AC voltage at the wind farm is converted into a high DC voltage on the transmission side and the dc power is transferred to the onshore system where the DC voltage is converted back into ac voltage as shown in Fig. 13. For certain power level, a Light HVDC transmission system, based on voltage source converter technology, may be used in such a system instead of the conventional thyristor based HVDC technology.

Another possible dc transmission system configuration is shown in Fig. 14, where each wind turbine has its own power electronic converter, so that it is possible to operate each wind turbine at an individual optimal speed.

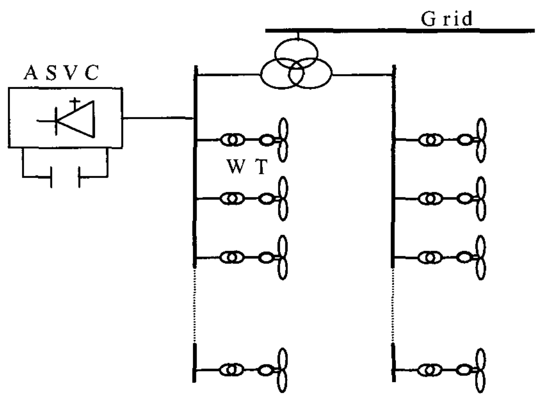

Fig. 12. Single line diagram of a wind farm (40 turbines) with an ASVC unit for power quality improvements.

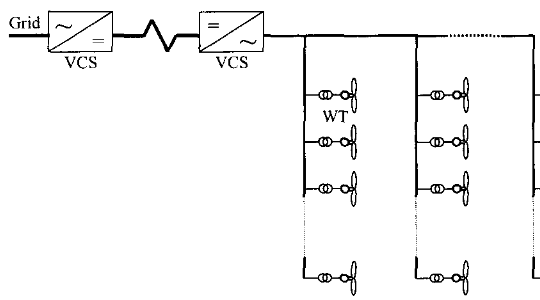

Fig. 13. A wind farm with a Light HVDC transmission and common ac-grid.

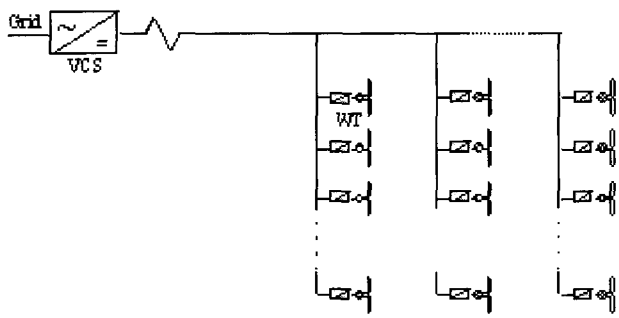

Fig. 14. Single-line diagram of a wind farm with an internal DC network.

6. Power electronics in future power systems

Power electronic technology is playing a more and more important role in modern power systems. Technologies, such as Flexible AC Transmission Systems (FACTs) and Customer Power Devices[7]-[9], have enhanced the power transfer capacity, controllability and reliability of modern power systems. It can be expected that the power electronic technology will further improve the system performance in the aforementioned areas.

Presently, the cost of fuel cells and photovoltaic cells are still too high to be considered as serious contenders on the economic field. However, these technologies are viewed as environmentally more acceptable than fuel-burning central-power stations. It should be expected that further preference could be given to these new developing technologies, again, power electronic will be an indispensable part in these cell based generation systems.

Instead of concentrated tradition thermal generation, one of significant features in future power systems is the dispersed generation. Although dispersed generation using renewable sources may not make a large impact immediately, it is certainly the way of the future. Dispersed generation in its manifold forms of cogeneration, wheeling, renewable generation, fuel cells, etc. must be properly considered not only because of potential competition but because they may afford new opportunities for utilities. The future load growth may be met by alternative strategies to new central plant construction and/or upgrade new transmission and distribution systems. In the long run, the energy demand of customers connected to a distribution network will be substantially covered by energy from renewable sources. By integrating the generation units into power system, the power electronic technology will play a key role in structuring the future power systems, whose potential impact on existing and future generation transmission, distribution, system protection, and substation facilities need to be further studied.

The control of the power system is another important issue. The key is to make dispersed generation units that have the properties of conventional power stations, i.e. a complete control of active and reactive power and thereby control of the voltage and the frequency. As presented some possible solutions already exist on how to integrate and control large wind farms. Such control capabilities can be obtained with power electronic converters. This is economic attractive, but there is a risk of instability in the power system where each generation unit tries to optimize the production completely individually and control the voltage on the local terminals independently. In some future applications the voltage and frequency might be controlled centralized or cooperatively via the power electronic converters in combination with dispersed generation units, although the fast control loops are still necessary on the individual generation units.

7. Conclusions

The paper discusses the applications of power electronic for renewable energy integration. The difference in the characteristics between the power from renewable energy systems and the load demand requires a grid connection operation or an energy storage device. The power electronic converters play a vital role in the integration. The developments of modern power electronics have been reviewed. The applications of power electronics in various kind of wind turbine generation systems and offshore wind farms have been presented. The power electronics' roles in future power systems have been briefed.

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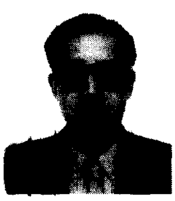
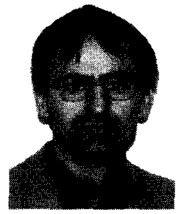


Zhe CHEN received BEng and MSc from Northeast China Institute of Electric Power Engineering, China, PhD from The University of Durham, UK. He was a Lecturer, then a Senior Lecturer with De Montfort University, Leicester, UK. Currently he is a Research Professor with Institute of Energy Technology, Aalborg University, Aalborg, Denmark, on leave from De Montfort University, UK. His main research areas are renewable energy, power systems and protection, power electronics and electrical machines. He is a member of IEE (London), a Chartered Engineer (UK) and a Senior Member of IEEE (USA).



Frede Blaabjerg received the M.Sc.EE. from Aalborg University, Denmark in 1987, and the PhD. degree from the Institute of Energy Technology, Aalborg University, in 1995. He was employed at ABB-Scandia, Randers, from 1987-1988. During 1988-1992 he was a PhD. student at Aalborg University. He became an Assistant Professor in 1992 at Aalborg University, in 1996 Associate Professor and in 1998 full professor in power electronics and drives the same place. In 2000 he was visiting professor in University of Padova, Italy as well as he became part-time programme research leader at Research Center Risoe in wind turbines. In 2002 he was visiting professor at Curtin University of Technology, Perth, Australia. His research areas are in power electronics, static power converters, ac drives, switched reluctance drives, modelling, characterization of power semiconductor devices and simulation, wind turbines and green power inverter. He is involved in more than ten research projects with the industry. Among them is the Danfoss Professor Programme in Power Electronics and Drives. He is the author or co-author of more than 250 publications in his research fields including the book "Control in Power Electronics"(Eds. M.P. Kazmierkowski, R. Krishnan, F. Blaabjerg) 2002, Academic Press. He is associated editor of the IEEE Transactions on Industry Applications, IEEE Transactions on Power Electronics, Journal of Power Electronics and of the Danish journal Elteknik. He has served as member of the Danish Technical Research Council in Denmark since 1997 and in 2001 he became chairman. He became also a member of the Danish Academy of Technical Science in 2001. In 2002 he became a member of the Board of the Danish Research Councils. He received the 1995 Angelos Award for his contribution in modulation technique and control of electric drives, and an Annual Teacher prize at Aalborg University, also 1995. In 1998 he received the Outstanding Young Power Electronics Engineer Award from the IEEE Power Electronics Society. He has received four IEEE Prize paper awards during the last five years. Finally, he received the C.Y. O'Connor fellowship 2002 from Perth, Australia. He is a fellow of IEEE.