DOI: 10.20472/IAC.2015.015.150

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PERMANENT MAGNET SYNCHRONOUS GENERATORS IN WIND TURBINES AND ITS IMPACT ON THE WIND ENERGY

Abstract:

With rapid development of wind power technologies and significant growth of wind power capacity installed worldwide, various wind turbine concepts have been developed. The wind energy conversion system is demanded to be more cost-competitive, so that comparisons of different wind generator systems are necessary. An overview of different wind generator systems and their comparisons are presented. First, the contemporary wind turbines are classified with respect to both their control features and drive train types, and their strengths and weaknesses are described. The promising permanent magnet generator types are also investigated. Then, the quantitative comparison and market penetration of different wind generator systems are presented. Finally, the developing trends of wind generator systems and appropriate comparison criteria are discussed.

Keywords:

Wind Power, Variable speed wing turbine, Full Scale Power Converter, Permanent Magnet Synchronous Generator and Gear-less Concept

JEL Classification: Q20, D40, O22

ISBN 978-80-87927-08-3, IISES

INTRODUCTION

Wind power may be considered as one of the most promising renewable energy sources after its progress during the last three decades. The global energy consumption is rising and an increasing attention is being paid to alternative methods of electricity generation. The very low environmental impact of the renewable energies makes them a very attractive solution for a growing demand. In this trend towards the diversification of the energy market, wind power is probably the most promising sustainable energy source. The progress of wind power in recent years has exceeded all expectations, with Europe leading the global market. Recent progress in wind technology has led to cost reduction to levels comparable, in many cases, with conventional methods of electricity generation. However, its integration into power systems has a number of technical challenges concerning security of supply, in terms of reliability, availability and power quality. Wind power impact mainly depends on its penetration level, but depends also on the power system size, the mix of generation capacity, the degree of interconnections to other systems and load variations. Since the penetration of wind power generation is growing, system operators have an increasing interest in analyzing the impact of wind power on the connected power system. For this reason, grid connection requirements are established. In the last few years, the connection requirements have incorporated, in addition to steady state problems, dynamic requirements, like voltage dip ride-through capability. Moreover, new wind turbine technology integrates power electronics and control making it possible for wind power generation to participate in active and reactive power control. The typical generator configuration for new variable speed turbine is the Permanent Magnet Synchronous generator (PMSG). This concept is, at the moment, the second most common topology in the wind power industry. However it has the chance in the next future to become the best solution as the higher cost is balanced by the power quality, harmonic compensation and full grid support.

WIND TURBINE CONCEPTS

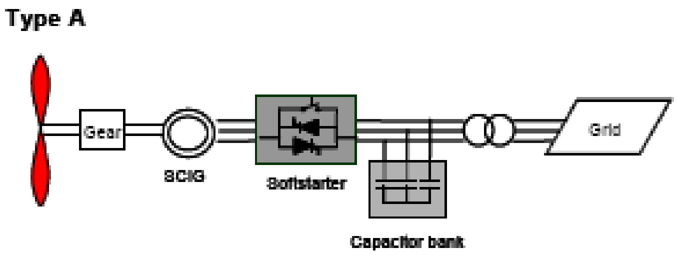
Generally speaking, wind power generation uses either fixed speed or variable speed turbines which can be characterized into four major types. The main changes between these wind turbine types are the ways how the aerodynamic efficiency of the rotor would be imperfect for different wind speed conditions.

1. Type A - fixed speed wind turbine:
2. Type B - variable speed wind turbine concept with variable rotor resistance.
3. Type C - variable speed wind turbine concept with partial-scale power converter (DFIG)
4. Type D - variable speed concept with full-scale power converter.

.1 Type A:

An asynchronous squirrel-cage induction generator (SCIG) directly connected to the grid via a transformer dealing with type ‘A’ wind turbine. The so-called “fix speed WT” comes from the point that the rotational speed of the wind turbine cannot be automatically controlled and will only differ by the wind speed. This type of wind turbine needs a switch to prevent motoring operation during low wind speeds, and also suffers a major drawback of reactive power consumption subsequently there is no reactive power regulator. Besides, this type of wind turbine transfers the wind variations to mechanical instabilities and further converts these into electrical power oscillations due to the fact that there are no speed or torque control loops. These electrical power oscillations can lead to an effect in the case of a weak grid.

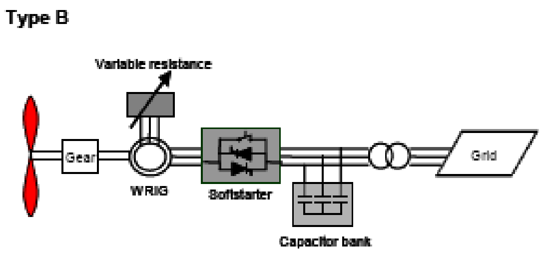
Figure 1:



.2 Type B:

A wound rotor induction generator (WRIG) directly connected to the grid deals with this type of wind turbine. The controlled resistances are connected in series with the rotor phase windings of the generator. In this way, the total rotor resistances can be regulated, and thus the slip and the output power can be controlled. Due to the limitation of the serial resistance sizes, the variable speed range is usually small, typically 0-10% above synchronous speed.

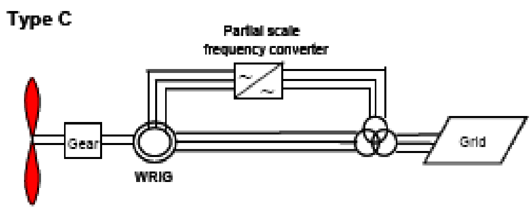
Figure 2:



.3 *Type C:*

This arrangement, known as the doubly-fed induction generator (DFIG) concept, uses a variable speed controlled wind turbine. The stator phase windings of the doubly fed induction generator are directly connected to the grid, while the rotor phase windings are connected to a back-to-back converter via slip rings. The power converters could control the rotor frequency and thus the rotor speed. The power rating of the power converters is typically rated ±30% around the rated power since the rotor of the DFIG would only deal with slip power. The smaller rating of the power converters makes this concept eye-catching from a cost-effective sight. Besides, this type of wind turbine can also achieve the desired reactive power compensation.

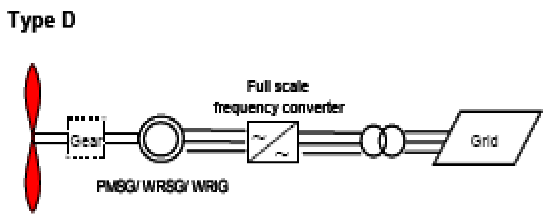
Figure 3:



.4 *Type D:*

This structure usually uses a permanent magnet synchronous generator (PMSG) and a full-scale power converter. The stator phase windings are connected to the grid through a full-scale power converter. Some of this type of wind turbines adopts a gearless concept, which means that instead of connecting a gearbox to the generator, a direct driven multi-pole generator is used without a gearbox. The generator can be excited electrically using permanent magnet excited type or squirrel cage induction generator. Typically, a direct driven, multipole synchronous generator (no gearbox) is used. This concept has full control of the speed range from 0 to 100% of the synchronous speed, but higher power loss in the power electronics compared to Type C, as all generated power has to pass through the power converter.

Figure 4:



VARIABLE SPEED DIRECT DRIVE CONCEPT WITH FULL-SCALE POWER CONCEPT

This configuration may correspond to a variable speed wind turbine with a direct-drive generator connected to the grid through a full-scale power converter. The most important difference between geared drive wind turbines and direct-drive types is the generator rotor speed. The direct-drive generator rotates at a low speed, because the generator rotor is directly connected on the hub of the turbine rotor. To deliver a certain power, the lower speed makes it necessary to produce a higher torque. A higher torque means a larger size of the generator. Therefore for direct-drive generators, the low speed and high torque operation require multi-poles, which demand a larger diameter for implementation of large number of poles with a reasonable pitch. Moreover, for a larger direct-drive generator, considering on the current loading and gap flux density limitations, a higher torque also requires a larger machine's volume, so that the torque density could not be further significantly increased.

To increase the efficiency, to reduce the weight of the active parts and to keep the end winding losses small, direct-drive generators are usually designed with a large diameter and small pole pitch. In addition, the advantages of direct-drive wind turbines are the simplified drive train, the high overall efficiency, the high reliability and availability by omitting the gearbox. Compared with the variable speed concept with a partial-scale power converter, the full-scale power converter can perform smooth grid connection over the entire speed range. However, it has a higher cost and a higher power loss in the power electronics, since all the generated power has to pass through the power converter.

PERMANENT MAGNET SYNCHRONOUS GENERATOR

- Key features of the PMSG based wind turbine generator system:
- The PMSG can achieve full speed regulation.
- The PMSG makes it possible to avoid a gearbox, therefore, there are no mechanical stress issues when experiencing wind gusts.
- The PMSG does not need the slip-rings and brushes, hence, less maintenance will be needed. Therefore, a PMSG-based wind turbine will be more stable than a DFIG-based one.
- The PMSG can also attain the real power and reactive power control. The control schemes are relatively simple and easy to implement.

Drawback:

The power converters of a PMSG-based WTGS have a full-scale power rating, which means that the power converters will cause high losses, generate high harmonic components, and have high cost.

In recent years, the use of PMs is more attractive than before, because the performance of PMs is improving and the cost of PM is decreasing. The trends make PM machines with a full-scale power converter more attractive for direct-drive wind turbines.

Currently, Harakosan and Mitsubishi are using this concept in 2 MW wind turbines in the market.

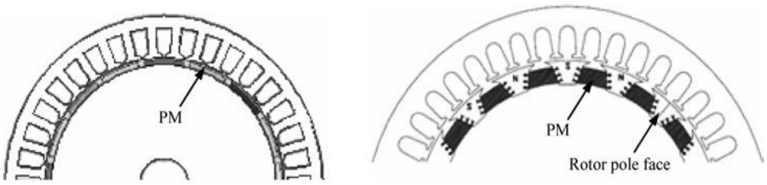
PM machines are not standard off-the-shelf machines and they allow a great deal of flexibility in their geometry, so that various topologies may be used. PM machines can be classified into the following types: radial flux, the axial flux and the transversal flux, based on the direction of flux penetration.

4.1 Radial flux PM machines:

The PMs of radial-flux machines are radically oriented. When using radial-flux PM (RFPM) machines for direct-drive wind turbines, the wind generator system can operate with a good performance over a wide range of speeds. In manufacture, the simple way of constructing the machine with high number of poles is gluing PMs on the rotor surface. In RFPM machines, the length of the machine and the air-gap diameter can be chosen independently. If necessary, the radial-flux machine can be made with a small diameter by using a long machine. RFPM machines have the advantage of better and higher torque density.

Two types of RFPM machines, the slotted surface mounted PM machine and the slotted flux concentrating PM machine. One rotor design with surface mounted magnets and one rotor design with flux concentration are shown:

Figure 5: a. Surface mounted b. Flux concentrating



a b

Compared with the flux concentration, magnets on the rotor surface have to have a remanent flux density higher than the required air-gap flux density, this leads to a very simple rotor design with a low weight. Also compared with the inner-rotor construction, the multi-pole structure can be easily accommodated because of the enlarged periphery of the outer-rotor drum, and therefore the total length of the magnetic path can be reduced.
As the rotor is directly exposed to the wind, the cooling condition can be improved for the magnets so that the resistance to temperature demagnetization is enhanced. Moreover, Chen et al. have also made a comparison of different PM wind generator topologies. In addition, Hanitsch and Korouji have designed a rare-earth RFPM wind-energy generator with a new topology, which is constructed from two rotors and one stator with short end windings. It can improve the performance of the machine by reducing the weight, increasing the efficiency and reducing the cost of active materials.

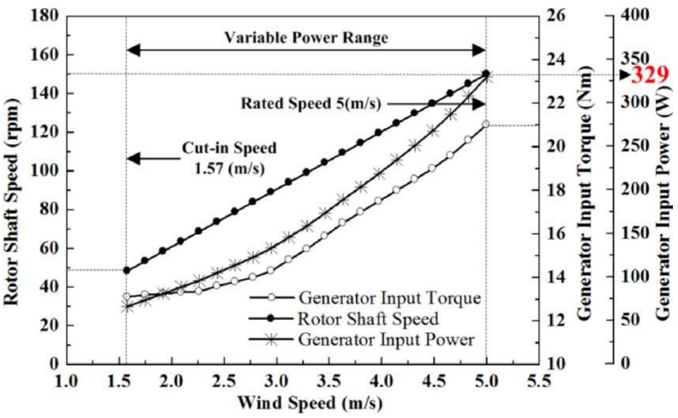
4.2 Axial flux PM machines:

The axial-flux PM (AFPM) machine is a machine producing magnetic flux in the axial direction, instead of the radial direction. Two types of AFPM machines, the slotless and slotted surface-mounted PM, have been mostly discussed. Compared with RFPM machines, the advantages of AFPM machines can be summarized as follows:

- simple winding,
- low cogging torque and noise (in slotless machine),
- short axial length,
- Higher torque/volume ratio.
- However, the disadvantages of AFPM machines in comparison with RFPM machines are as follows:
- lower torque/mass ratio
- larger outer diameter, large amount of PM and structural instability (in slotless machine)
- difficulty to maintain air gap in large diameter (in slotted machine)
- Difficulty in production of stator core (in slotted machine).

The possibility and potential of AFPM machines for large-scale direct-drive wind turbines are discussed here. Owing to its higher energy density compared with other conventional radial flux permanent magnet (PM) type machines, the axial flux PM machine is widely applied in various industrial settings. In particular, when it is employed in high-power systems, it can offer dramatic size reduction. In previous studies, they have generally analyzed axial flux machines using the three-dimensional finite element method (FEM) because of their own structural features, but this is not effective in the initial design stage because it requires a very long analysis time to consider many design variations.
Moreover, because the wind turbine characteristics are essential in the design stage and for the generation performance, one considers the wind turbine characteristics according to wind speed. In addition, the real wind speed is not constant, so it is highly necessary to evaluate the performance under randomly distributed wind speeds. Therefore, we use a back-to-back test system for experiments under varying wind speeds; the results agree well with all the analytical results.

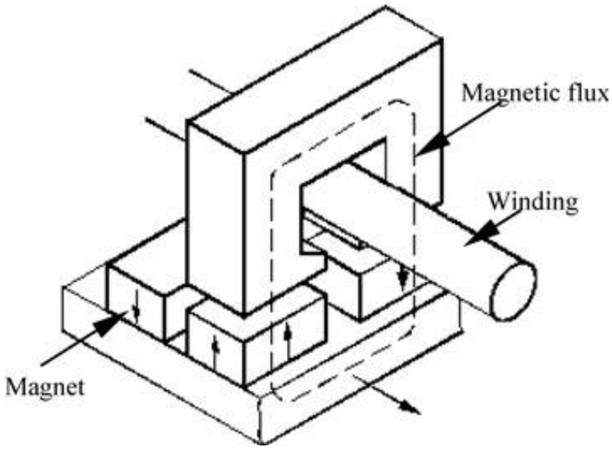
Figure 6:



4.3 Transversal-flux PM machines:

The transverse-flux principle means that the path of the magnetic flux is perpendicular to the direction of the rotor rotation. There are also some different rotor structures for this technology, such as the rotor with single-sided surface magnets with single-sided flux concentration and with double-sided flux concentration.

Figure 7: Surface mounted transversal PM machine



A transverse flux PM (TFPM) machine is a synchronous machine in nature, and it will function in a manner similar to any other PMSG in principle. Compared with longitudinal machines, TFPM machines have some advantages, such as higher force density, considerably low copper losses and simple winding. However, the force density of TFPM machines with large air gap may be a little high or even low depending on the outside diameter. The construction of TFPM machines is much more complicated than longitudinal flux machines. Compared with RFPM or AFPM machines, a major difference is that TFPM machines allow an increase in the space for the simple windings without decreasing the available space for the main flux, and so that the machines have very low copper losses. TFPM machines can also be made with a very small pole pitch; however, the electromagnetic structure is much more complicated. TFPM machines have also the low power factor, which leads to an increase in the necessary rating of the power electronic converter.

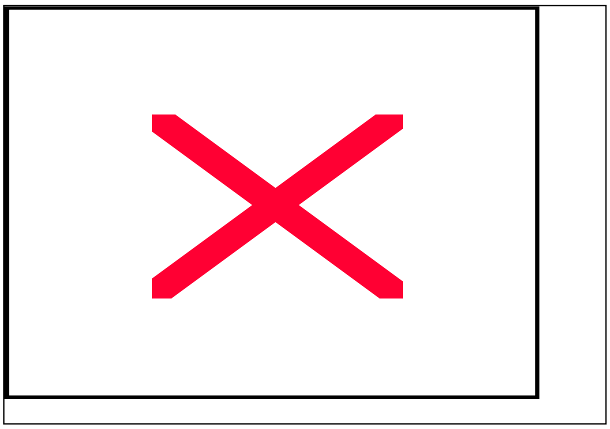
MARKET PENETRATION OF DIFFERENT WIND TURBINE CONCEPTS:

Various types of wind turbines have been on the market with different power levels. In order to present the trends of different wind generator systems on the market, Table 1 shows some wind turbines with a rated power over 2 MW from different manufactures, such as Vestas, Gamesa, GE wind, Repower, Nordex and so on, where the wind turbine concept, generator type, rated power and turbine rotor speed are obtained from manufacturers' websites. As it can be seen, most manufactures are using geared-drive wind turbine concepts. The wind turbines produced by Vestas, Gamesa, GE wind, Repower, Nordex and Ecotecnia

are using DFIG with a multiple-stage gearbox. According to this survey, it is clear that the wind market is still dominated by DFIG with a multiple-stage gearbox, and the mostly used generator type is still the induction generator (DFIG, SCIG and WRIG). Two companies, Multibrid and WinWind, use PMSG with a single-stage gearbox. Direct-drive wind turbines are used in Enercon and Zephyros. Enercon have applied EESG, and Zepyros have applied PMSG. Vestas manufacturer maintains its position as the world's largest manufacturer, followed by the Gamesa, Enercon and GE Wind. The world market share at the end of 2004 for each company is 34%, 17%, 15% and 11%.

The figure below depicts the market penetration and share of different wind generator systems based on the recorded world suppliers' market data over a 10-year period (1995–2004) . As it can be seen, the fixed-speed SCIG system has decreased about 3-fold over 10 years, from almost 70% in 1995 to almost 25% in 2004. Market penetration of the Optislip Concept has declined since 1997 in favor of the more attractive variable speed concept (DFIG). The trend clearly indicates that the WRIG type is being phased out of the market. The DFIG wind turbines have increased from 0% to almost 55% of the yearly installed wind power over 10 years, and it clearly becomes the most dominant concept at the end of 2004. Market penetration of the SG concept (EESG or PMSG) has altered little over 10 years, with no such dramatic changes as observed for SCIG, WRIG and DFIG. There is, however, a slight increasing trend over the last 3 years (2002 2004). During the 10 years, the direct-drive SG (EESG and PMSG) has ranked third or fourth.

Figure 8: **World share of yearly installed power for different wind generator systems.**



Source: IET Renewable Power Generation Volume 2

Table 1: Wind Turbine and its Types and Manufacturers.

Wind turbine concept	Generator Type	Power/rotor diameter/ Speed	Manufacturer
Variable speed single-stage gearbox with full-scale power converter	PMSG	5 MW/116 m/14.8 rpm	Multibrid
		3 MW/90 m/16 rpm	Winwind
		2.5 MW/93 m/ 15.5 rpm	Clipper Windpower
Variable speed multiple-stage gearbox with full-scale power converter	SCIG	3.6 MW/107 m/13 rpm	Siemens Wind Power
	PMSG	2 MW/88 m/16.5 rpm	GE Wind
Limited variable speed with multiple-stage gearbox	WRIG	2 MW/88 m/17 rpm	Suzlon
Variable speed direct-drive with full-scale power converter	EESG	4.5 MW/114 m/13 rpm	Enercon
	PMSG	2 MW/71 m/23 rpm	Zephyros

Source: IET Renewable Power Generation Volume 2

TRENDS DISCUSSION

With rapid development of wind turbine technologies, future trends in the wind turbine industry will probably be focused on the gradual improvement of already known technologies, which can be summarized as follows.

- The power level of a single wind turbine will continue to increase, because this reduces the cost of placing wind turbines, especially for offshore wind farms.
- Offshore wind energy is more attractive, because of higher wind speed and more space than on shore wind energy.
- An increasing trend is to remove dispersed single wind turbine in favour of concentrated wind turbines in large wind farms.
- An increasing trend in the penetration of wind power into the power system.

GRID CONNECTION REQUIREMENTS

The penetration of wind power into the power system continues to increase, which implies the situation of the large wind farms is changing from being simple energy sources to having power plant status with grid support characteristics. One major challenge in the present and coming years is the connection and optimized integration of large wind farms into electrical grids. With increased wind power capacity, transmission system operators (TSOs) have become concerned about the impact of high levels of wind power generation on power systems. To handle large-scale integration of wind power, TSOs have issued grid codes and grid requirements for wind turbines connection and operation. The main issues of grid codes can be summarized as follows:

- active power control,
- reactive power control,
- voltage and frequency control,
- power quality, for example, flickers and harmonics,
- Fault ride-through capability.

As mentioned above, the power-control capability and the fault ride-through capability are mainly concerned by some TSOs. Wind farms are required to behave as conventional power plants in power systems, such as regulating active and reactive power and performing frequency and voltage control. And the fault ride-through capability is required to avoid significant loss of wind power production in the event of grid faults. This means wind turbines should stay connected and contribute to the grid in case of a disturbance such as a voltage dip. They should immediately supply active and reactive power for frequency and voltage recovery after the fault has been cleared. Only when the grid voltage drops below the curve (in duration or voltage level), the turbine is allowed to be disconnected.

TRENDS OF WIND GENERATOR SYSTEMS

According to the survey of different wind generator systems and considering the grid connection requirements on wind turbines, the developing trends of wind generator systems may be summarized as follows.

.1*Variable speed concept:*

Variable speed operation is very attractive for a number of reasons, including reduced mechanical stress and increased power capture. As mentioned, the market share of the fixed speed concept has decreased slightly, whereas variable speed wind turbine increases. For various variable speed wind turbine concepts, a multiple-stage geared-drive DFIG with a partial-scale power converter is still dominant in the current market. Compared with other variable speed concepts with a full-scale power converter, the main advantage of this concept is only 30% of the generated power passing through the power converter, so that it may have substantial cost advantages even with low cost power electronics in the future. However, from the viewpoint of the fault ride-through capability, the DFIG system has to endure large peak currents during grid faults, an advanced protection system may be required. On the contrary, variable speed wind turbines with a full-scale power converter may be more effective and less complicated to deal with grid related problems. Therefore variable speed wind turbine concepts with a full-scale power converter will become more attractive.

.2*Direct-drive concept:*

Compared with geared-drive wind generator systems, the main advantages of direct-drive wind generator systems are higher overall efficiency, reliability and availability because of omitting the gearbox. Although the size of direct-drive generators is usually larger, it may not be a serious disadvantage for the offshore wind energy.

.3*PM excited generator type:*

PM machines are more attractive and superior with higher efficiency and energy yield, higher reliability and power to weight ratio compared with electricity excited machines. According to the above survey of RFPM, AFPM and TFPM machines, RFPM machines with surface-mounted PM may be more suitable for direct-drive PM generator types, because of allowing the simple generator structure, good utilization of the active materials and also allowing the relatively small diameter in comparison with AFPM and TRPM machines. In the case of AFPM machines, the disadvantages, which make the machine cost increase and manufacturing difficult, must be solved or improved significantly. Although TFPM machines have some advantages, such as high-force density and simple winding with low copper losses, the disadvantages, such as low-force density in large air gap, complicated construction in manufacturing and low power factor may be obvious. However, TFPM still have potential to be used as a direct-drive PM generator with new topology design, since the machines are more flexible for new topologies. Considering the performance of PMs is improving and the cost of PM is decreasing in recent years, in addition to that the cost of power electronics is decreasing, variable speed direct-drive PM machines with a full-scale power converter become more attractive for offshore wind powers. On the other hand, variable speed concepts with a full-scale power converter and a single- or multiple-stage gearbox drive train may be interesting solutions not only in respect to the annual energy yield per cost but also in respect to the total weight. For example, the market interest of PMSG system with a multiple-stage gearbox or a single-stage gearbox is increasing Although the market share in the fixed-speed wind turbine concept has decreased, the market interest in SCIG based on wind turbines may increase, if it is demonstrated that High Voltage Direct Current Transmission (HVDC) technologies-based wind farms consisting of such SCIG are robust to grid faults. Because HVDC can enhance the ability against power system faults, consequently, the generators, which are sensitive to power system faults such as SCIG, can be used without the problem of ride through power system faults. Furthermore, a variable speed SCIG system with a full-scale power converter has been used for over 3 MW wind turbines, such as Bonus 107 model 3.6 MW of Siemens wind power. It is clear that power electronics will continue to play an important role in the integration of future large wind farms and design of wind generator systems.

DISCUSSIONS OF COMPARISON CRITERIA

Various criteria may be used for comparing different wind generator systems, including the torque density, the cost per torque, the efficiency, the active material weight, the outer diameter, the total length, the total volume, the total generator cost, the annual energy yield, the energy yield per cost, the cost of energy and so on. However, with the increase in wind energy penetration into grids and the development of grid connection requirements, overall qualitative comparison criteria considering wind power quality and wind energy yield may be worthwhile for consideration.

- Current trends of research and development of wind turbine concepts are mostly related to offshore wind energy. The most important difference between the requirements for onshore and offshore wind energy technologies is that it is much more important for offshore turbines to be robust and maintenance free because it is extremely expensive and difficult and even impossible to do offshore maintenance and reparations under some weather conditions, so that the reliability and availability of large wind generator systems may be more important aspects to be taken into consideration.
- With the increasing penetration of wind energy into the grid, some performances related with grid connection requirements may need to be considered in the quantitative comparison. For example, the solution of the flicker problem may yield an extra cost depending on the types of wind generator systems. The fault ride-through capability is also strongly related to the type of the wind generator systems.
- Some performance indexes referred to wind turbines may have important effects on the annual energy yield of wind generator systems. For example, the cut-in and cut-off wind speeds need to be taken into consideration for comparison of different wind generator systems, because they can influence the annual energy output and the available operational time of wind turbines, with variation of generator types .

The further development of variable speed wind turbine concepts would be focused on optimized turbines and thus moving towards more cost-effective machines. An overall and practical comparison of different wind generator systems, including techniques, economy, control function, availability and reliability, may require to be further investigated.

CONCLUSION

The paper provides an overview of different wind turbine concepts and possible generator types. The basic configurations and characteristics of various wind generator systems based on contemporary wind turbine concepts are described with their advantages and disadvantages. The promising direct-drive PM machines, such as AFPM, RFPM and TFPM machines, have been surveyed. A detailed analysis has been performed based on the survey of the quantitative comparison of different wind generator systems as well as their market penetration. The developing trends of wind generator systems have been presented, and some comparison criteria have also been discussed.

The performance of PMs is improving and the cost of PMs is decreasing in recent years, which make variable speed direct-drive PM machines with a full-scale power converter more attractive for offshore wind power generations. With the increasing levels of wind turbine penetration in modern power systems, grid connection issues have posed several new challenges to wind turbine design and development.

The future success of different wind turbine concepts will strongly depend on their ability of complying with both market expectations and the requirements of grid utility companies.

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